Geochemistry and Isotopes for Resource Evaluation in the Fractured Rock Aquifers of the Table Mountain Group

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Report to the Water Research Commission
by the
Division of Water, Environment and Forestry Technology
CSIR

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GEOCHEMISTRY AND ISOTOPES FOR RESOURCE EVALUATION IN THE FRACTURED ROCK AQUIFERS OF THE TABLE MOUNTAIN GROUP

Report to the
WATER RESEARCH COMMISSION

by

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INTRODUCTION

Fractured rocks are the major source of groundwater supplies in South Africa. Over about 90 % of the surface area of South Africa, groundwater occurs in secondary openings in so-called hard rocks. Reliable tools for resource evaluation in fractured rock aquifers are needed for efficient management of this resource. This is especially true for the Table Mountain Group which is the second largest aquifer system in South Africa, after the dolomites. The Water Research Commission identified the field of hard rock (or fractured rock) aquifers as a field of groundwater research requiring a high priority in terms of funding. The present project is therefore a part of the WRC Fractured Rock Research.

Isotopic and hydrochemical methods provide a well-tested, though relatively under-utilised approach to practical water management. Both isotopic and hydrochemical studies are based on different sets of assumptions than those used in traditional hydrogeologic assessments, and provide a unique record of groundwater processes that commonly yields superior insight. There are, however, too few examples where these techniques are well integrated with the other geohydrological approaches. The present project was designed to do so.

OBJECTIVES

The overall aim of this project as formulated in the agreement between the CSIR and the WRC is:

- ➢ To assess the applicability and usefulness of hydrochemical time-series and isotope time-series monitoring as a tool in fractured rock (Cape Rock) resource evaluation.

The specific aims are :

- ➢ To relate hydrochemical variations and hydrographs to recharge and resource evaluation of the Cape Rocks.
- ➢ To relate groundwater isotopes to hydrochemical variations and hydrographs for the estimation of groundwater residence time and groundwater recharge source areas.

It was envisaged that geochemical and isotopic data could be used to create a groundwater recharge model for this aquifer type. This model will then aid the successful exploitation and management of the fractured rock groundwater resources in many areas of the Western Cape.

PROJECT PROGRESS

Two study sites were selected in order to achieve results within a reasonable time span. The requirements for a study site were that:

- the geology should be reasonably simple and well-understood, and
- there should be existing boreholes with some historical data.

The two sites eventually selected were:

- Agter-Witzenberg, a mountain valley north-west of Ceres and
- Struisbaai, a coastal aquifer near Cape Agulhas on the Cape South Coast.

Eleven research boreholes were drilled, by the DWAF boring branch to supplement existing boreholes in covering both areas and to obtain geological information. Sampling networks were established at the sites for the collection of groundwater, rainfall and surface water data. During the field work phase of the project, volume and water level measurements were taken and water samples collected regularly for chemical and isotopic analysis. Data gathered was then checked and stored in a database for later processing. Additional data was obtained from automatic recorders at some of the sites. Graphs of hydrochemical and isotopic parameters and time series plots were prepared as an aid to data analysis and interpretation. The information could then be compiled into a conceptual recharge model for this aquifer type.

STRUISBAAI

Struisbaai was regarded as a suitable test aquifer since it is an isolated block of Table Mountain group quartzites bounded by faults and the sea, and thus could be studied in isolation. There were also a number (over 10) of existing boreholes for which some data was available. Hydrogeological reports from previous studies, including hydrochemical data were available. In addition there was an existing hydrogeological problem in that the source of high salinities in the groundwater needed clarification. This latter problem was not a research objective, but was regarded as a useful by-product if it could be clarified.

It became evident from analysis of the results of the first year, that the Struisbaai aquifer was not suited for the aims of this project: time related changes. There were no meaningful seasonal variations in any of the isotopic or hydrochemical parameters. Sample collection was therefore abandoned.

The data has been analysed in detail and has been submitted as an MSc thesis to the University of the Orange Free State by John Weaver. The thesis is attached to this report as Appendix G.

The conclusions from the work at Struisbaai are:

- The salinity observed in groundwater at Struisbaai is due to wind-blown sea-salt.

- Using the chloride balance method groundwater recharge is estimated as 5 % to 16 % of annual rainfall.

- ^{14}C analysis of borehole water indicates that the groundwater flow is from the inland towards the sea which confirms the conceptual hydrogeological model.

- Isotopes have provided some useful additional information in understanding the aquifer at Struisbaai.

In order to quantify the water balance of this area it is recommended that:

- Cumulative samplers should be installed at a number of points in order to understand the rainfall and rain quality parameters and refine the recharge estimates.

- Aquifer tests be carried out, followed by a flow-model in order to quantify the total resource available. This is needed before increased large-scale exploitation takes place. This exploitation is likely to occur as further development takes place in the Struisbaai area.

AGTER-WITZENBERG

Reasons for selecting the site in the Agter-Witzenberg valley appeared to be:

- The geology and physiography are simple.
- An apparent minimum of major faulting with folding being the only structural feature.
- There is a minimum of cultural interference on the hydrochemistry.
- Access is good, and
- The transect chosen was at the water divide, with drainage from the valley being to the north and south.

The only unanticipated factor was that there is a stream crossing the transect which drains to the east. This apparent complicating factor turned out to play an important role in the recharge and isotopic model developed for the study site.

In the Agter-Witzenberg area sampling and analysis commenced in earnest in October 1993 after seven research boreholes had been completed. Further sampling continued until January 1996. The parameters analysed for were adapted to the perceived usefulness of the data at that time. During the last year, for instance, stream water sampling was intensified since it was realised that this component plays a major role in the water balance of the valley. A simplified cumulative rainfall collector was deployed during the last rainy season to supplement the collection devices originally established.

The cross-section of the valley that was studied consists of a mountainous area (~300 metre relief) of Table Mountain Group quartzites extending into the valley floor. The rest of the valley floor is made up of Bokkeveld shales. Both shallow and deep boreholes were established to sample each of these features. Na, Cl, alkalinity, ^{18}O, ^{14}C and ^{87}Sr proved to be the most revealing parameters in the sense that their levels in the different boreholes and their variations with time showed useful and more or less consistent patterns. ^{14}C could not be used to date water here since its concentration is primarily determined by the extent of dissolution of carbonate rather than radioactive decay. This appears to be a common feature in the Cape Rocks.

A conceptual flow model for the water movement in the Agter-Witzenberg aquifer could be set up. The main flow components consist of recharge in the mountains (to the extent of 50 % of the rainfall) which discharges at the base of the mountain and drains away in streams, with some ponding as well. Some isotope enrichment occurs during ponding. In winter most of the stream water drains away in surface streams. Recharge from surface water occurs mainly in summer when farmers draw down the water levels in neighbouring boreholes dramatically. The isotope differences between the mountain recharge and the evaporated stream water provide a useful tracer, with chloride and alkalinity, to follow the movement of this water.

The contact between the Bokkeveld shales and Table Mountain Quartzites is a zone of relatively high hydraulic conductivity providing a mixing conduit for the deep seated older groundwater which has the ^{18}O signature of the rainfall recharge in the high mountain areas and the recharged stream water. Variations of chemical and isotopic parameters from this contact zone are due to the different seasonal mixing regimes. These are obviously mixtures with the end members representing young (< 10 years) stream recharge water and older (50-200 years) deeper water originally recharged in the mountains.

Extensive gain of sodium, and pH increase, caused by ion exchange can be seen in a single borehole drilled through the Bokkeveld shales into the quartzites. The nature and location of this process is not known at this stage, but it could develop into a useful geochemical marker if properly identified.

Cumulative rainfall sampling is a viable, cheap method to characterize rainfall isotopically and with some chemical parameters.

CONCLUSIONS

TMG quartzites and medium-seated groundwater flow

The quartzites of the TMG are recognised as being one of the top three aquifers in South Africa in terms of yield and wide areal distribution. The other two are the dolomites of the Malmani Subgroup and the sands and gravels of the Cenozoic. These TMG quartzites have a high potential for regional water-supply projects in the Western and Southern Cape.

The relevance and potential for development have been further enhanced by the embargo on further dam-building by Minister Kadar Asmal "until all alternate water-supplies have been investigated and developed". In the past the TMG has not been hydrogeologically investigated to the same extent as has been the other two aquifers, consequently there are shortcomings in our understanding of these aquifers which in turn has inhibited large-scale development of the aquifers.

One of the major obstacles is quantification of the available groundwater resource. In theory this is a vast resource. The area covered is tens of thousands of square kilometres and with the Peninsula Formation being 1500 m thick and the Nardouw being 1000 m thick the aquifer volume is enormous. Furthermore, as quartzite is highly competent, fractures at depth will tend to remain open, as opposed to granite (and most of South African hard rocks) for which fractures at depths greater than 200 m will close with time. Added to the above is that the TMG quartzites have undergone intense tectonic activity resulting in areas which have extensive fracturing.

Of particular relevance to the question of quantification is proof of the existence of groundwater from the medium-seated zone of the aquifer. There is abundant evidence of an extensive shallow-seated aquifer. Many boreholes in the 10 to 200 metre depth exist and they pump large quantities of water. The high-yielding hot-water springs are proof that deep-seated flow occurs.

Knowledge that medium-seated groundwater flow does occur makes resources available to the water-supply manager that previously could not be calculated nor relied upon. In addition it makes available the possibility of a method of optimum exploitation of the TMG aquifers.

This method complements the Mediterranean climate of the Western Cape of no rain in summer when water-demand is highest. The method is to "over-pump" the aquifer in summer and lower the water-table tens and up to hundreds of metres. In winter when there is excess recharge this aquifer is allowed to fill up. However, in order to implement such a method, knowledge must be available and confidence must exist for medium-seated flow. The results of this project provide the first set of data that prove that medium-seated flow does occur.

The deep quartzite borehole (G39939) exhibits a number of chemical and isotopic signatures which indicate that it intersects groundwater from deeper levels of the aquifer than either the shallow quartzite boreholes (G39937) or the shale boreholes (G39938).

The graph of $\delta^{18}O$ versus Cl shows that the deep water is a mixture of mountain water and valley water. Tritium and ^{14}C show that this is much older water than encountered in boreholes tapping shallow mountain and valley waters.

The graph of $\delta^{18}O$ versus ^{14}C shows that the shallow mountain and shallow valley boreholes are the youngest water with the valley waters showing an evaporative signature. The two deeper boreholes show older water with the deep quartzite borehole having an $\delta^{18}O$ signature close to the mountain recharge water signature and the deep shale having a signature closer to the valley recharge. Significantly, however, is that the two end members are shallow water. The weight of evidence shown by interpretation of these graphs is that a portion of the recharge occurring in the mountains circulates through the deeper layers before mixing with shallower recharge water from the valley. It is thus concluded that both chemistry and isotopes show that medium-seated groundwater flow does occur.

Down-the-hole geophysical logging showed that the temperature gradient for the deep quartzite borehole was steeper than for the other boreholes and also steeper than expected. This is further evidence that this water has travelled via deeper levels than currently encountered.

Summer pumping and winter-recharge aquifer management

This method of exploitation has been proposed by Prof A Issar of Ben Gurion University who is an advisor to DWAF. This method, for various reasons, has not been adopted as a method of exploitation. Hydrographs from the Agter Witzenberg show that this method of exploitation is indeed being used in the valley by the farmers. The closest pumping borehole is more than 500 metres away, yet water-levels for the deep valley boreholes dropped by 30 metres during the 94/95 pumping season. Elsewhere water-level drops of 80 metres were recorded. At the end of the following winter recharge season water-levels had recovered. This shows that this TMG groundwater management method does work.

Recharge in the TMG quartzites

The very rugged nature of the outcrop together with the coarse sandy soil developed from weathering of the TMG quartzites indicates a high recharge potential. If this can be proved this will be further support for the summer-pumping winter-recharge aquifer management method. For most of South African aquifers recharge is taken to be less than 10 %. Very rarely are double figures mentioned, with the Cenozoic sands being regarded as exceptional at 15 % to 20 %.

Comparing Cl and $\delta^{18}O$ for the two mountain boreholes and the spring with values obtained from five cumulative rainfall samplers the indicated recharge is 50 %. This is an extraordinarily high figure which means that if this potential recharge can be recovered in summer, then the sustainable yield of these aquifers is much higher than has been previously assumed.

Recharge in the past would have been taken to be 8 % to 15 % which is $^{1}/_{6}$ to $^{1}/_{3}$ of the observed value. The excess recharge is lost to the aquifer due to the aquifer being "full" and the excess recharged groundwater discharges as base-flow. Investigations in the Jonkershoek Valley (Midgeley and Scott, 1994) have shown that even in winter river highflow conditions most of the riverwater is groundwater. It is this excess groundwater which should be captured by summer-pumping winter-recharging management.

Cumulative rainfall sampler

The cumulative rainfall samplers have proved to be very useful in collecting a representative annual sample of rainfall quality. Some refinement is needed to prevent insects and bird droppings from contaminating the sample. However, the consistent volume of sample collected for the 8 samplers installed at five sample stations (two were rejected), the consistent chloride and the consistent $\delta^{18}O$ show that these samplers will be very useful for future groundwater studies where aquifer input chemistry and oxygen isotope values are needed.

Achievements and the aims of the project

The original aims of the project were:

- To relate hydrochemical variations and hydrographs to recharge and resource evaluation of the Cape Rocks.
- To relate groundwater isotopes to the hydrochemical variations and hydrographs for the estimation of groundwater residence time and groundwater recharge source areas.

Together these aims have been achieved. The hydrograph and hydrochemical variations suggested distinctions between the aquifers in the area and seasonal changes. It required the addition of the groundwater isotope data and then the rain and surface water measurements to be able to relate the components to each other. The fractured nature of the aquifer causes water in the boreholes to be mixtures from different sources each with its own residence time. A range of residence times is therefore possible for each component of the water balance.

The study of the Agter Witzenberg aquifer has become a good example of the integrated approach to ground water studies in the Cape Rocks. To the authors' knowledge such a wide range of data on a single site has not been attempted either in South Africa or elsewhere. The characterisation of different water sources contributing to an aquifer is only possible by a holistic view of all the data.

RECOMMENDATIONS

- The establishment of the Agter-Witzenberg aquifer as a test site of Cape Fractured Rocks is recommended. This area has now shown itself as a useful testing ground for concepts regarding flow in the Cape Rocks, for which other applications are likely to exist elsewhere in the province. Continuation of some form of monitoring at the boreholes of this site will therefore allow its later availability for other similar studies. On the one hand more data from the site would enable one to confirm or amplify the conclusions reached during the present project. On the other hand it would be a good testing area for techniques or ideas that might develop at a later stage. For such later potential use, it would be useful to continue monitoring water levels, rainfall and to collect rainfall, stream and groundwater samples on a regular basis for analysis of some components. The existence of the research boreholes here and the keen interest of the local farmers will form a good basis for continued operation of such an establishment.
- A detailed proposal for the establishment of the Cape Aquifer Test Site (CATS) is presented as Appendix F.
- The determination of a proper water balance for the valley would be a useful continuation of this project. This would entail stream flow gauging on a regular basis, some monitoring of farmers' water comsumption and estimates of the likely recharge in the agricultural parts of the valley. Analyses of some of the parameters measured in the present study should be continued. Attention should also be given to the water situation further west into the valley and extended towards the south and north where larger water level variations have been reported.
- The applicability of the approach developed in the AgterWitzenberg Valley needs to be tested elsewhere now. Locations where this could be done would be in the Cape Rocks, preferably in contact with other rocks, where large seasonal ground water level variations occur. One would firstly determine whether concurrent chemical and isotopic variations exist at all and then look for likely sources thereof.
- A more detailed groundwater and tracer modeling exercise than the one presented here, would be a useful addition to attempt quantification of the ideas developed here.
- These can yield information on the chemical character that water can assume when in contact with specific

rocks or minerals and possibly set limits to the reaction rates involved. Such studies can include ^{13}C and ^{87}Sr. They are also likely to yield some data on the transient chemical effects when a freshly drilled borehole is exploited. The results obtained from water/rock interaction for Struisbaai have provided valuable insight into the origins of the groundwater salinity. Further studies for a variety of rock types have the potential to develop into a useful chemical/isotopic fingerprinting technique.

- Cumulative rainfall sampling is a viable, cheap method to characterize rainfall isotopically, though not quite as effective for hydrochemical measurements. These should be used more often in groundwater *investigations where either recharge* estimations are made, or where the geochemical input into a catchment is studied.

THESES

Two MSc theses have emanated from this project. The results of the first two sampling runs formed the basis of an MSc dissertation submitted by K Pietersen to the University of the Orange Free State in 1994 and a paper presented at the Groundwater '95 conference in Midrand. The Struisbaai data was used by John Weaver for an MSc dissertation to the University of the Orange Free State in 1997. This latter thesis is part of this report and is presented as Appendix G.

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➢ The Water Research Commission for funding the project and in particular Mr. A.G. Reynders for his active support.

➢ The Steering Committee of this project for their advice and support. The inaugural (1993) Steering Committee consisted of the following persons:

Mr A.G. Reynders	Water Research Commission - Chairman
Mr. H.M. du Plessis	Water Research Commission
Dr D.B. Bredenkamp	DWAF
Prof J. Kirchner	IGS, UOFS
Dr. J.C. Vogel	Ematek, CSIR
Mr. Z.M. Dziembowski	DWAF
Dr. F. Walraven	Geological Survey
Dr. G. Tredoux	Watertek, CSIR
Mr. S. Meyer	DWAF
Dr. J.N.E. Fleisher	Watertek, CSIR

During the course of the project there were some Steering Committee personnel changes, thus the final (1996) Steering Committee comprised the following:

Mr A.G. Reynders	Water Research Commission - Chairman
Mr. H.M. du Plessis	Water Research Commission
Dr. J.C. Vogel	Environmentek, CSIR
Dr. G. Tredoux	Environmentek, CSIR
Mr. Z.M. Dziembowski	DWAF
Mr. S. Meyer	DWAF
Dr. B.M. Eglington	Council for Geoscience
Prof. F.D.I. Hodgson	IGS, UOFS
Prof J. Kirchner	Private consultant
Ms. J. Kotze	SRK

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→ drilling of eleven boreholes,
→ geophysical logging of boreholes (Mr. Barry Venter),
→ equipping four boreholes with water level recorders and rainfall recorders, and
→ the collection of the graphs from these recorders.

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  Mr. I. Hanekom
  Mr. R. Fell

- The Struisbaai Municipality.

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- Ingrid van der Voort for carrying out the flow-modelling of the Agter-Witzenberg aquifer.

- All our colleagues at the CSIR and elsewhere for valuable discussions which increased our insight into the project.

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- Mr. Schalk Meyer of DWAF for the initial site selection.

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CHAPTER 1.

INTRODUCTION

1. INTRODUCTION

1.1 Preface

Groundwater provides an essential water resource which needs to be managed properly to ensure sustainability. Successful resource evaluation of an aquifer requires accurate information on the origin, age, source and migration paths of groundwater. To characterise and quantify regional and transient effects in an aquifer using only hydrogeologic methods often requires the difficult and costly collection of data from multiple wells, time-series analysis of water levels, discharge monitoring and permeability and aquifer boundary determinations (Criss and Davisson 1996).

Fractured rocks are the major source of groundwater supplies in South Africa. Over about 90 % of the surface area of South Africa, groundwater occurs in secondary openings in so-called hard rocks (Vegter 1995). Reliable tools for resource evaluation in fractured rock aquifers are needed for efficient management of this resource. This is especially true for the Table Mountain Group which is the second largest aquifer system in South Africa, after the dolomites.

"The customary approach to wellfield evaluation viz. short term aquifer testing and data analysis to derive hydraulic parameters, is of questionable value in a complex fractured medium such as the Table Mountain Group sandstones. Groundwater management by means of long-term aquifer monitoring seems to be a more meaningful method of groundwater resource evaluation" (DWAF 1994).

The Water Research Commission identified the field of hard rock (or fractured rock) aquifers as a field of groundwater research requiring a high priority in terms of funding. This was highlighted at a "Workshop on fractured rock aquifers" held on 10 April 1992. This project, however, was proposed in 1991 and work commenced in January 1992. As such it preceded the workshop, but now forms part of the WRC Fractured Rock Research Programme.

Isotopic methods provide a well-tested, but curiously under-utilised means for practical water management. Isotopic studies are based on a completely independent set of assumptions than those used in traditional hydrogeologic assessments, and provide a unique record of groundwater processes that commonly yields superior insight (Criss and Davisson 1996). There are, however, too few examples where isotopic and hydrochemical techniques are well integrated with the other geohydrological approaches.

Hendry (1988) regards isotopes as being a neglected tool for use in groundwater studies and makes the following three statements concerning the use of isotopes in hydrogeological studies:

- "Ask them (isotope geochemists) whether their work is useful and they will reply, 'Of course, isotopes are an indispensable tool of the modern hydrogeologist!' A quick review of the literature, however, indicates that this indispensable tool is hardly ever used."

- "I personally feel isotopes are an indispensable tool to the modern hydrogeologist. As we learn more about the unique ways in which isotopes behave in flow systems, it becomes clear that they are different from a plain old ion, and they can be interpreted in different ways."

- "The burden for the lack of familiarity with the usefulness of isotopes cannot, I feel be placed on the shoulders of practising hydrogeologists. It must rest squarely on the shoulders of the isotope geochemists. We who use isotopes have, as a group, failed to perform the most important aspect of our research endeavours which is technology transfer."

In a (semi-) arid country where recharge and water flow is a very erratic occurrence and therefore difficult to quantify, studies such as the Orapa/Lethlakeng collaboration of Verhagen and others (1996) are now indicating the direction that needs to be taken: full integration of the elements of 'classical' geohydrology and the modelling thereof together with that of hydrochemistry and isotopes.

1.2 Objectives and aims of the project

The aims of the project as formulated in the original proposal to the WRC are:

Overall Aim:

- To assess the applicability and usefulness of hydrochemical time-series and isotope time-series monitoring as a tool in fractured rock (Cape Rock) resource evaluation.

Specific Aims:

- To relate hydrochemical variations and hydrographs to recharge and resource evaluation of the Cape Rocks.
- To relate groundwater isotopes to the hydrochemical variations and hydrographs for the estimation of groundwater residence time and groundwater recharge source areas.

It was envisaged that geochemical and isotopic data could be used to create a groundwater recharge model for this aquifer type. This model will then aid the successful exploitation and management of the fractured rock groundwater resources in many areas of the Western Cape.

1.3 Site selection

During 1990, the Directorate Geohydrology, Department of Water Affairs and Forestry (DWAF) embarked on a project to characterise the groundwater resources of the Table Mountain Group. The project leader is Mr. S. Meyer, formerly of the Western Cape Office of the DWAF, now of the George Office. He identified 33 areas where substantial abstraction of groundwater occurs. Monitoring networks were established at about ten of these sites. During pre-proposal discussions, three sites were identified as suitable study areas for this project, namely St. Francis Bay , the Klein Karoo and Agter-Witzenberg.

The requirements for a study site were that:

- the geology should be reasonably simple and well-understood, and,
- there should be existing boreholes with some historical data.

Further discussion resulted in the Klein Karoo and St. Francis Bay being discarded as study sites and the two sites selected for study were:

- Agter-Witzenberg, a mountain valley north-west of Ceres and
- Struisbaai, a coastal aquifer near Cape Agulhas on the Cape South Coast.

The site in the Agter-Witzenberg Valley was well-suited to a study of this nature:

- The geology and physiography are simple.
- There is a minimum (an apparent absence) of major faulting with folding being the only structural effect present.
- There is a minimum of cultural interference on the hydrochemistry.
- Access is good, and
- the transect chosen was at the water divide, with drainage from the valley being to the north and south.

The only unanticipated factor was that there is a stream crossing the transect which drains to the east. This apparent complicating factor turned out to play an important role in the recharge and isotopic model developed for the study-site.

Struisbaai was chosen as a study site as:

- The block of Table Mountain Group Quartzites is bounded on three sides; to the south and east by the sea and to the north by a downthrow fault, the graben of which is filled with Jurassic sediments.
- The pre-Bredasdorp Formation topography is flat as a result of an ancient wave-cut platform.

- → The general physiography is flat, resulting in local recharge, with no apparent regional surface flow.
- → The Department of Water Affairs and Forestry had carried out some hydrological investigations there.
- → There was some historical geochemical data.

It was discovered from analysis of the data, that the study site at Struisbaai was not ideally suited for this type of work. Further sampling at this site was therefore discontinued after one year. The data showed that there is no variation of isotope ratios across the site except for ^{14}C. The chemical variations are related to salinity probably due to the proximity of the sea. The cover of the Bredasdorp Formation was regarded as a complicating factor, not allowing a detailed observation of Table Mountain Group geology. Thus all conclusions regarding the Table Mountain Group were interpolations which were regarded as unsatisfactory. The study at Struisbaai was thus discontinued in early 1995.

1.4 Previous work

No comprehensive geohydrological investigations had been conducted in the Agter-Witzenberg Valley before commencement of this project.

During the course of this project, work on the geohydrology and hydrochemistry of the Agter-Witzenberg aquifers formed the basis of an M.Sc. dissertation by Pietersen (1994) and a paper entitled *Hydrogeochemical study of the Agter-Witzenberg Valley aquifers, Western Cape* (Pietersen *et al.*, 1995) presented at Groundwater '95, Ground Water Recharge and Rural Water Supply Conference in September 1995. This work summarised the results of the first sample trip to the Agter-Witzenberg Valley.

For Struisbaai a number of previous investigations have been undertaken:

- ➢ Meyer (1986a) looked at alternative drilling sites for water supply.
- ➢ Meyer (1986b) investigated the high salinity in the groundwater.
- ➢ McLea (1990) conducted a groundwater exploration project which replaced the existing boreholes which had high salinities.
- ➢ Toens (1992) carried out a regional groundwater hydrocensus and made some recommendations regarding alternate drilling sites.

1.5 Report structure

A brief introduction to the use of various stable and radioactive isotopes in hydrological studies, specifically in relation to groundwater, appears in the following chapter. The information has been derived from a literature review and includes some of the case studies where these tools have been used.

Results and their discussion from the two study areas have been divided into separate chapters. Chapter 3 presents work undertaken in the Agter-Witzenberg Valley. It includes the findings from this work and the inferred recharge mechanisms and groundwater movement patterns.

Conclusions on the applicability of geochemical and isotopic techniques for groundwater resource evaluation form the focus of Chapter 4 followed by recommendations for future work in this field and technology transfer actions in Chapter 5.

Throughout the report, the policy has been adopted to include the figures and tables in the main body of the text wherever possible to avoid disrupting the flow of ideas and reduce the necessity for constant paging backwards and forwards. Large indigestible tables of values have been avoided and instead pertinent information has been conveyed graphically. The full data set collected during the course of the project does, however, appear in the Appendices at the end of the report. Details of the borehole construction for Agter-Witzenberg have also been attached as an Appendix, except where they are vital to the understanding of the groundwater chemistry.

A large number of graphs have been compiled to illustrate many of the findings and concepts. The problem arose as to how to present and explain the implications of these figures in a manner that was easy to read and absorb. Thus we have departed from the conventional reporting style and have chosen instead to present each graph as a separate unit with an extended discussion rather than a caption below the figure.

The work carried out at Struisbaai has been analysed in detail and has been used for an MSc thesis submitted to the University of the Orange Free State by John Weaver. This thesis is reproduced in its entirety and is contained in Appendix G. The decision to present the data in this manner is for two reasons. Firstly the data and results do not contribute to the overall aim of this WRC project. Secondly the results have proven to be a very useful contribution to the question of groundwater salinity. This is the first South African recorded case of sea-spray being the cause of salinity in groundwater and as such is regarded as being worthy of publication by the WRC.

CHAPTER 2.

Uses of Environmental Isotopes in Geohydrology

2. USES OF ENVIRONMENTAL ISOTOPES IN GEOHYDROLOGY

The naturally occurring stable isotopes, hydrogen (H), deuterium (D), oxygen-16 (^{16}O), oxygen-18 (^{18}O), carbon-12 (^{12}C) and carbon-13 (^{13}C) and the radioactive forms, tritium (T) and carbon-14 (^{14}C), have become useful tools in groundwater studies. The main hydrogeological use of environmental isotopes can be summarised as follows:

- ➢ to provide a signature to a particular water type
- ➢ to identify the occurrence of mixing two or more water types
- ➢ to provide residence time information about groundwaters
- ➢ to provide information concerning travel times and groundwater velocities
- ➢ to provide information on water-rock interaction (Lloyd and Heathcote 1985)

As it is not useful to present the absolute concentration of a single isotope, stable isotopic abundances are reported as a ratio to some abundant isotope of the same element or as positive or negative deviations of these isotope ratios (R) away from a standard. The relative difference is designated by δ (normally expressed in parts per thousand, permil ‰).

$$\delta_x = \frac{R_x - R_{std}}{R_{std}} * 1000$$

R is the particular isotopic ratio (for example $^{18}O/^{16}O$ or $^{13}C/^{12}C$) for the sample and standard . The standard used for carbon is PDB (Pee Dee Belemnite) and for oxygen and hydrogen SMOW (Standard Mean Ocean Water).

The isotope ratios of natural compounds may change as a consequence of the history and processes to which such compounds have been submitted in the environment. The mass differences between isotopes of the same element produces small differences in their chemical and physical behaviour which in turn establish slightly different isotopic compositions (isotope fractionations), among co-existing chemical compounds or phases (Unesco 1973).

2.1 Stable isotopes of oxygen and hydrogen in the hydrological cycle

The most important physical process causing variation of isotopic composition in natural waters is vapour-liquid fractionation during evaporation and condensation. The vapour pressure of water containing the light isotopes (^{1}H and ^{16}O) is greater than that of water containing the heavier isotopes (D and ^{18}O). When liquid water and water vapour are in equilibrium, the vapour is isotopically lighter with respect to both D/H and $^{18}O/^{16}O$ than the liquid, and hence water vapour in the atmosphere is isotopically lighter than water in the ocean (Drever 1988). Water vapour which evaporates from the ocean is depleted by 10-15‰ in ^{18}O and by 80-120‰ in D with respect to SMOW (Standard Mean Ocean Water) (Unesco 1973; Drever 1988).

When water vapour condenses to form rain, fractionation takes place in the reverse direction, with the liquid being isotopically heavier than the vapour. The fractionation during evaporation is thus largely reversed during condensation and the first rain to fall from water vapour over the ocean would have an isotopic composition of about -3 ‰ (Drever 1988). If this rain again forms a vapour, ^{18}O will be selectively removed from the vapour phase and $\delta^{18}O$ of the vapour will become progressively more negative as the rain continues to fall. By this process of *Rayleigh fractionation*, rainfall becomes progressively lighter in both δD and $\delta^{18}O$ as it occurs further from the ocean source. The δD and $\delta^{18}O$ values in precipitation generally plot close to a straight line (the *meteoric water line*) with equation:

$$\delta D = 8 * \delta^{18}O + 10$$

The slope (8) is a general constant determined by the physical properties of the isotopes. The intercept (10), also called the d-excess, is a general one applicable to the world's composite set of samples (Dansgaard 1964). Locally d-excess values ranging from 0 to +25 have been observed (IAEA 1992; Gat and Carmi 1970).

Water with an isotopic composition falling on the meteoric water line is assumed to have originated from the atmosphere and to be unaffected by other isotopic processes. Evaporation from open water and exchange with rock minerals are two of the more commonly observed processes causing deviations from the meteoric water line (Domenico and Schwartz 1990).

As temperature has a dominant effect on isotopic fractionation, variations in isotopic concentrations in precipitation can relate to climate and altitude (Lloyd and Heathcote 1985). This dependency on temperature produces seasonal isotope variations (winter precipitation is depleted in heavy isotopes with respect to summer precipitation); latitude variations (high latitude precipitation is depleted with respect to low latitude precipitation) altitude effects (the heavy isotope content of precipitation decreases with increasing altitude) and amount effects (larger rainstorms tend to have lower heavy isotope content). In regional hydrological studies, the altitude effect can be used to differentiate groundwaters derived from recharge areas at different elevations. In general there is about a 0.3 ‰ decrease in $\delta^{18}O$ and 2.5 ‰ decrease in δD per 100 metres increase in elevation (Unesco 1973; Midgley and Scott 1994).

Isotopes of oxygen and hydrogen are, in a certain sense, ideal geochemical tracers of underground water because their concentrations are not subject to changes by interaction with the aquifer material (Unesco 1973). Once underground and removed from zones of evaporation, the isotope ratios are conservative and only affected by mixing. When precipitation infiltrates to feed groundwater, mixing in the unsaturated zone smoothes the isotopic variations, so water in the saturated zone has a composition corresponding to the mean isotopic composition of infiltration in the area. This may differ slightly from the mean isotopic composition of precipitation due to the fact that not all precipitation during the year infiltrates in the same proportion (Unesco 1973).

Analyses of D and ^{18}O can be used to identify the probable source of an underground water. If the isotopic composition of an underground water plots close to the meteoric water line in a position similar to that of present-day precipitation in the same region, the water is almost certainly meteoric. Although the isotopic composition of precipitation at a particular location is approximately constant, it varies from season to season and from one rainstorm to another. The variations can be used to identify the season at which most of the recharge takes place (Drever 1988).

Groundwater recharged by seepage from surface waters such as rivers or lakes should reflect the isotopic signature of the surface water body eg. a river may collect water which originates at higher altitudes and is depleted in heavy isotopes while seepage from lake waters which have been evaporated will be enriched in heavy isotopes. Isotopic imaging of surface water/groundwater interactions is a useful application of D and ^{18}O data. Groundwater isotope data across the Sacremento Valley, California has been used to establish groundwater mining of ancient groundwater and to identify regions of limited recharge by surface water and areas of rapid recharge by irrigation water (Criss and Davisson 1996). Such information can now be used to design an aquifer management scheme for the region.

In some areas palaeowaters may be present with different isotope ratios, often lower than those of present (Heaton *et al.* 1986). These were recharged under different climatic conditions from those prevailing now, and are generally of great age.

2.2 Tritium

Tritium (^{3}H or T) is a radioactive isotope of hydrogen having mass 3 and a half-life of 12.26 years (Unesco 1973). The radioactive decay of T to ^{3}He is accompanied by the measurable emission of β particles, which makes tritium detectable at very low concentrations. The concentration of tritium in water is expressed by the ratio of T atoms to H atoms:

a ratio of **T/H = 10^{-18}** is defined as **1 tritium unit (1 TU)** (Mazor 1991)

Tritium occurs in the environment as a result of both natural (cosmic radiation) and man-made (thermonuclear devices) processes. Most tritium produced in the atmosphere is rapidly oxidised to HTO and incorporated in the hydrological cycle.

The natural production of tritium introduces about 5 TU to precipitation and surface water (Mazor 1991). In the saturated zone, this water is isolated from the atmosphere and the drop in tritium concentration due to radioactive decay should provide a useful water dating tool. However, this is complicated by mixing of waters, and the large inputs of atmospheric T added by hydrogen bomb testing since 1952. The age calculated, from tritium concentrations is therefore not the real age of the water, but rather an average, or *effective age* (Mazor 1991).

In Southern Africa, the tritium in rainfall produced by the nuclear weapon tests reached levels of 60 to 80 TU in the 1960's and has since fallen off to about 5 TU. Age determinations accurate to the year using tritium concentrations are impossible, however semi-quantitative data obtained from tritium studies can sometimes be informative in groundwater investigations:

- Water with zero tritium (in practice <0.5 TU) has a pre-1952 age.
- Water with significant tritium concentrations (in practice >5 TU in the southern hemisphere) is of a post-1952 age.
- Water with little, but measurable, tritium (between 0.5 and 5 TU) seems to be a mixture of pre- and post-1952 water (Mazor 1991).

2.3 Carbon isotopes

Three isotopes of carbon occur naturally: stable ^{12}C and ^{13}C and radioactive ^{14}C (radiocarbon).

The behaviour of the $^{13}C/^{12}C$ ratio in groundwater is determined by the relative influences of the CO_2 present in soil due to plant respiration and the interaction with the carbonates present in the aquifer rock. This system can be complex in the subsurface and the most important application of ^{13}C data is in process identification (Domenico and Schwartz 1990).

$\delta^{13}C$ in soil CO_2 is determined by the $\delta^{13}C$ of the local plants (-25 to -22 ‰ PDB in this area). Dissolution of solid carbonate by this acid solution increases the ^{13}C content of the resulting water. Further changes in $\delta^{13}C$ and alkalinity may occur due to interaction between water and rock during transit through the aquifer. Chemical/isotope changes that may occur are:

- Dissolution of calcite, aragonite, or dolomite from limestone, which introduces relatively heavy carbon.
- Oxidation of organic matter, which introduces relatively light carbon.
- Transport of CO_2 gas from a soil atmosphere, which also introduces relatively light carbon.
- Weathering of silicate minerals that will convert dissolved CO_2 to bicarbonate, thus increasing the alkalinity and pH without changing the ^{13}C content of the water at all.

Carbon may be lost from the water by precipitation of a carbonate mineral or by loss of CO_2 gas. In general ^{13}C is used to identify sources of carbon and the processes occurring underground. It is particularly valuable for distinguishing between carbon derived from organic matter (light) and carbon derived from carbonate minerals (heavy) (Drever 1988).

Radiocarbon (^{14}C) is produced in the atmosphere by the interaction of cosmic rays with nitrogen. Additional quantities were produced by nuclear weapons testing in the 1950's and 1960's. ^{14}C has a half-life of 5730 years, making it a useful tool for dating waters as old as 50 000 years. The ^{14}C generated in the atmosphere is carried down to the earth's surface by precipitation, and becomes incorporated into the biomass or transported into water bodies such as lakes, the ocean and groundwater (Drever 1988).

Measurements of ^{14}C are reported in terms of per cent modern carbon (pmc) where:

$$A=\frac{(^{14}C/^{12}C)_{sample}}{(^{14}C/^{12}C)_{modern}}*100pmc$$

There are some complications in the behaviour of ^{14}C in groundwater, causing difficulties so that the "absolute" age of a groundwater cannot be determined reliably. If the ^{14}C concentration is measured at several points along a flow line within an aquifer, the differences in age between the points and hence the flow velocity can be determined (Vogel 1967). One complication is that dissolution of organic matter or carbonate minerals within the aquifer may add "old" or "dead" (no detectable ^{14}C) carbon to the water, giving an erroneously old age. The contribution of carbon from these sources can sometimes be estimated from the $^{13}C/^{12}C$ measurements and chemical arguments enabling corrections to be made (Pearson, 1967; Talma *et al.*, 1984). Another complication is mixing between different water types in an aquifer. A low ^{14}C concentration may mean that we are looking at relatively "old" water, or it may mean that we are looking at a mixture of relatively "young" water and "dead" water. The proper interpretation of ^{14}C measurements in groundwater requires knowledge of the flow of the water, the sources of dissolved inorganic carbon in the water and a conceptualization of the underground chemical processes. Chemistry, other isotopes and basic geohydrological observations and measurements are required to establish this (Drever 1988).

2.4 Strontium Isotopes

Strontium isotopes, expressed as the ratio of the isotopes ^{87}Sr and ^{86}Sr, are another useful tracer pair. This ratio is not influenced by any biochemical process and varies in water according to the age of the source rocks from which it is derived and its Rb/Sr ratio (Eglington *et al.* 1993). Sr occurs in most silicate minerals and in carbonate rocks and is released into the water by weathering. Earlier work has shown that the strontium isotope ratio varies widely in different water types, according to some systematic pattern (Kirchner 1995, Talma *et al.* 1996). Strontium is particularly useful to distinguish between marine water (with Sr=8 mg/l and $^{87}Sr/^{86}Sr=0.7092$) and terrestrial water (usually with higher $^{87}Sr/^{86}Sr$ ratio and lower Sr content). The advantage of the use of Sr isotopes as tracer is that the isotope ratio is preserved even when the element concentration might reduce due to precipitation or adsorption. Isotope ratio changes can only be caused by the addition of Sr due to mineral dissolution or mixture with another water type (Eglington and Meyer 1996).

CHAPTER 3.

Agter-Witzenberg

3. AGTER-WITZENBERG

3.1 Physiography

The Agter-Witzenberg Valley is located approximately 140 km from Cape Town, near the town of Ceres in the southwestern Cape (Figure 3.1). The study area consists of a north-south trending basin covering an area of 245 km^2, located in mountainous terrain. It forms part of the NNW-SSE striking Cedarberg folds of the Cape Fold Belt (De Beer 1989). The intense folding is ascribed to flat plate subduction (Lock 1980). This resulted in the competent sandstone units forming the mountain ranges, with the more erodible shales of the Bokkeveld Group forming the valley. The Agter-Witzenberg aquifer is surrounded by the Skurweberg and Witzenberg mountain ranges (Figure 3.2). The highest peak, Sneeugat, rises 1884 metres above mean sea level. Within the valley, elevations range between 600 and 900 metres above sea level.

Streams originating in the valley drain part of Tertiary catchment area E10A (Midgley et al., 1994). Natural drainage in the valley is diverted northwards and southwards by the presence of a topographic mound. The valley is a catchment source for both the Breede river which flows to the Indian Ocean and the Olifants river which flows to the Atlantic. Mean annual surface runoff from the catchment area E10A is 61.4 x 10^6 m^3 (Pitman *et al.*, 1981).

Native vegetation in the area was *Macchia* (fynbos) but this was cleared for agricultural use. Deciduous crops are now grown in the region and groundwater is primarily used for irrigation of these crops, particularly in the dry summer months.

3.2 Climate

The Agter-Witzenberg area falls in the mediterranean climate region of South Africa, with rainfall occurring predominately during the winter months. Average annual rainfall and evaporation is in the region of 890 mm and 1650 mm, respectively (Pitman *et al.*, 1981). The mean monthly figures are shown in the graph (Figure 3.3).

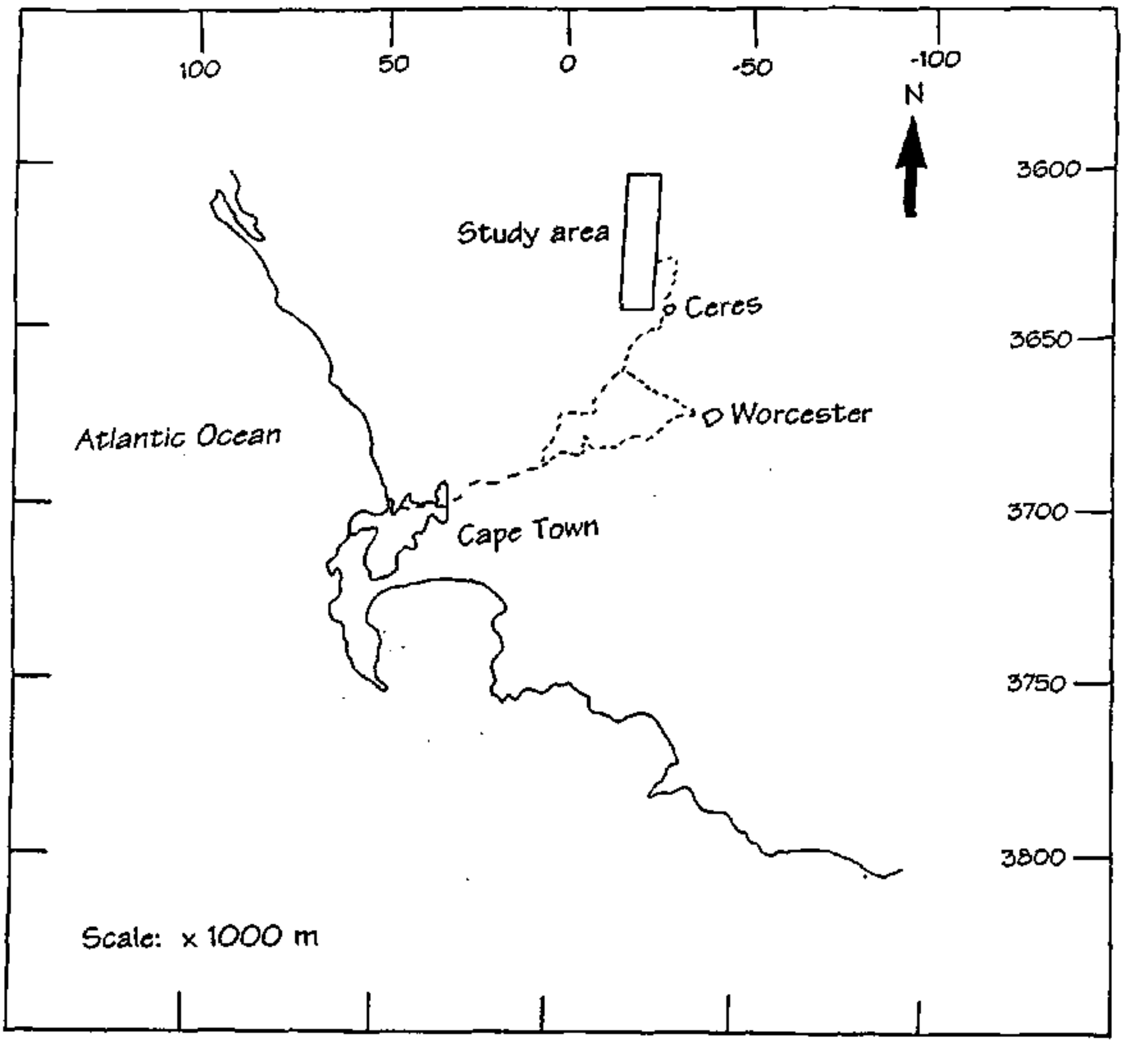

Figure 3.1 : Location of the Agter-Witzenberg Valley.

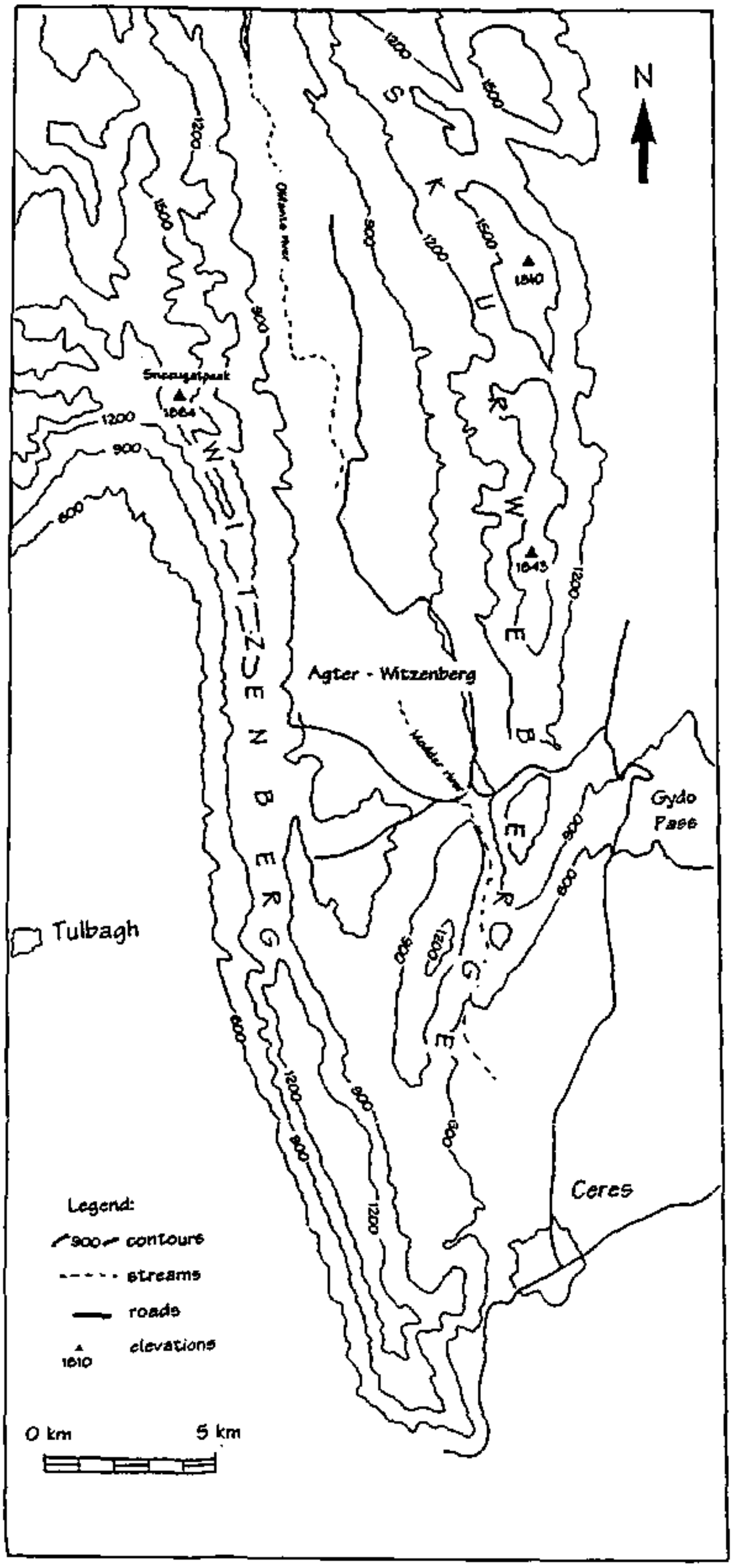

Figure 3.2 : Topography of the Agter-Witzenberg Valley.

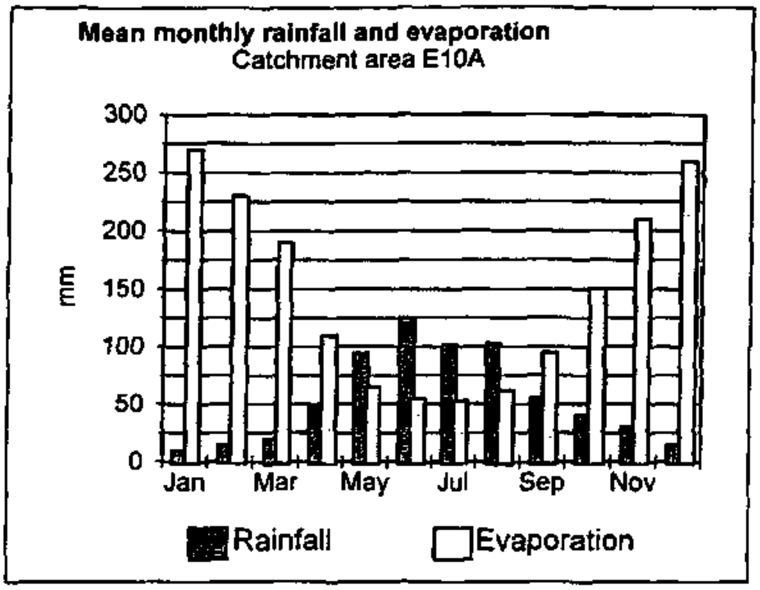

Figure 3.3: Comparison of mean monthly rainfall with mean monthly evaporation for catchment area E10A (from Pitman *et al.*, 1981).

3.3 Geology

The surface geology of the Agter-Witzenberg Valley is shown in Figure 3.4.

The lithostratigraphic groups from oldest to youngest found in the valley are:

- Malmesbury Group
- Table Mountain Group
- Bokkeveld Group

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Figure 3.4
Geology Map - Agter Witzenberg
(Geology after 1 : 125000 Geological Map 3319A Ceres, Geological Survey, 1975)

Legend

- ═ Tracks
- ⋀ Farm Boundaries
- ·74 Spot Elevation
- ~ Contours (20m interval)
- ▨ Wetland
- ●BH5 Borehole
- ═ Probable TMG Bokkeveld Contact
- ▨ Bidou Subgroup; Shale, Silt, Sandstone
- ■ Ceres Subgroup; Shale, Sandstone
- ▨ Nardouw Subgroup; Quartzite
- ■ Cedarberg Formation; Shale
- ☐ Peninsula Formation; Quartzite

N

0 0,5 1,0
kilometre

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Table 3.1 : Lithostratigraphy of the Agter-Witzenberg Valley (After Tankard *et al.*, 1982)

Group	Subgroup	Formation	Thickness (m)	Lithology
Bokkeveld	Bidouw	Waboomberg	200	siltstone, quartz, arenite, shale, black shale near top.
	Ceres	Boplaas	30	quartz arenite and lithic arenite.
		Tra-Tra	85	mudstone, siltstone, subordinate sandstone
		Hex River	100	arkose, lithic arenite and quartz arenite
		Voorstehoek	115	siltstone, shale, fine-grained sandstone
		Gamka	135	feldspathic sandstone, quartz arenite and mudstone.
		Gydo	160	black shale, mudstone and siltstone
Table Mountain	Nardouw	Goudini Skurweberg Rietvlei	1100	quartz arenite
		Cedarberg	140	siltstone, mudstone, fine-grained sandstone
		Pakhuis	120	sandstone, conglomerate, diamictite
		Peninsula	1800	quartzitic sandstone
Malmesbury		Porterville	?	Phyllitic shale, schist and greywacke

Malmesbury Group

Metasediments of this Group form the basement of the study area. Rock types found in the Malmesbury Group are predominantly greywacke, with subordinate conglomeratic, limestone and chert units (Tankard *et al.*, 1982). Groundwater located in the Malmesbury Group was not considered in this project as it occurs at great depth in the study area.

Table Mountain Group

The Table Mountain Group is a quartz arenite complex. The two lowermost formations of the Table Mountain Group, the Graafwater and Piekeniers Formations are absent in the study area. Formations present in the region are:

- Peninsula Formation
- Pakhuis Formation
- Cedarberg Formation
- Nardouw Subgroup

The Nardouw Subgroup is of importance for this study because the boreholes drilled in the Table Mountain Group are located entirely within this subgroup. In the region it comprises a 30 to 1100 metre thick westward-thickening wedge of quartz arenites that are postulated to have been deposited in a barrier beach or shallow shelf environment (Pietersen 1994). Thin shale and conglomerate lenses are found in the sandstone. For the study site the Cedarberg Formation, Pakhuis Formation and the Peninsula Formation are not exposed or monitored as they lie below the Nardouw Formation.

Bokkeveld Group

Overlying the Table Mountain Group is the Bokkeveld Group representing the most dynamic phase of Cape Basin development (Tankard *et al.*, 1982). The Bokkeveld Group consists of alternating shale and sandstone units formed by fluvial and shallow water delta processes. This implies a history of tectonically controlled regressions and transgressions (Theron 1972). The Ceres Subgroup of the Bokkeveld Group is represented in the study area. It consists of three laterally continuous, upward coarsening megacycles comprising mudrock which grades into siltstone and sandstone. The Bokkeveld Group contains a diverse suite of invertebrate fossils which date the group as Early Devonian (Theron and Johnson 1991).

Most of the irrigation boreholes in the valley area are located within the Bokkeveld Group. Some water is also drawn from springs at the foot of the mountains.

3.4 Hydrogeology

Both the Bokkeveld and Table Mountain Group units have the capacity to yield significant quantities of water. The relative abundances of groundwater resources, however, varies from place to place (Pietersen 1994) The nature of the semi-unconfined aquifer in the Agter-Witzenberg Valley is controlled by the lithology, stratigraphy, synclinal structure and fracturing of the geologic formations.

3.4.1 *Table Mountain Group*

A network of joints controls the infiltration, recharge, storage and movement of groundwater in the competent and often brittle-natured arenaceous units of the Table Mountain Group. Due to the fractured nature of the sandstones in generally high rainfall regions, recharge is favourable and infiltration rates of up to 15% of precipitation in certain areas, is not unrealistic. From a quantitative point of view the Table Mountain Group thus offers by far the most favourable opportunity for groundwater development from fractured aquifers in the Southwestern Cape region (Meyer 1996. *Pers. comm.*)

The quality of groundwater from the TMG is excellent with EC generally ranging between 5 and 70 mS/m. The water is inclined to be acidic and has a tendency to be corrosive (DWAF 1994).

Deep groundwater circulation is a feature of the Table Mountain Group aquifers. Figure 3.5 shows that borehole yields are often greatest when the borehole is over 200 m deep.

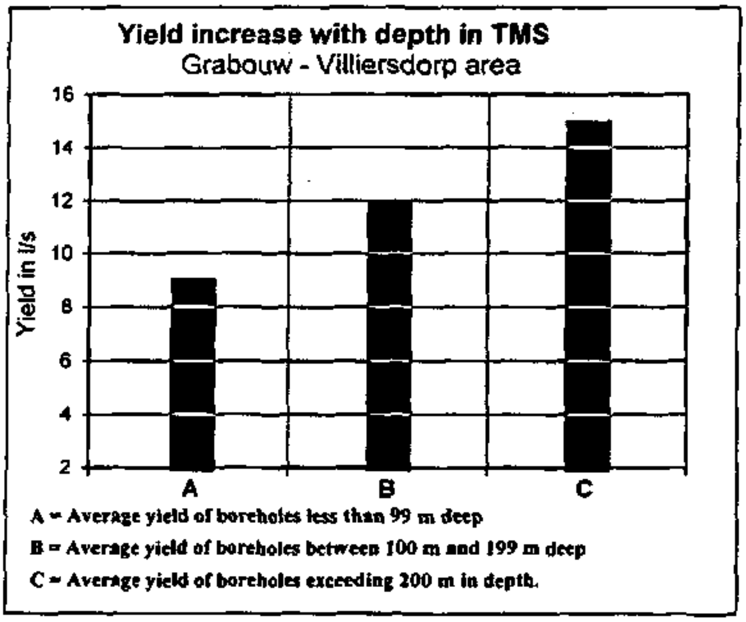

Figure 3.5: Yield increase with depth in Table Mountain sandstone (analysis of 77 records) from DWAF, 1994.

3.4.2 *Bokkeveld Group*

The Bokkeveld Group is roughly divided into three categories, Rûens-Bokkeveld, Kansa-Bokkeveld and Hex-Bokkeveld, based on the increasing arenaceous content of the rocks. The Bokkeveld rocks in the study area fall under the Hex-Bokkeveld. High yielding boreholes with yields of up to 20 l/s and more can be expected, provided there is regular recharge (DWAF 1994).

The rocks of the Bokkeveld Group are predominantly pelitic, but the proportion of arenaceous material tends to increase in the northern areas. This means that the groundwaters in the Hex-Bokkeveld are generally of better quality than those found in the other areas as they contain less soluble material. EC values of less than 100 mS/m are common in the Hex-Bokkeveld.

3.5 Sampling Network

Positions of the sampling points in the study area are indicated on the map in Figure 3.6.

3.5.1 *Rainfall*

Three types of rainfall collecting and measuring devices were installed in the Agter-Witzenberg Valley to provide information on the volume, hydrochemical and isotopic input to the groundwater.

- Automatic chart recorders - G39936 and G39937.
- Rainwater collectors - AWR1 and AWR2.
- Cumulative rainfall samplers - A to J.

The positions of these samplers are shown in Figure 3.7.

The automatic chart recorders were installed adjacent to boreholes G39936 and G39937. These recorders are fitted with a strip chart which keeps a continuous record of the water level in a collector so that the rainfall volume over any given period of time can be determined. They are serviced monthly by the Department of Water Affairs and Forestry. Rainfall data is also available from the nearby Weather Bureau stations at Avalon, Remhoogte and Bokveldskloof.

Rainwater samples were collected in order to compare chemistry and isotopes of recharge water and groundwater. The two rainwater collectors, AWR1 and AWR2, were set up adjacent to the chart recorders. These have a collecting funnel attached to a tube leading down into a sealed container. The other end of the tube is placed inside a sample bottle which stands upright in the bottom of the container. The diameter of the tube is narrower than the bottle neck to allow for overflow into the outer container which removes floating material from the sample bottle. The water from each rainstorm collects in the inner sample bottle from which a chemistry sample is taken during each (monthly) field visit. The data for these samplers thus represents the cumulative rainfall composition since the preceding sampling date. With knowledge of the rainfall quantities of the same period, an estimate of the annual isotope and chemical input at each site can be made.

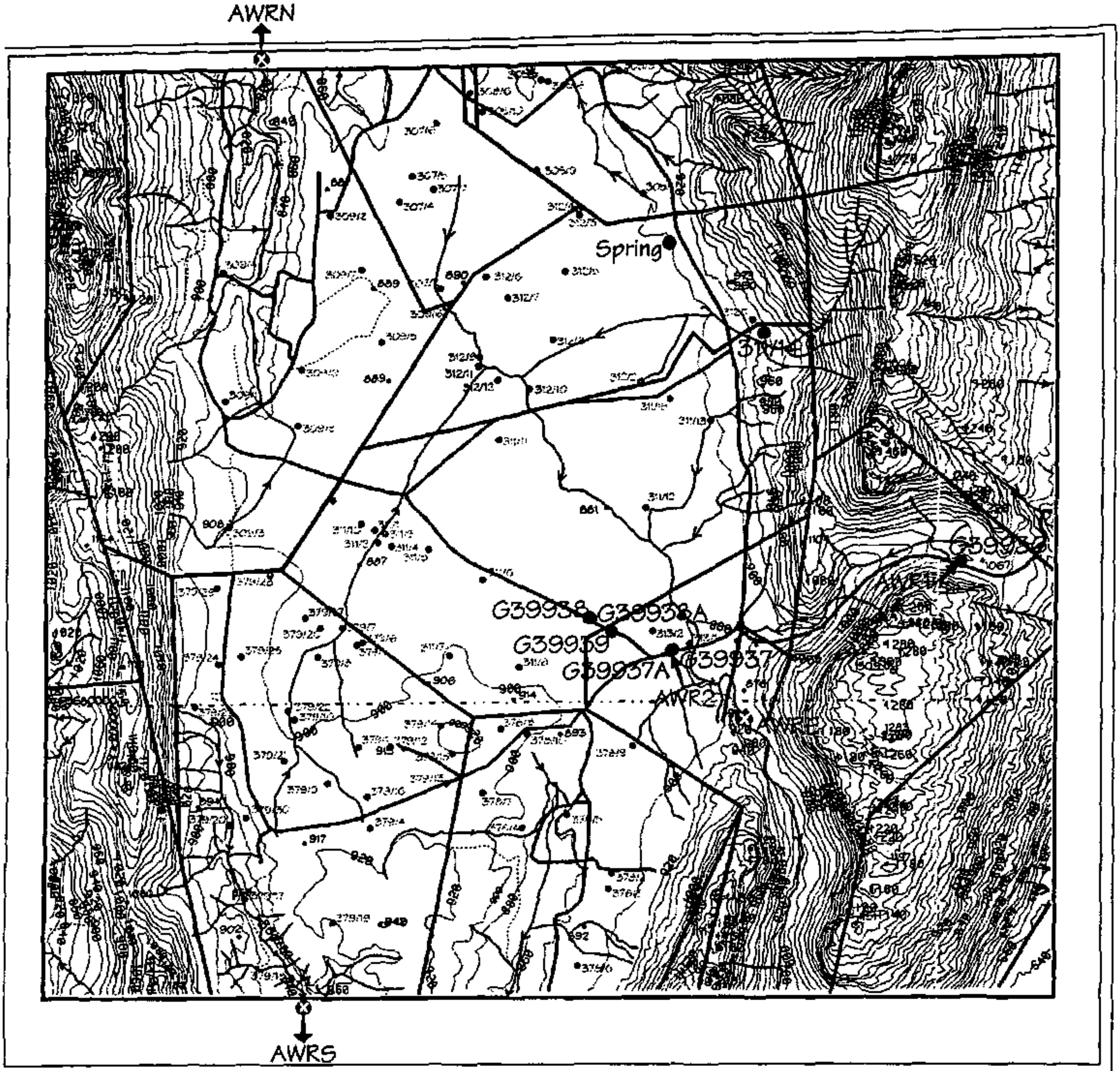

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Figure 3.6

Location of sampling boreholes - Agter Witzenberg

Legend

Tracks	Farm Boundaries
·74 Spot Elevation	—40— Contours (20m interval)
Wetland	● 379/41 Borehole
	●G39938 Sampling borehole

0 0,5 1,0
kilometre

N

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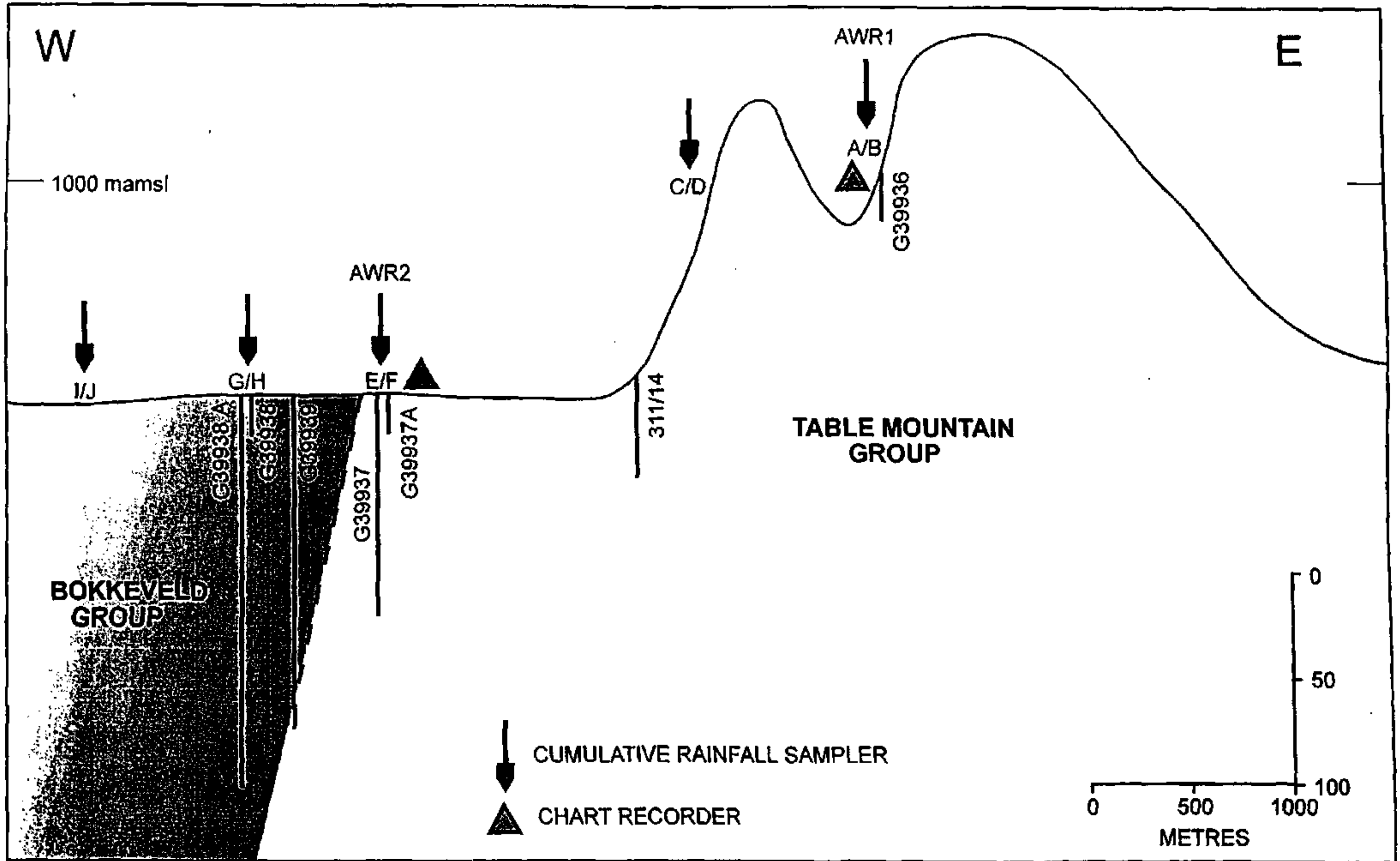

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Figure 3.7: Positions of rainfall sampling devices in the Agter-Witzenberg Valley

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3.5.1.1 New cumulative rainwater sampler

To supplement this approach, a cumulative sampler has been developed and is being tested in the study area and elsewhere. It consists of a PVC pipe mounted vertically and filled with a small amount of silicone oil to prevent evaporation of the collected water (Figure 3.8).

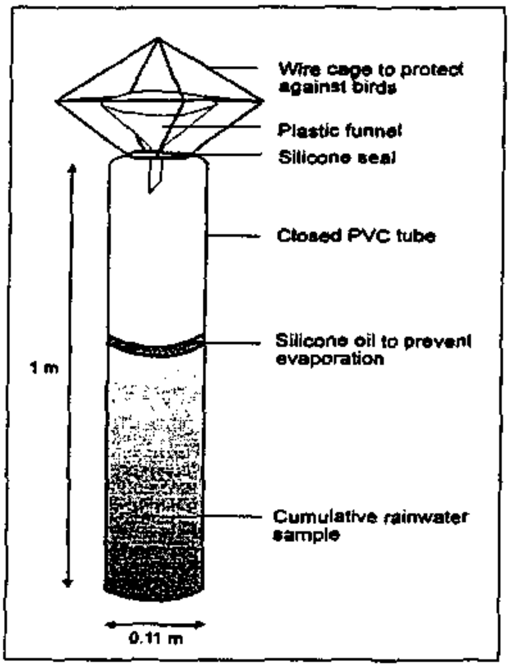


Figure 3.8 : Construction of new cumulative rainwater sampler

The idea is that these collectors can be left unattended for long periods without significant isotopic and chemical change to the water (Friedman *et al.*, 1992) They have been used by the US Geological Survey with some success (Warren Wood 1995, *Pers. comm.*) and could become quite useful in our country. Five pairs of these collectors (A-J) were installed along the profile of the Agter-Witzenberg Valley in May 1995 and emptied one year later.

3.5.2 *Surface Water*

Surface water samples were collected at three sampling stations labelled AWRN, AWRS and AWRE on streams draining the valley to the north, south and east respectively. A limited number of analyses were done on these samples. Flow gauging was also undertaken at these points to determine the volume of water removed from the valley by surface drainage. The details of the stream flow gauging are given in the field report included in Appendix B.

3.5.3 *Groundwater*

Six research boreholes were drilled at the outset of the project to compensate for the lack of geological and hydrogeological control on the existing boreholes in the valley. The boreholes were sited along a profile perpendicular to the trend of the valley (Figure 3.9). This meant that information about the influence of the lateral variations in geology on the aquifer could be obtained.

Since the project was dependent on the accurate measurement of chemical constituents and isotopic concentrations, borehole construction materials were chosen that would not interfere with the composition of the groundwater. Standard class 12 uPVC screw-in type borehole casing and screens were fitted and the construction was completed with a gravel pack. uPVC is not subject to galvanic and electrochemical erosion and will not interact chemically with natural waters.

G39936, G39937A and G39938 were drilled down to the first water strike and fitted with uPVC screens and casing. Two deep boreholes, G39937 and G39938A, have no casing. Borehole G39939 was drilled down through the Bokkeveld into the Table Mountain sandstones. Initially the borehole was drilled down to the contact of the Bokkeveld Group and the Table Mountain Group. Steel casing was then installed and a bentonite plug was poured down the hole to seal off the Bokkeveld water. A narrower drill bit was then used to drill further into the Table Mountain Group. uPVC screens were installed at the bottom of the hole, with solid uPVC casing thereafter. Borehole G39939 therefore should yield water from the deep lying Table Mountain Group only.

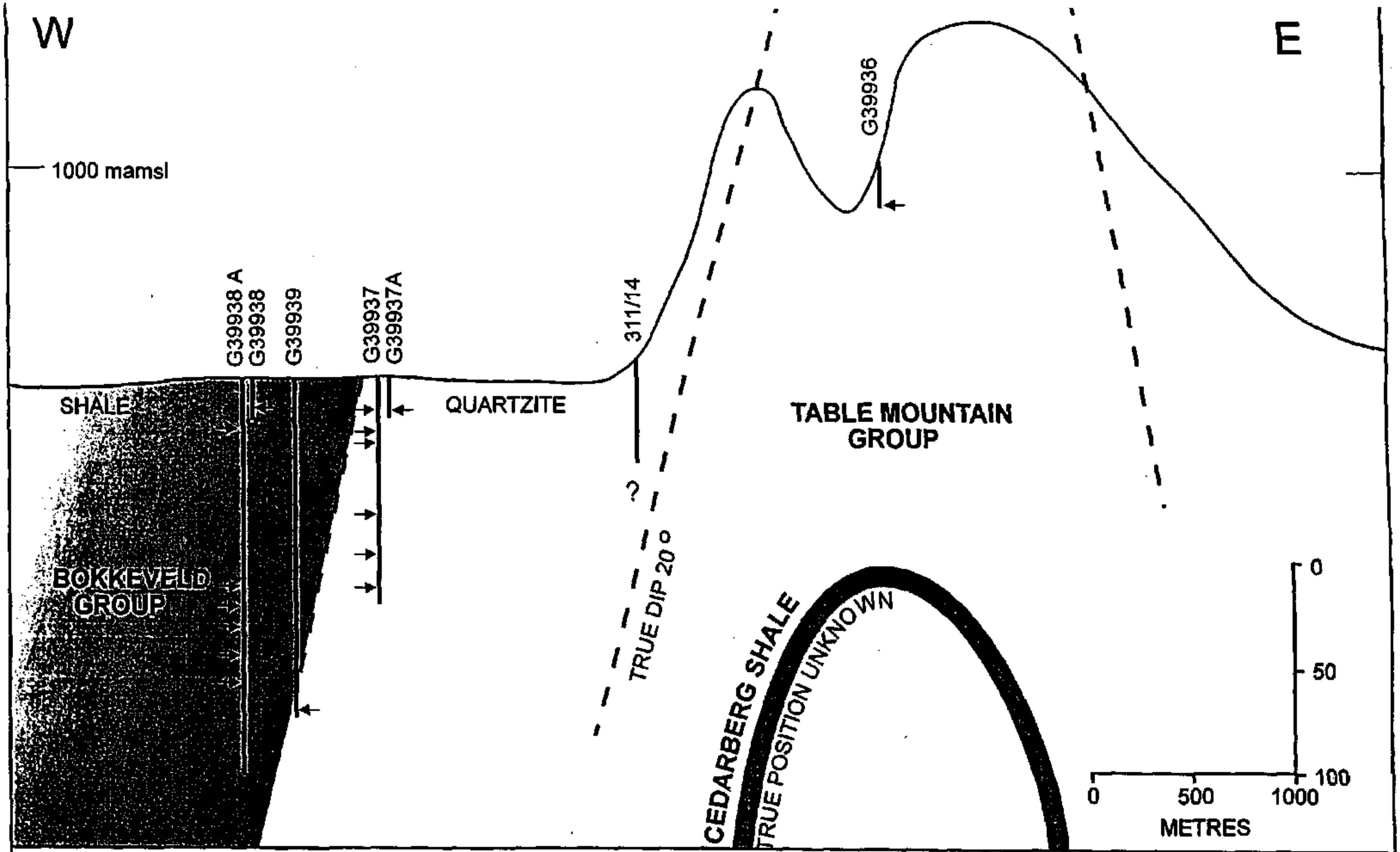
Drilling logs and construction details for the six research boreholes are included as Appendix E.

Boreholes G39936 and G39937 are equipped with automatic water level recorders. The six research boreholes together with 311/14 on the farm Sterkwater and a natural spring to the north of the research boreholes constitute the core of the groundwater sampling network. Additional boreholes in the area, 311/10, 311/11, 311/15 and 313/1, were also sampled on a once-off basis at the beginning of the field work phase.

3.6 Methodology

3.6.1 *Water levels*

Automatic chart recorders maintained by the Department of Water Affairs and Forestry provide a continuous record of the water levels in boreholes G39936 and G39937. The results from these are presented on the graphs in section 3.7.3.



GEOCHEMISTRY AND ISOTOPES

Figure 3.9 Cross section along Agter-Witzenberg valley profile showing borehole positions, depths and water strikes.

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Water levels were also measured manually for each of the boreholes in the sampling network, with the exception of 311/14. G39938 was often found to be dry in the summer months and so has no data for many of the sampling runs. Water levels were measured as depth below datum using a water level probe.

3.6.2 *Sampling Methods*

Regular groundwater sampling was conducted at 2-monthly intervals. Because of the seasonal fluctuations in water table it was not always possible to collect samples from G39938. This is particularly so in the valley in summer when the local farmers pump heavily and the water level drops below the base of the borehole.

For this study, the following determinants were required:

Table 3.2 : Physical and chemical determinants measured.

Group	Determinants
Physical determinants	EC, pH, temperature
Major cations	K, Na, Ca, Mg, NH_4
Major anions	Cl, SO_4, NO_x
Aggregate determinants	Alkalinity, DOC, TIC
Other elements	P, Si
Metals	Cu, Fe, Mn, Zn
Microconstituents	Sr, Rb, Ba, Li
Isotopes	^{13}C, ^{18}O, Deuterium, ^{15}N (stable) ^{14}C, Tritium (radioactive) $^{87}Sr/^{86}Sr$ (radiogenic)

Field data sheets were prepared before each sampling run. Standard sampling and sample handling procedures as set out in Weaver (1992) were followed. Some of the environmental isotopes and chemical constituents required specialised sampling mechanisms or preservation measures. ^{14}C, for example required the processing of 200 litres of water due to the very low alkalinity of the waters.

Before collecting a sample, the static water level at each borehole was measured. The borehole was then pumped for a period long enough to purge the hole of stagnant water. This allows representative samples of the *in-situ* groundwater to be taken. During pumping the electrical conductivity was monitored continuously and sampling begun once the reading had stabilised.

Temperature, EC and pH were measured in the field for the following reasons:

- These are parameters which can change after removal of water from the sampling point and are best measured as soon as possible. EC and pH are temperature-dependent parameters and are influenced by precipitation of salts out of solution or sample degassing.
- These parameters provide a preliminary overview of the water quality which can be used to decide the extent of sample collection necessary.
- They provide a check on laboratory data. (Lloyd and Heathcote 1985).

Water samples were collected in PVC plastic bottles which were acid washed prior to sampling to remove all leachable materials. Unfiltered samples were collected for major cations and anions, alkalinity, hardness and DOC. Each bottle was rinsed at least twice with the sampled water before filling.

For filtered samples a hand-held syringe was fitted with a 0.45 micron filter membrane and the collected sample filtered into a sample bottle containing enough nitric acid to adjust the pH to less than 2. These preservation measures are necessary to prevent the metal ions coming out of solution or forming complexes with organic or other ligands in the water before reaching the laboratory. The syringe and filter holder were also rinsed with the sample water before collecting filtered samples for metal analyses.

For environmental isotopes, two 250 ml samples were collected for ^{18}O and D, and one sample preserved with 1 ml $HgCl_2$ for ^{13}C. Tritium samples required at least a litre of water. The sampling procedure for ^{14}C was more complex. Because the isotope occurs at very low concentrations, suitable samples for transport and laboratory analysis require a large volume of sample and specialised treatment. Approximately 200 litres had to be acidified and the formed CO_2 expelled with air in a closed system. The CO_2 was trapped in an absorber filled with caustic soda solution in the field for later analysis of the precipitated carbonate in the laboratory (Vogel 1967).

All samples were delivered to the laboratories as soon as possible after collection to minimise the possibility of sample deterioration.

3.6.3 *Laboratory analysis*

Chemical analysis of water samples was undertaken by the CSIR laboratories in Stellenbosch. Methods used conformed to guidelines set out in *Standard methods for the examination of water and wastewater* (APHA 1989). Ion balances were checked to be within 5 % for data quality control. Isotope analyses were carried out at the Environmentek laboratories in Pretoria. The analytical results as well as a list of precision and recovery data appears in Appendix D.

Selected samples were also sent for ICPMS analysis . The first batch were tested at the Anglo-American Research Laboratories and the later samples at the Pretoria laboratories of the Institute of Soil, Climate and Water (Agricultural Research Council). It was hoped that these low-concentration metals could provide additional or supporting information to that derived from the major ion chemistry. At this stage, however, no useful correlations have been found. The results of the exercise are nevertheless presented as a part of Appendix D. ICPMS is a relatively inexpensive analytical method which can generate large amounts of data on microchemistry. The usefulness and applicability of this method to groundwater studies needs to be assessed in relation to traditional methods.

3.6.4 *The carbonate system in water*

The low pH of the Agter-Witzenberg groundwater and its low alkalinity placed demands on the capability to describe the carbonate chemistry sufficiently well. These waters are oversaturated with CO_2 gas which can easily be released when samples are handled (Pearson *et al.*, 1978) Field pH measurements were taken on the fresh water in each case. Subsequent laboratory pH measurements show that some pH shifts do occur during transport (Figure 3.10) consistent with CO_2 loss. Alkalinity was not analysed on site, but only in the lab, though this was usually within a few days. Total inorganic carbon TIC (i.e. the sum of dissolved CO_2 , HCO_3 and CO_3) was determined by acid extraction of the CO_2 from a water sample. Water samples were stored in medical flat plastic bottles, poisoned with mercuric chloride and kept cool as far as possible. In the (Pretoria) laboratory, the water was transferred to a vacuum flask containing phosphoric acid and the released CO_2 collected, its quantity measured and the isotope ratio of the carbon analysed.

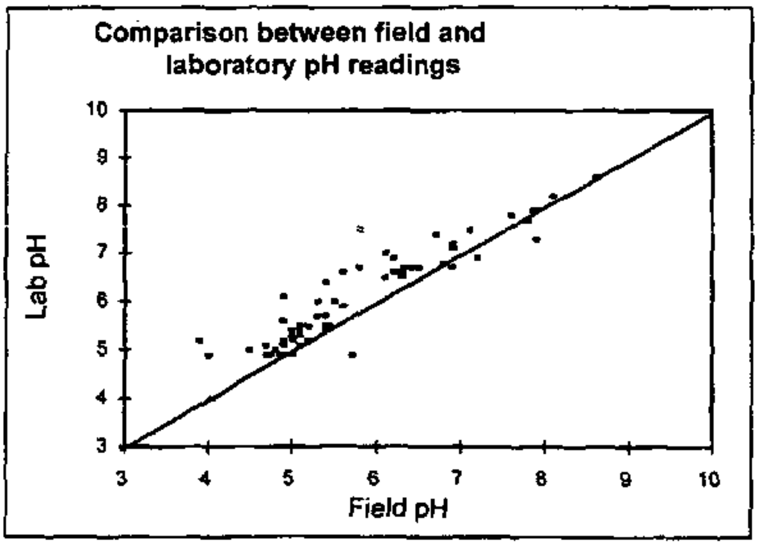

Figure 3.10: Graph showing comparison between laboratory and field readings of pH to illustrate the effects of temperature changes and degassing.

While this is a common enough method, it was considered worthwhile to check whether any significant CO_2 loss might occur during transport of these type of samples. To this end a set of pre-evacuated vacuum flasks was filled with samples on site during a run as well. These were transported to the lab and then extracted. This procedure ensures that no sample loss can occur and its results were compared with the 'standard' method (Table 3.3). The results of this comparison indicate that there is indeed some loss of CO_2, as is also evident from the higher pH measured in the lab. The reported TIC values are therefore not much more precise than 10 % and are probably too low by 5 %. A slight bias towards lower ^{13}C content is also evident, but not significant within the total context.

Table 3.3 : Comparison between field and laboratory measured parameters.

Borehole	Field TIC	Lab TIC	Field ^{13}C	Lab ^{13}C	TIC change	^{13}C shift
G39937A	0.52	0.44	-21.2	-21.1	-15 %	+0.1
G39937	0.68	0.50	-20.4	-20.0	-26 %	+0.4
G39936	0.72	0.69	-23.2	-22.8	-4 %	+0.4
311/14	0.89	0.68	-22.4	-22.2	-24 %	+0.2
G39939	1.31	1.28	-18.2	-18.1	-2 %	+0.2
G39938A	1.56	1.40	-19.3	-18.7	-10 %	+0.6
G39938	1.76	1.35	-20.8	-18.6	-23 %	+2.2
				Average	-15 %	+0.6
				Std Dev	9 %	0.7

3.6.5 *Data handling*

All water levels, chemical and isotopic analyses results were stored on an electronic database using the HYDRASYS software programme designed by the CSIR. The software converts the water level measurements to a water level height in metres above mean sea level automatically using the surveyed datum height. Time series graphs were prepared using this software. The data was also imported into a Quattro-Pro spreadsheet from which the chemistry and isotopes graphs were prepared. The full set of results appears in the Appendices at the end of this report.

This project has generated a large database of chemical and isotopic results. Many of these are presented graphically in the following section to discuss trends and patterns where they occur. For ease of reading and comprehension, the style has been adapted to incorporate the figures into the text wherever possible, with an extended discussion of each graph immediately below the figure.

3.7 Discussion of Data

3.7.1 *Rainfall*

Rainfall data was collected to determine the recharge inputs to the chemistry and isotopic composition of the groundwater in the Agter-Witzenberg Valley. Average monthly rainfall values for the region were obtained from three weather stations at Avalon, Remhoogte and Bokmanskloof for the duration of the project. These are shown in Figure 3.11. The automatic chart recorders provide a record of the volumes from each rainfall event. These volumes can be seen in the figures in section 3.7.2 below. It must be noted that the recorder at G39937 was not always fully operational and certain events may have been missed.) In addition, the total rainfall for May 1995 to May 1996 (ie winter 1995 and summer 1995/1996) was measured for each of the cumulative rainfall samplers.

The measured rainfall chemistry data for AWR1 and AWR2 form part of Appendix A.

Figure 3.12

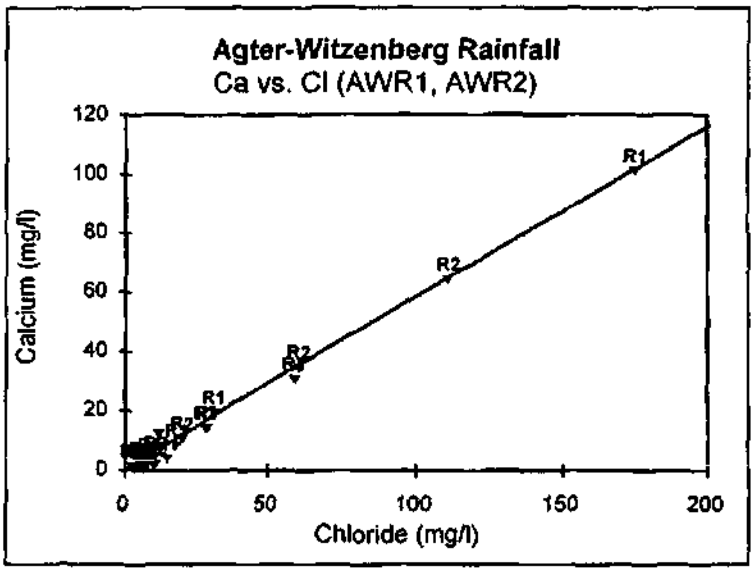

FIGURE DISCUSSION

Anomalously high $CaCl_2$ *levels were observed for the AWR1 and AWR2 collectors. This phenomenon could not be explained at this stage. Discussions with a number of atmospheric scientists could not provide any answers. Local application of agricultural chemicals is unlikely as the sampler in the mountains shows these anomalies with the same or even greater intensity than the one in the valley. A possible explanation is that this is due to atmospheric dust fallout. It is noted, however, that the higher calcium and chloride were more prevalent during 1995 than 1996.*

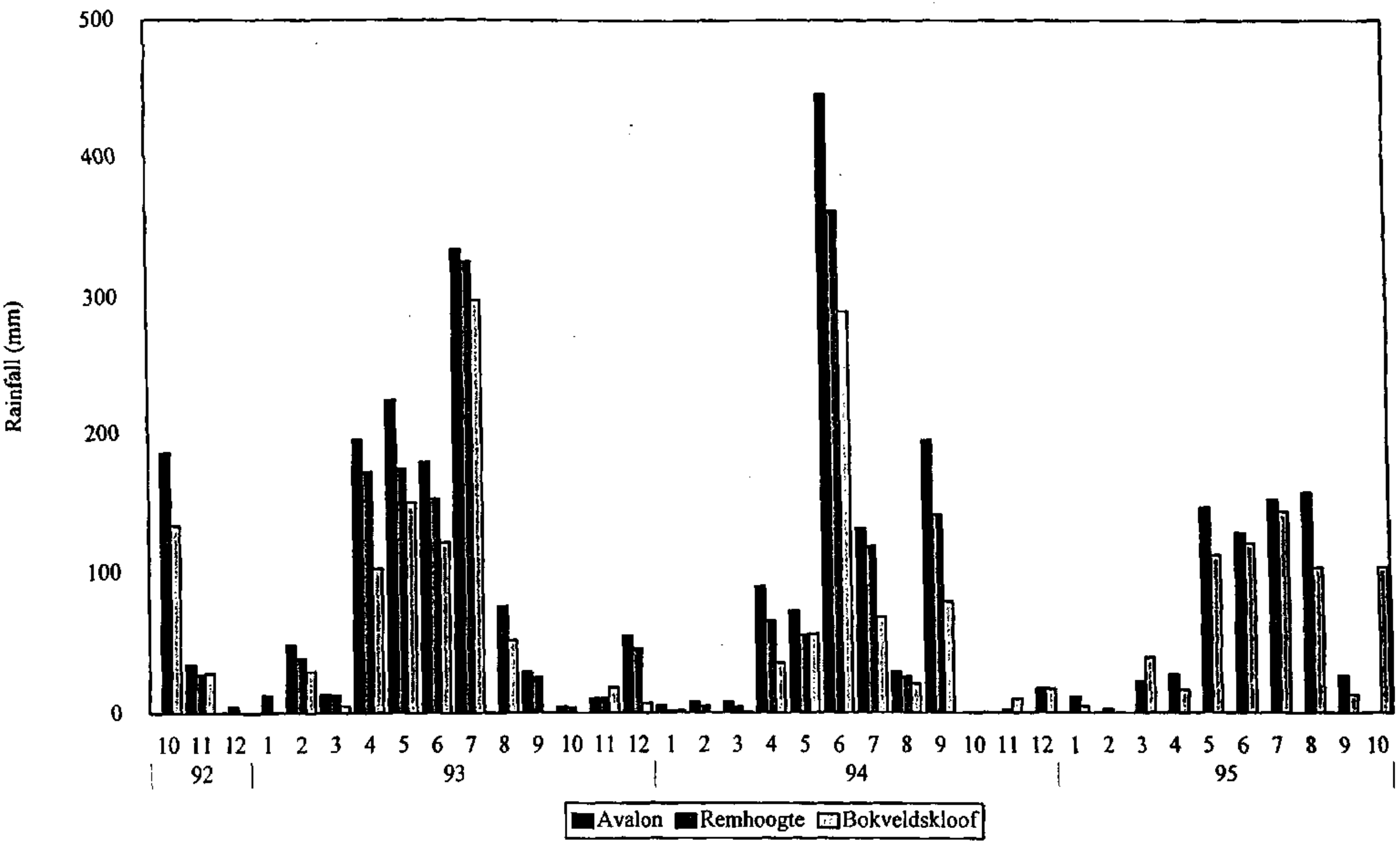

Figure 3.11 Monthly rainfall data from nearby stations in the Agter-Witzenberg area.

Rainfall chemistry and isotopic compositions from the cumulative rainfall samplers are presented in Table 3.4. The collectors were installed on 25 May 1995 and emptied on 10 May 1996 so the concentrations in the table below reflect the average chemical and isotopic input to the groundwater over this period. At each site, two cumulative rainfall collectors were installed so that there would still be data for the remaining collector if one were damaged. Where both collectors were undamaged, the data for both has been averaged.

Table 3.4 : Chemical and isotopic composition of rainfall in the Agter-Witzenberg Valley. Concentrations in mg/l unless otherwise specified.

Collector	A/B	C	F	G/H	I/J
K	2.7	12.4	8.8	8.9	9.8
Na	2.6	5.4	3.3	4.1	4.3
Ca	4.8	1	3.3	6.8	5.3
Mg	0.7	0.7	2.4	1.6	1.4
NH4-N	3.8	5.2	0.3	2.8	5.6
SO4	3.7	1.9	7.5	12.6	24.4
Cl	2.9	6.6	4	5.1	5.1
Alk($CaCO_3$)	0.8	24.5	12.3	7.7	8.3
$\delta^{18}O$ (‰)	-6.47	-6.33	-6.06	-6.20	-6.24
δD (‰)	-35.25	-33.6	-34.5	-33.65	-32.5
d-excess (‰)	+16.5	+17.0	+14.0	+15.9	+17.4
Volume (mm)	579	548	724	676	777

Data from collector D has been disregarded as the collector was found to contain a suspiciously small volume of water suggesting it may have been tampered with. Collector E was also excluded from the data analysis because the sample was contaminated with an excessive number of insects. The levels of potassium, alkalinity and ammonia for the remaining samples are artificially high for rainfall samples and are probably attributable to the influence of insects and birds on the collector. Cumulative rainfall volumes for the year of study were also measured using these samplers.

Figure 3.13

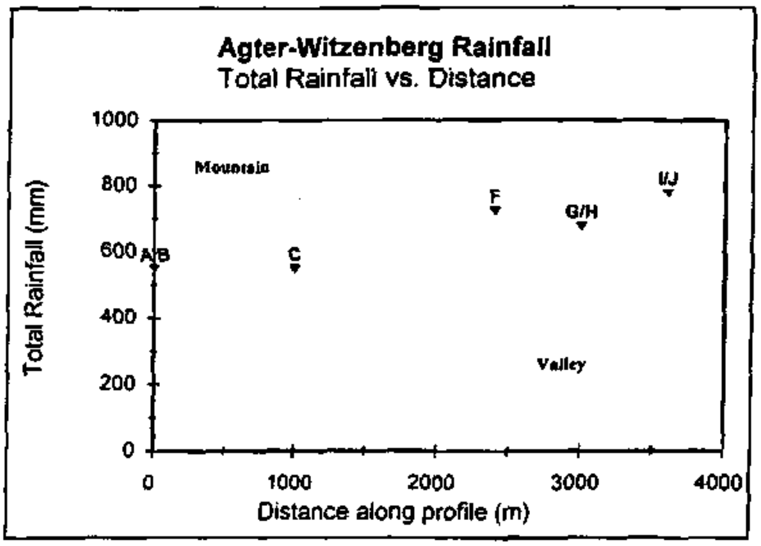

FIGURE DISCUSSION

Rainfall totals measured by the cumulative samplers (May 1995- May 1996).

The graph shows a trend of increasing rainfall amounts from the mountainous areas down across into the valley. A/B and C, situated at higher altitudes, record rainfall totals of less than 600 mm for the period of sampling, while the samplers lower down in the valley have rainfall totals 100 mm or more higher than this.

Normally one would expect rainfall in the valley to be lower than in the higher lying mountains. A possible explanation is that the mountain samplers are in a gorge cut through the mountains and thus the collectors could be in a rain-shadow. Alternatively, collector I/J is closest to the westernmost mountain range which would have the most effect on the rain clouds coming from the west. G/H, F and C, A/B are further to the east and thus deeper into the rain shadow.

Figure 3.14

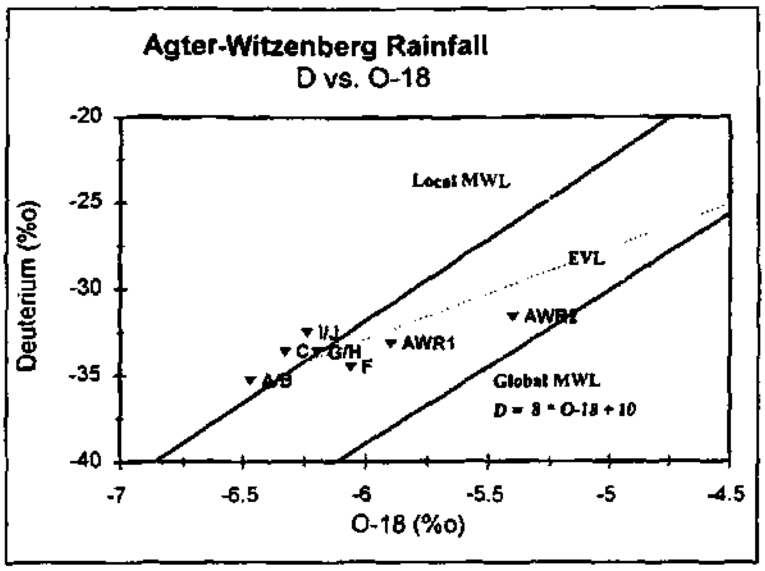

FIGURE DISCUSSION

The $\delta^{18}O$-δD values of the cumulative rainfall collectors cluster together quite tightly. The calculated d-excess averages at +16.2‰ thereby justifying a local meteoric water line of

$$\delta D = 8 * \delta^{18}O + 16.2$$

For comparison it can be noted that the average d-excess at Cape Town is 13.8 ‰ (data from IAEA 1992)

Data from the automatic chart recorders were used to calculate the volume of rain that fell between sampling runs for the two rainwater collectors, AWR1 and AWR2. These volumes could then be used to calculate a weighted average for any of the chemical parameters. It is these volume-weighted averages for $\delta^{18}O$ and D that appear in the graph. (Unfortunately, the automatic recorder at G39937 was malfunctioning for a large part of project duration, so the weighting of AWR2 is only based on two sample values).

The volume-weighted averages for AWR1 and AWR2 are displaced from the local meteoric water line (MWL), defined by the cumulative samples (A-J). They lie instead parallel to an evaporation line (EVL) of slope 5. The rainwater collectors, unlike the cumulative rainfall collectors, did not have a layer of silicone oil to protect the sample from evaporation effects. The higher $\delta^{18}O$ and δD values are likely to be the result of further fractionation after the rainfall was in the collector. For this *reason the isotopic results from AWR1 and AWR2 were not regarded as a true reflection of the average isotopic composition of the rainfall at the collector sites. The cumulative rainfall collectors, even though they have only been in operation during the last year, are considered to have yielded more reliable samples.*

Figure 3.15

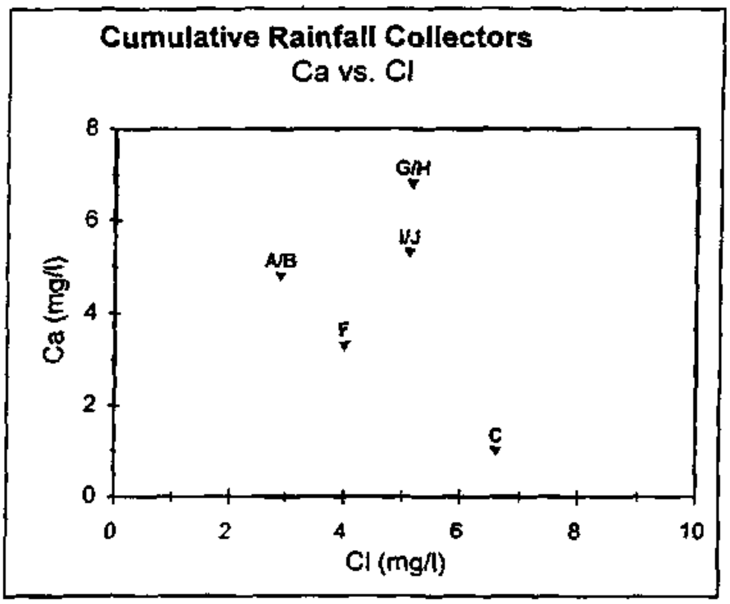

FIGURE DISCUSSION

Ca vs. Cl for cumulative rainfall samplers

There is no correlation between calcium and chloride concentrations in this data set. The anomalously high values of these found in AWR1 and AWR2 are also missing.

3.7.2 *Surface Water*

Surface water in the Agter-Witzenberg Valley was sampled at three monitoring points on the streams shown as AWRN, AWRS and AWRE on Figure 3.6. The chemistry data for these points appears in Appendix B. Flow gauging was also undertaken at these sampling stations to estimate the magnitude of surface runoff in the valley.

The results are presented in Table 3.5.

Table 3.5 : Streamflow measurements.

	Flow measurements (m^3/second)		
Date	**AWRE**	**AWRN**	**AWRS**
1996/03/26 (summer)	0.00284	0.038351	0.0031

Figure 3.16

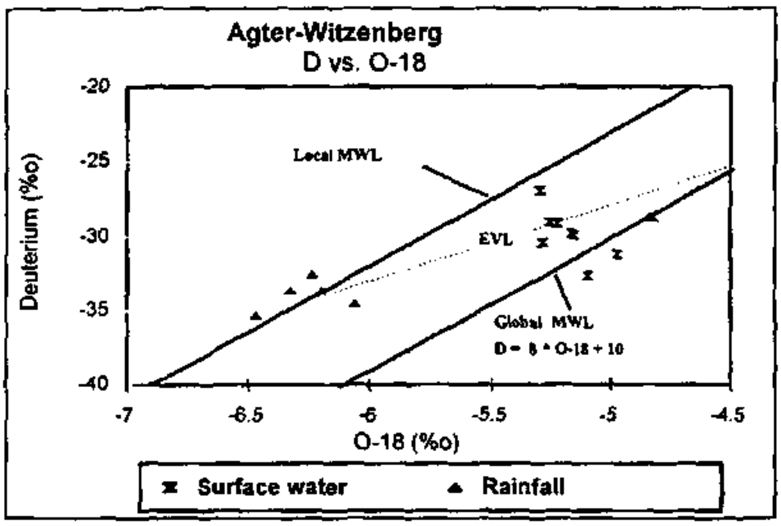

FIGURE DISCUSSION

The surface water samples are enriched in ^{18}O and D compared with the rainfall values. Evaporation of the open surface water bodies during the summer months leads to isotopic fractionation, so the data points are also displaced from the local meteoric water line (MWL) along an evaporation line (EVL). The distinctive isotopic signatures of the rainfall and surface water samples provide a basis for the interpretation of the nature of the recharge sources for the groundwater.

Figure 3.17

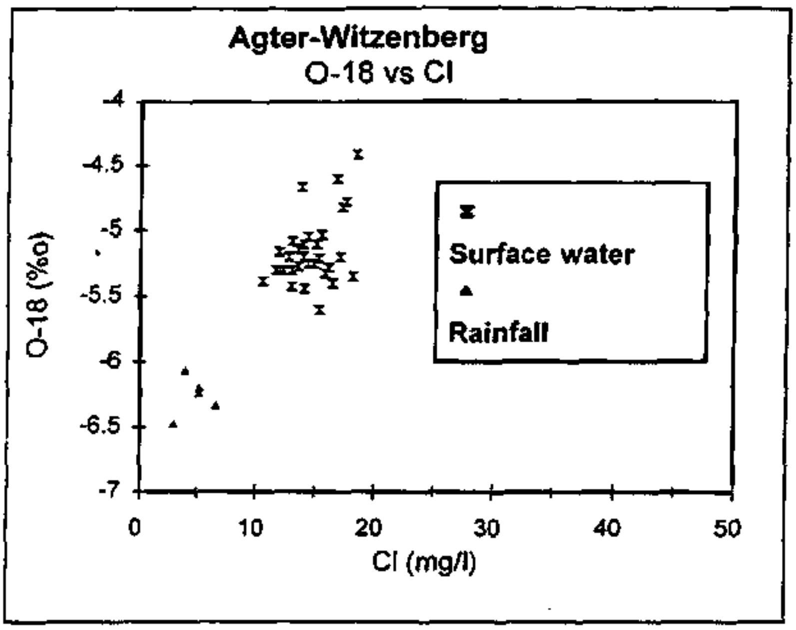

FIGURE DISCUSSION

The surface water generally has a higher chloride ion content than the rainwater due to evaporation which also increases δ^{18}O.

A time series plot of the δ^{18}O values for AWRN, AWRS and AWRE (Figure 3.18) shows that the surface waters are most enriched in ^{18}O in summer when evaporation is high. During winter the pervasive rains flush out the enriched water and replace it with fresh, unevaporated rainwater.

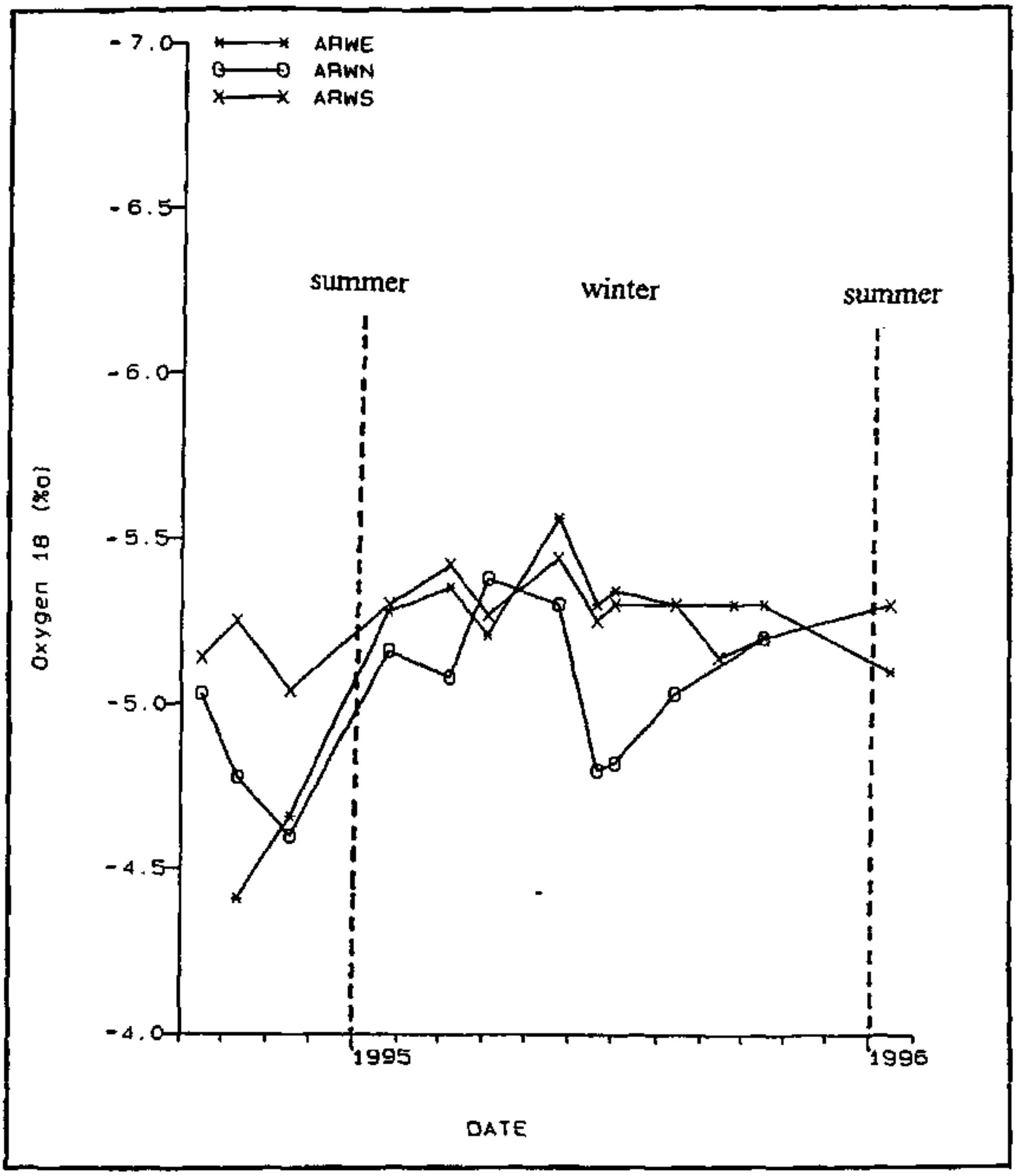

Figure 3.18 : Agter-Witzenberg Surface Water δ¹⁸C Time Series.

3.7.3 *Groundwater*

3.7.3.1 Water levels

Data from automatic water level recorders at G39936 and G39937 are presented in Figures 3.19 and 3.20. Borehole water levels measured manually during the course of this project are presented in Figure 3.21.

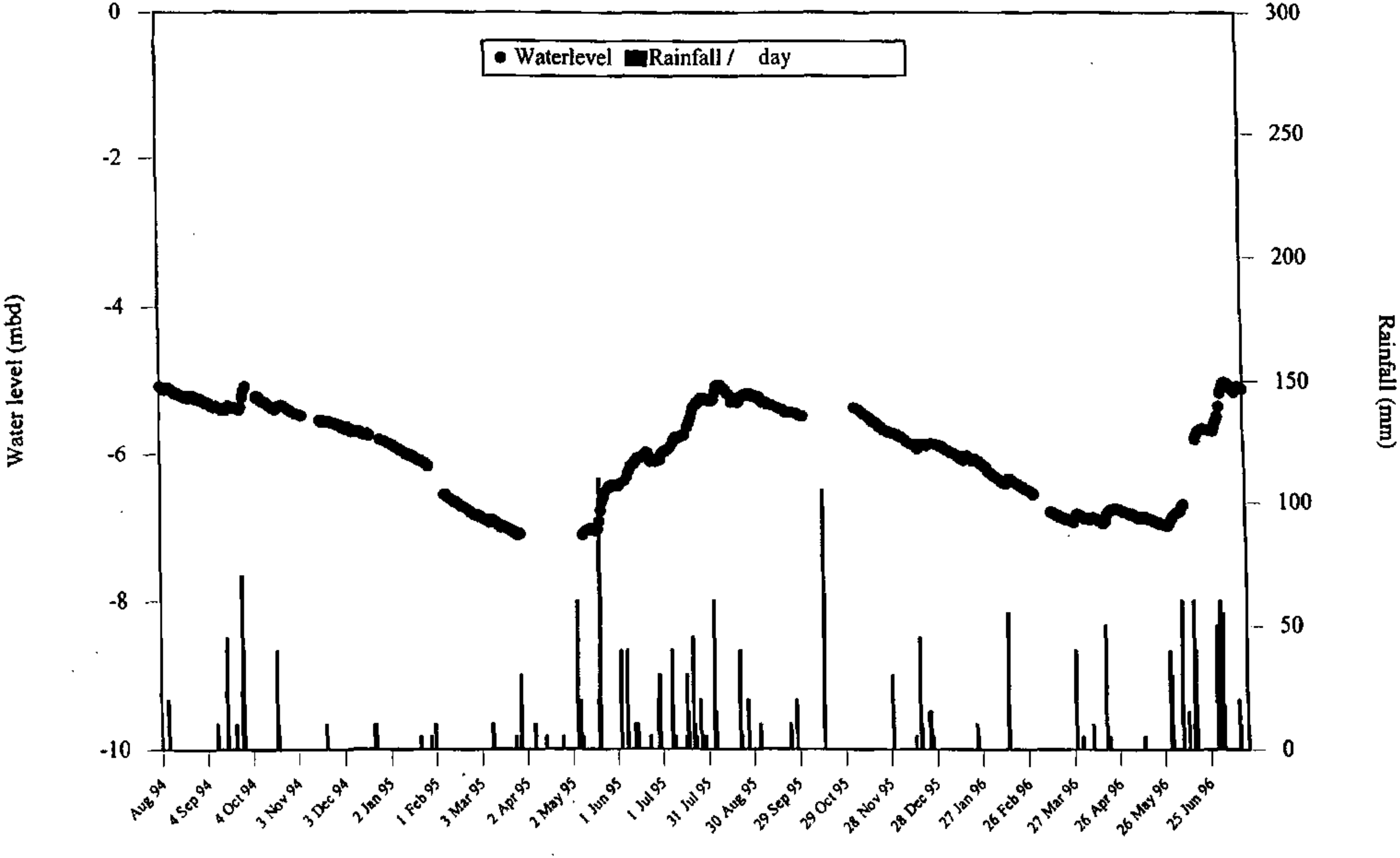

Figure 3.19 Water level and rainfall recorded at borehole G 39936 equipped with automatic rainfall and water level gauges.

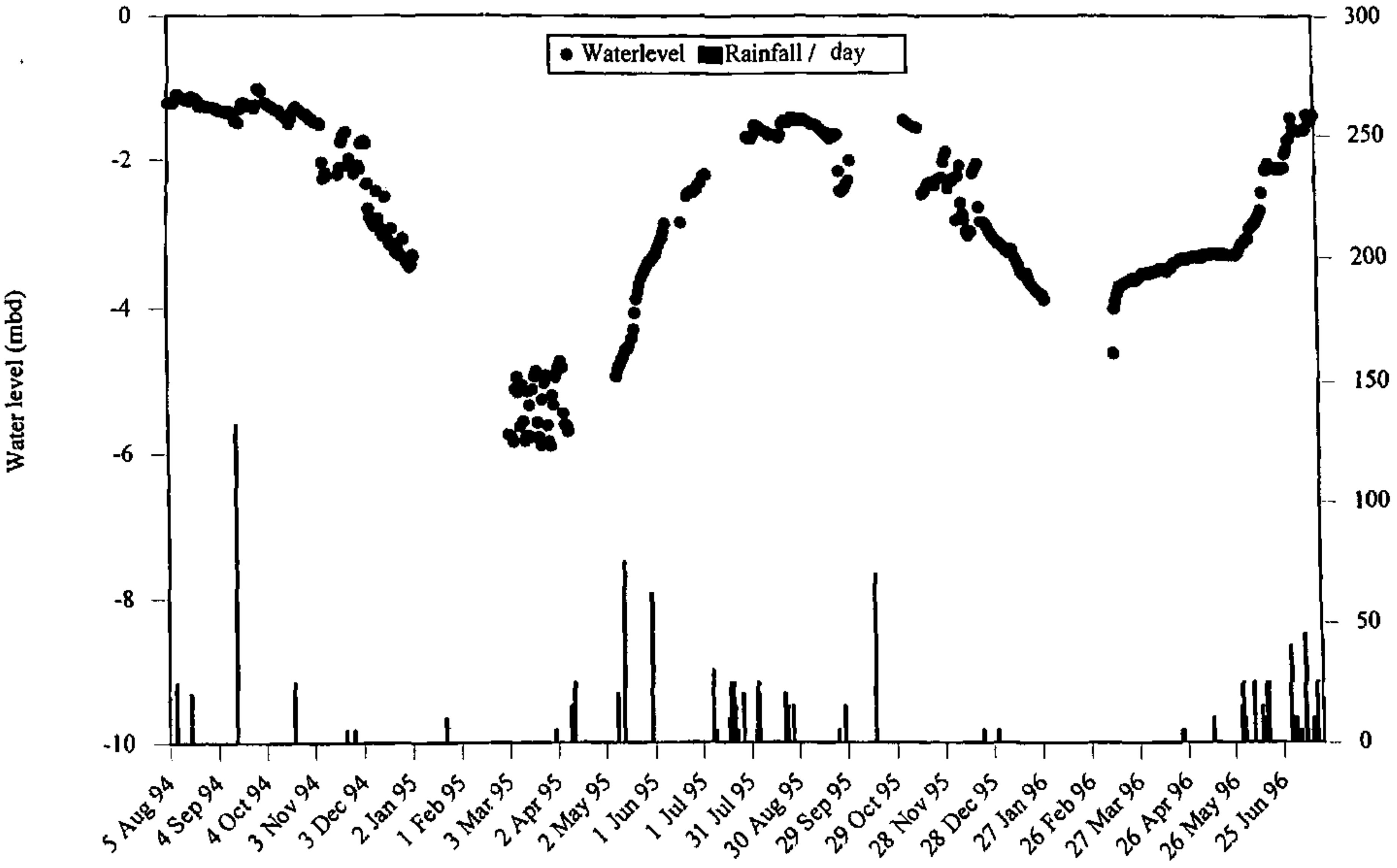

Figure 3.20 Waterlevels and rainfall recorded at borehole G39937 equipped with automatic rainfall and water level gauges

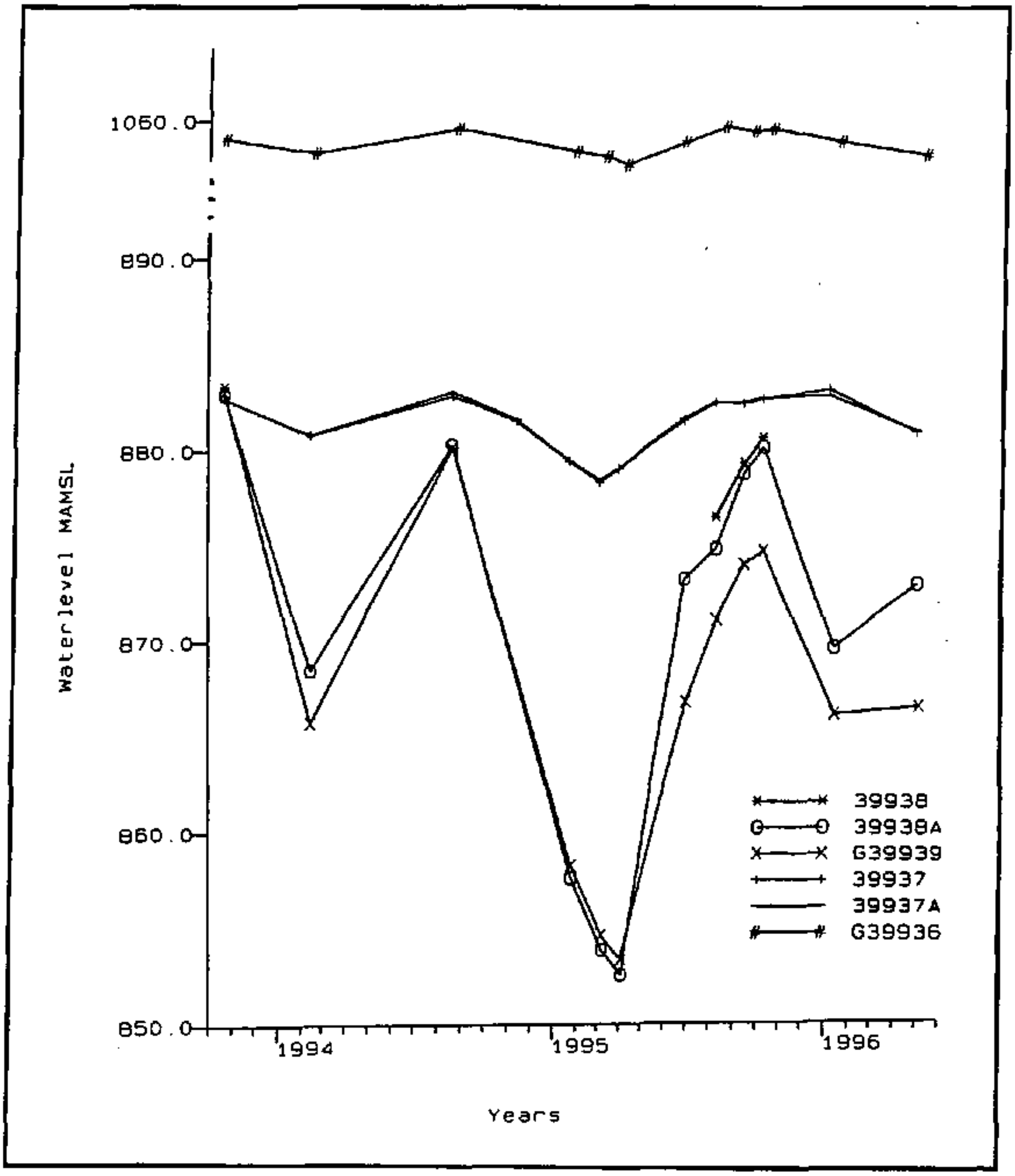

Figure 3.21 : Agter-Witzenberg Boreholes. Waterlevel Time Series.

G39936, in the mountainous area, shows the effects of seasonal fluctuations in recharge without any pumping effects. There is a difference of approximately 2 m between the water level troughs which occur in late summer (February/March) and the peak water levels after the wet winter season (August/September). It is also seen that the discharge slope is shallower than the recharge slope. For the date of 20th May 1995 there a rainfall event of 120 mm and there is an immediate water level rise of 600 mm which implies a minimum porosity of 20 % for the shallow zone of the aquifer if there is no run-off. Similar reactions are seen for 26th September 1994, 12th October 1995, 15th June 1996 and 2nd July 1996.

G39937 and G39937A also display this seasonal oscillation, but with a greater amplitude of approximately 5 m. Being on flat topography one would expect to observe a lesser fluctuation for these levels than for G39936 which is close to the water divide at the crest of the mountain pass. However this larger amplitude is regarded as the effect of farmers pumping. The fact that the water levels are the same for the shallow (37A) and deep (37) boreholes show that both boreholes sample the same semi-unconfined aquifer and that there is hydraulic continuity between the shallow portion of the aquifer and deep portion at this point. This is confirmed by identical chemical results for both boreholes (Discussed later in section 3.7.3)

Further into the valley and thus closer to the farmers' pumping boreholes we see dramatic fluctuations in water levels for boreholes G39938A and G39939 as shown in Figure 3.21. During the dry summer months, heavy pumping results in a drop of over 30 m in the water table for the valley boreholes. The fact that the boreholes G39937 and G39937A, also located in the valley, do not show as large a fluctuation as G39938A is a combination of:

- the lower transmissivity of the Table Mountain quartzites compared to the Bokkeveld rocks,
- greater distance from the pumping boreholes and,
- local constant head recharge from the stream adjacent to G39937.

It is noted that Mr. Fell, the farmer at the southern end of the valley reported that during the summer of 1995 the water level in eight of his nine boreholes dropped to below the base of the holes. The water levels in these same boreholes is 10 to 15 metres below the surface in winter and they are approximately 100 metres deep. This implies a water level variation of some 80 metres during 1995.

3.7.3.2 *Hydrochemistry*

The complete hydrochemical data set for the boreholes sampled during this project appears in Appendix D. Some of the most important trends can be observed in the following graphs:

Figure 3.22

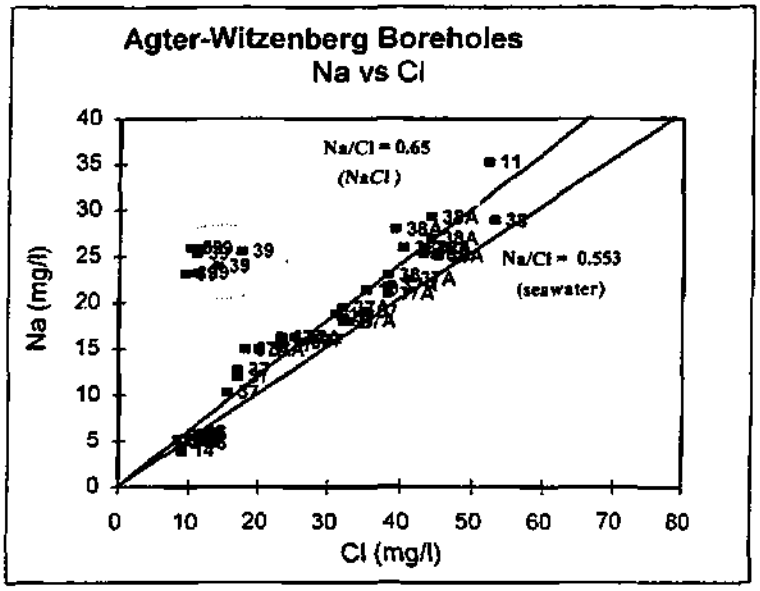

FIGURE DISCUSSION

The clear relation between sodium and chloride concentrations in this plot indicates either addition of seawater or dissolution of rock sodium chloride into the groundwater as it travels through the aquifer. The two mountain boreholes G39936 and 311/14 have the lowest concentrations, very similar to those encountered in the rainfall. Concentrations increase progressively as the water passes through the Table Mountain quartzites (G39937/ G39937A) and into the Bokkeveld shales (G39938A).

Borehole G39939 is exceptional in that its water shows elevated sodium levels without the accompanying increase in chloride. This is most likely due to sodium addition by ion exchange processes involving the clay minerals in the shales along the Table Mountain Group/Bokkeveld Group contact zone. Cation exchange in clay minerals can be simply stated as (Caroll, 1959):

$$Na_{Clay} + H^{+}_{aq} = H_{Clay} + Na^{+}_{aq}$$

Thus an increase in sodium concentration in the water should be accompanied by a decrease in hydrogen ion concentration, i.e. and increase in pH. This is true for borehole G39939 as can be seen in Figure 3.23.

Figure 3.23

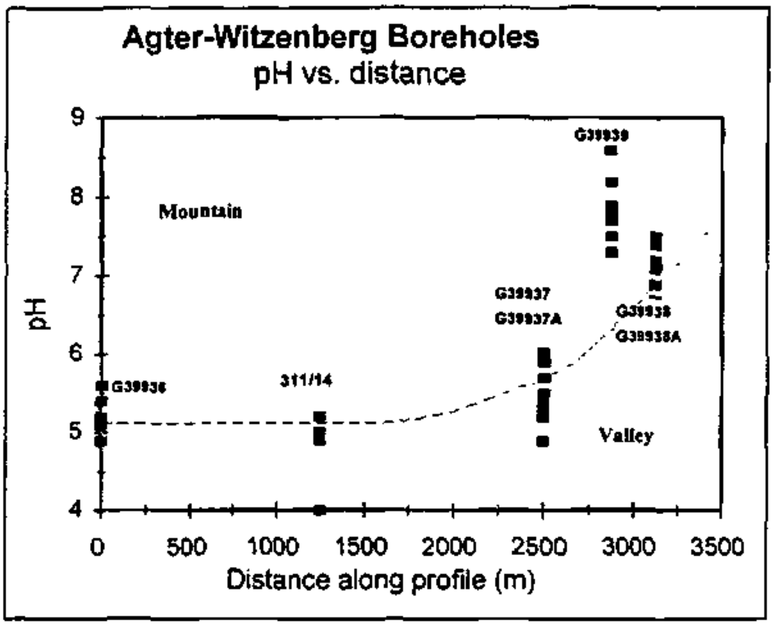

FIGURE DISCUSSION

The general increase in pH from the mountain samples down into the valley indicates the increased dissolution of carbonate along the flowpath. This increase is parallelled by calcium concentration (Figure 3.24) and alkalinity (Figure 3.25) increases.

Figure 3.24

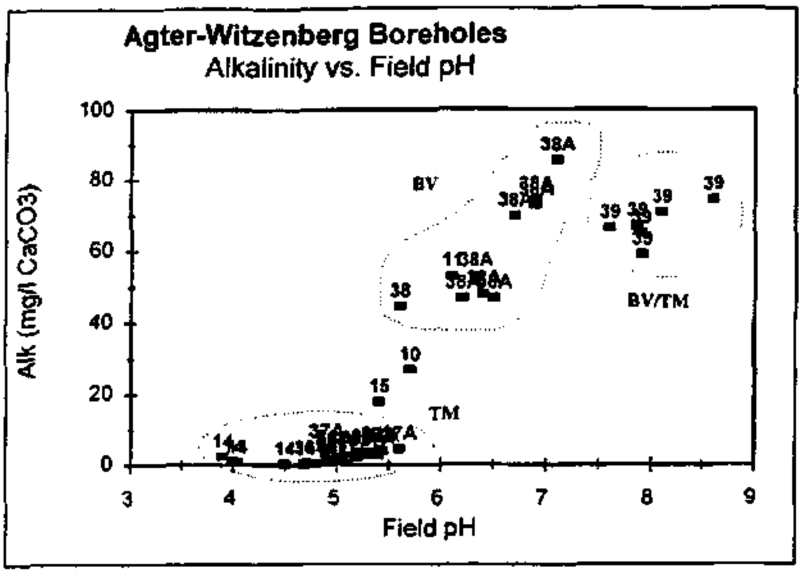

Figure 3.25

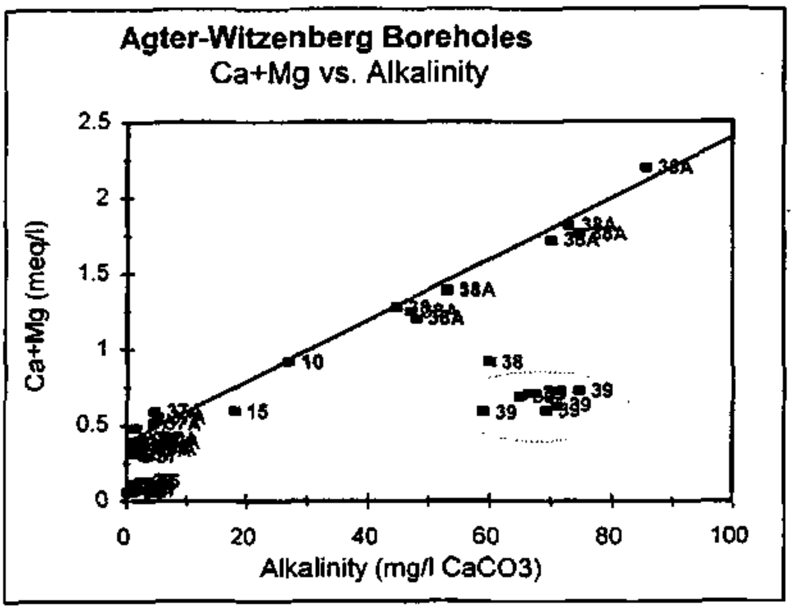

FIGURE DISCUSSION

The first graph illustrates the rapid increase in pH at low alkalinity due to carbonate solution. The trend starts to steepen later in the Bokkeveld Group boreholes, where pH increase is slow near to the *equilibrium value of pH 7. In both graphs borehole G39939 is once again the exception. The pH increase without an increase in alkalinity for borehole G39939 shows that the rise in pH takes place by a different mechanism to that of the other boreholes ie. by ion exchange rather than carbonate dissolution.*

Table 3.6 : Saturation Indices of water from mineral equilibrium calculations

Sample	Date	Rock	calcite	chalcedony	talc
311/14	1995/01/25	Table Mountain Quartzite	-7.1	-0.3	-28
G39938A	1995/03/09	Bokkeveld Shale	-2.0	+0.4	-7.6
G39939	1995/05/04	Contact Zone	-0.4	+0.4	0

Negative values indicate undersaturation, while positive values indicate oversaturation.
Zero values occur at equilibrium.

Mineral equilibrium calculations were carried out on a few typical water samples using the aqueous speciation software WATEQ (Plummer *et al.*, 1994). Table 3.6 indicates that the valley waters are increasingly becoming saturated with respect to the various minerals. This confirms the Alkalinity-pH relation in Figure 3.24. It should be noted that even the groundwater in borehole G39938A is not yet completely saturated with calcite despite its position in the valley shales. There is still potential for further carbonate dissolution by this water.

Only G39939, with excess sodium over chloride (Figure 3.22) is shown in the table to be close to saturation with calcite. Equilibrium of the water in borehole G39939 with talc might just be the exchange reaction responsible for this additional sodium content. Equilibrium with chalcedony (and other less organized forms of silica) probably determines the maximum silica content of the water. The higher silica content observed for the groundwater in the shales is derived from chemical weathering of silicate minerals. The quartzites yield water with lower silica due to the slow solubility rate of quartz in water and the resistance of this mineral to chemical weathering. Note that in most waters (Hem, 1985) it is fully evident that the dissolved silicon does not behave like a charged ion and is thus not taken into account in the ion balance, nor does it exhibit behaviour typical of a colloid in most waters.

Time variations

Figures 3.26 to 3.29 display the temporal variations of a number of the chemical parameters measured during the course of the project.

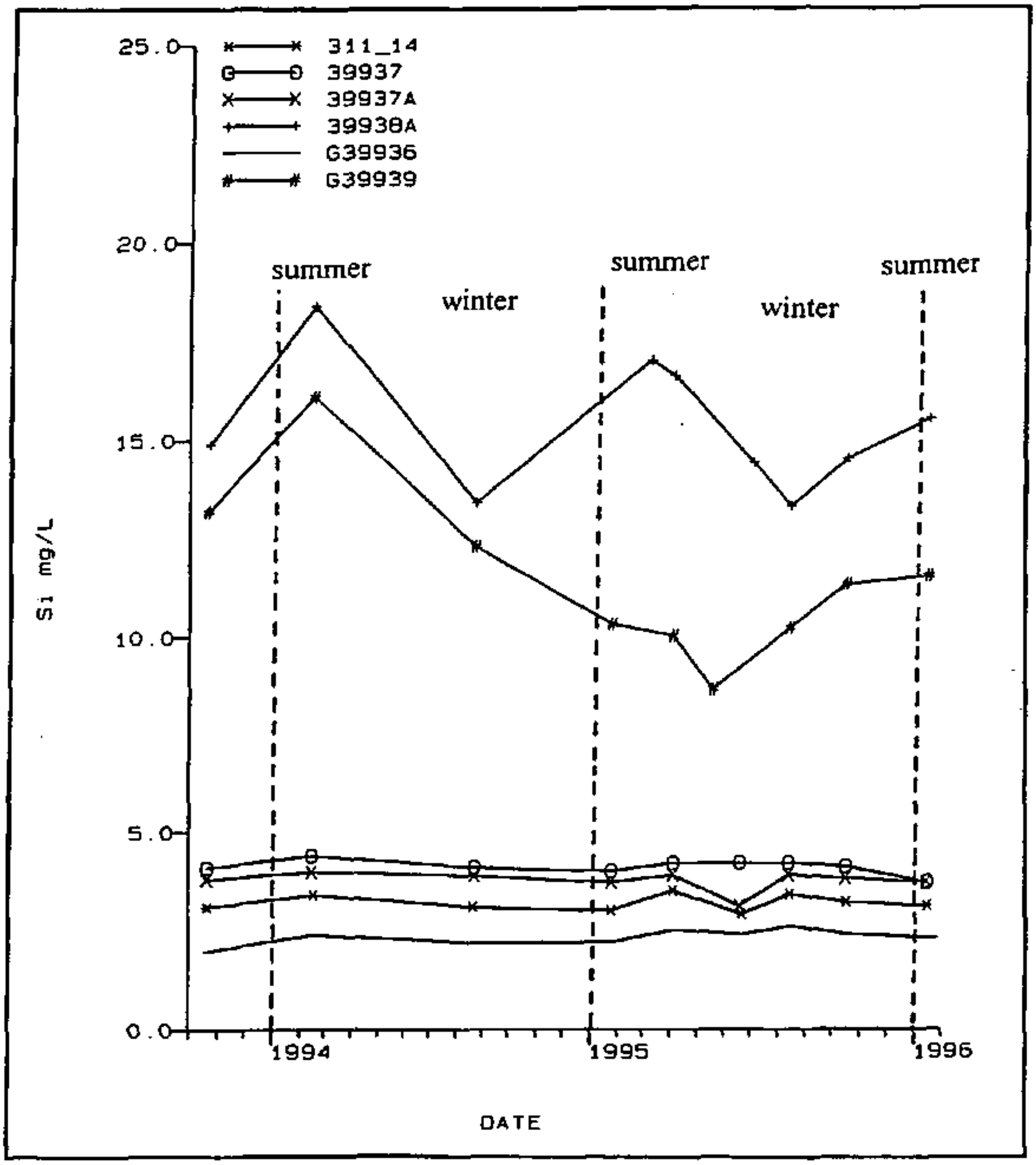

Figure 3.26 : Agter-Witzenberg Boreholes. Silica Time Series.

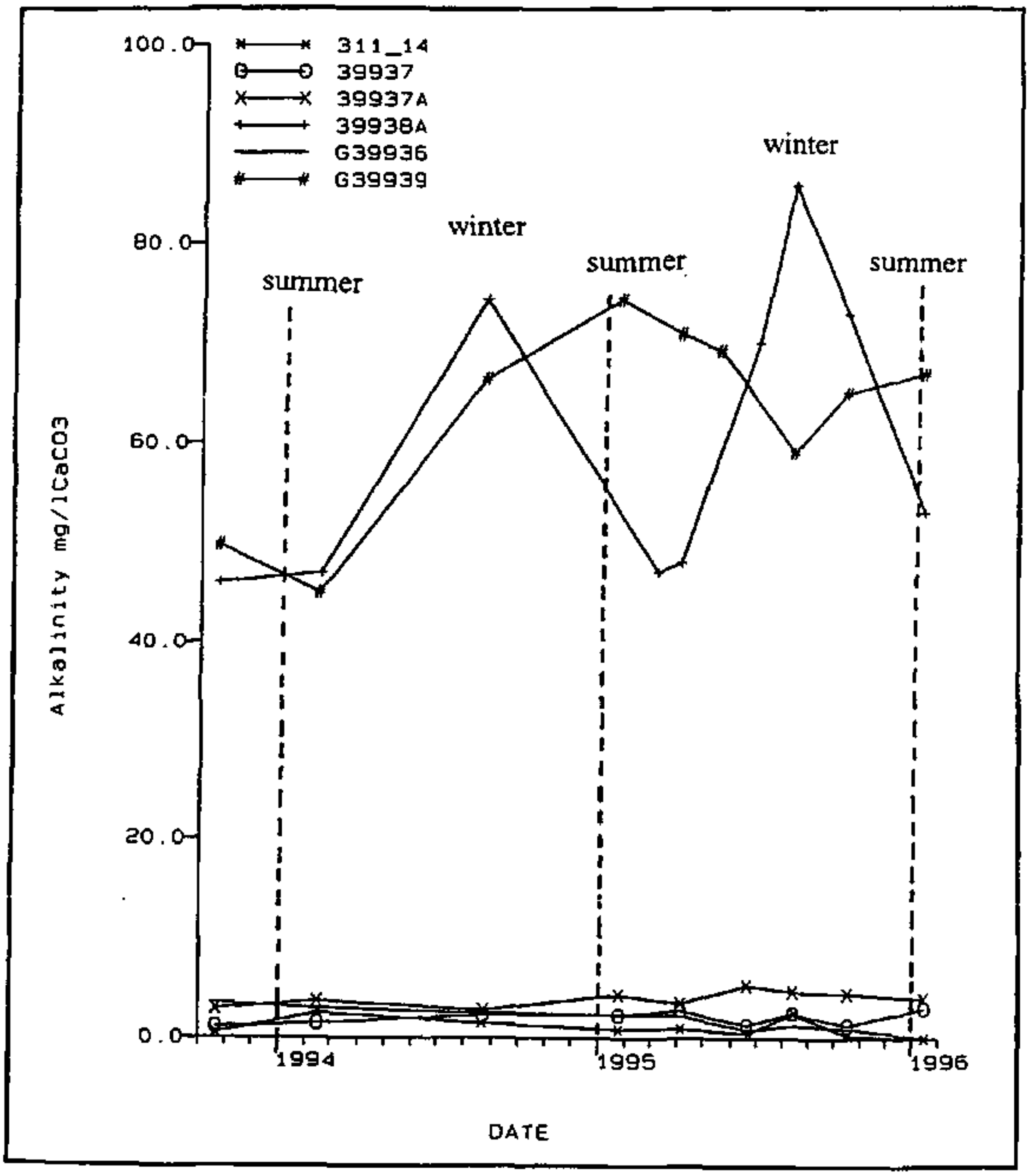

Figure 3.27 : Agter-Witzenberg Boreholes. Alkalinity Time Series.

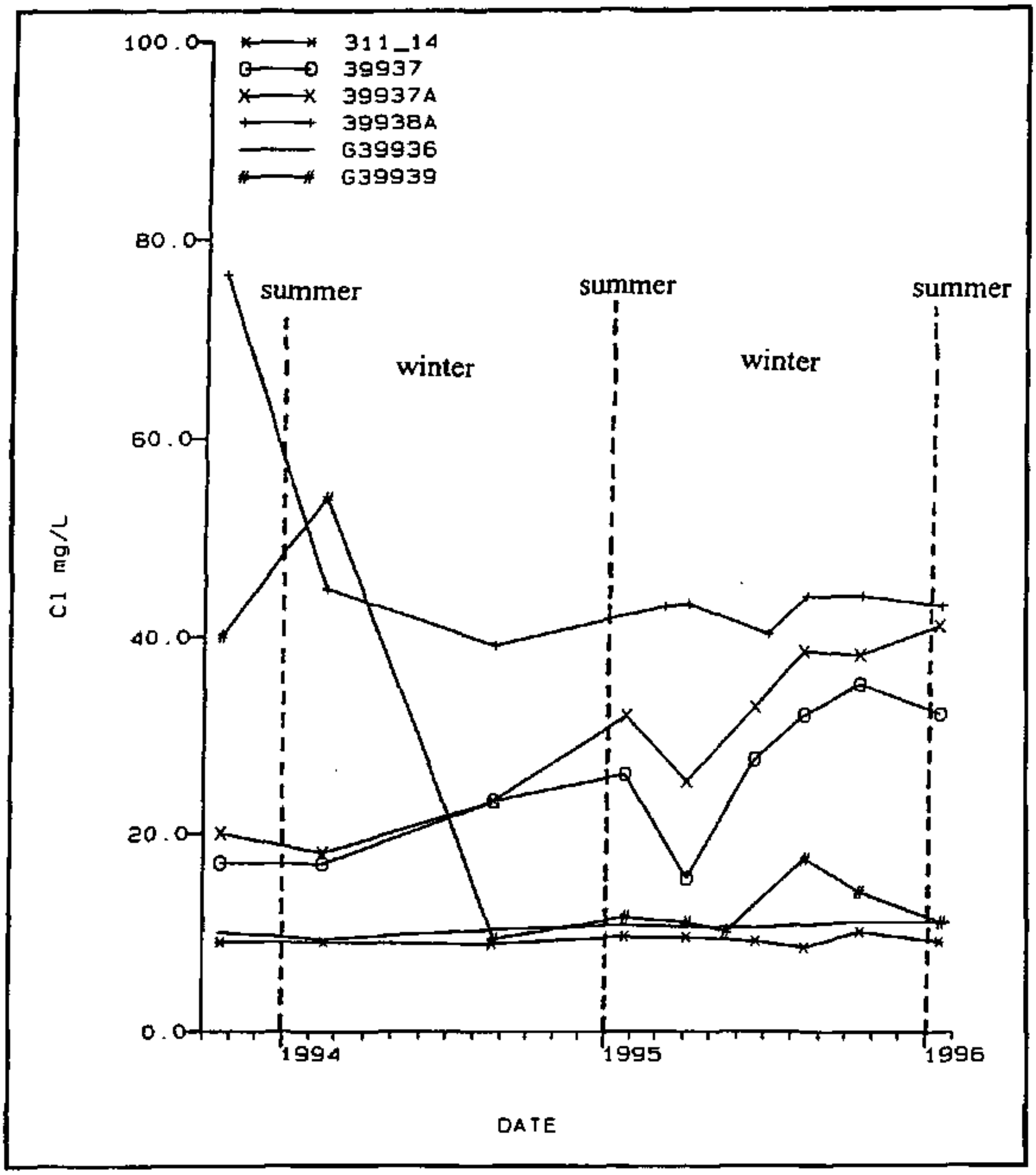

Figure 3.28 : Agter-Witzenberg Boreholes. Chloride Time Series.

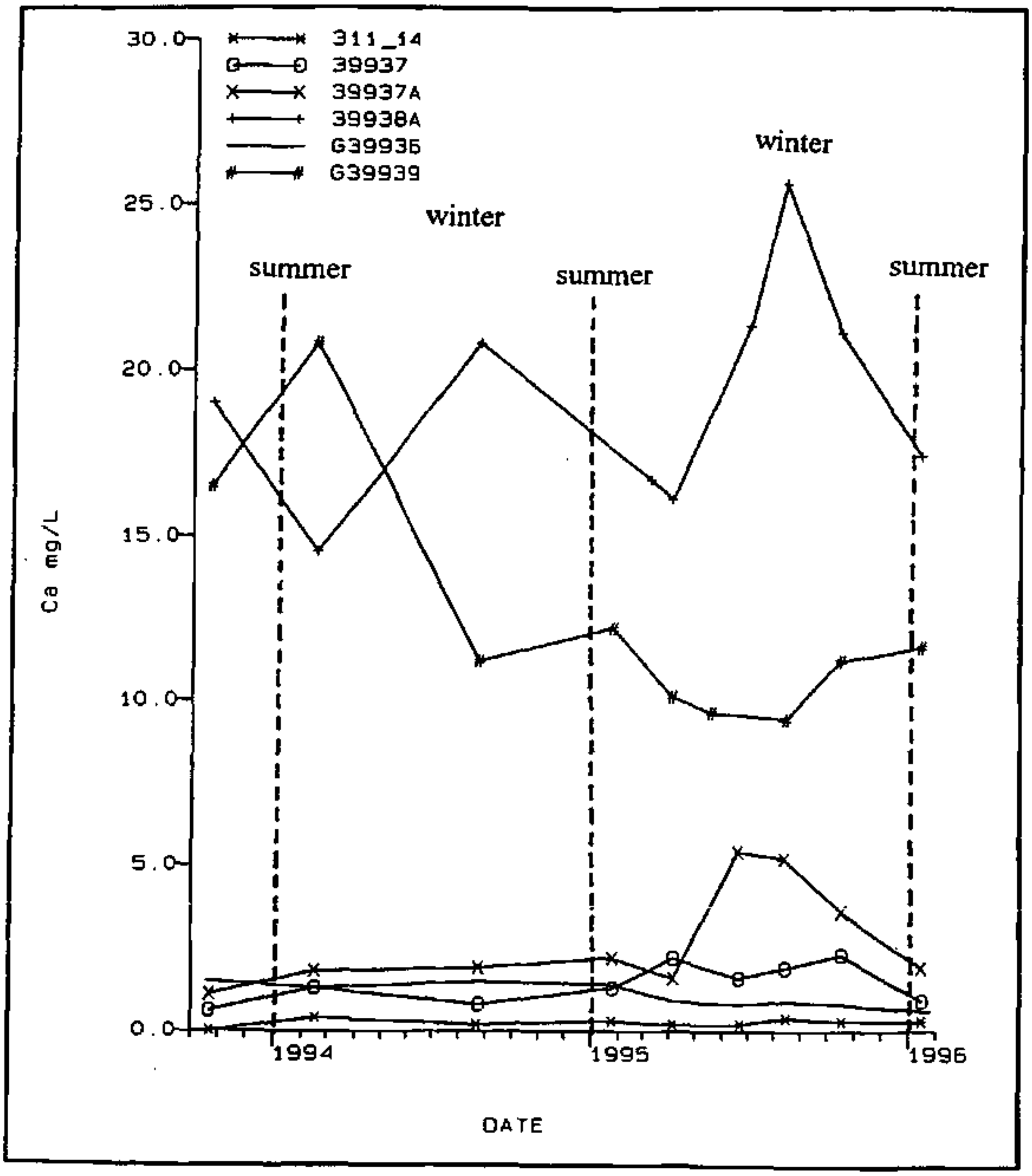

Figure 3.29 : Agter-Witzenberg Boreholes. Calcium Time Series.

FIGURE DISCUSSION

Transient variations: are initially found in the same valley boreholes. High chloride, calcium, magnesium and silica levels and low alkalinity and pH in G39939 and G39938A at the start of the monitoring programme probably reflect the rapid weathering and leaching of freshly exposed Bokkeveld shale surfaces after drilling of the boreholes. There is no known relation of these values to drilling fluid. These anomalous points have been excluded from the other graphs in this report.

It is interesting to note that G39939, sampling the Bokkeveld/Table Mountain Group contact, starts out with a signature similar to that of G39938A drilled directly into the shales. Later on concentrations drop to intermediate values closer to those encountered in the Table Mountain groundwaters of G39937 and G39937A for silica and calcium. The effect is even more pronounced in the chloride time series graph where the concentrations in G39939 have fallen to the same levels as the mountain groundwaters (G39936 and 311/14) at times. Only the alkalinity in G39939 remains at levels similar to G39938A.

Seasonal variations: are only encountered in the valley boreholes which occur in and adjacent to the Bokkeveld shales (G39938A and G39939).

G39938A shows alkalinity and calcium lows in late summer at the end of the dry season, with peaks after the winter rains when dissolution of carbonate minerals in the shales increases once again. The opposite pattern is observable for silica, which reaches its peak concentrations in summer. Chloride trends are difficult to distinguish.

Calcium and alkalinity trends for borehole G39939 are the opposite to those for G39938A during the 1995 season. Before this, interference by initial transient effects complicate the interpretation of seasonal trends.

Trends: Some parameters appear to show some increase over time, regardless of the season e.g. sodium, chloride and sulphate have all risen in boreholes G39937 and G39937A. This could be from increased salinity of the recharge water due to excessive pumping during the summer of 1995/1996 or short term variations due to changes in rainfall.

3.7.3.3 Isotopes

Graphs of $\delta^{18}O$ vs. chloride ion concentration are useful as an aid to tracing the recharge pathways in the Agter-Witzenberg Valley.

Figure 3.30

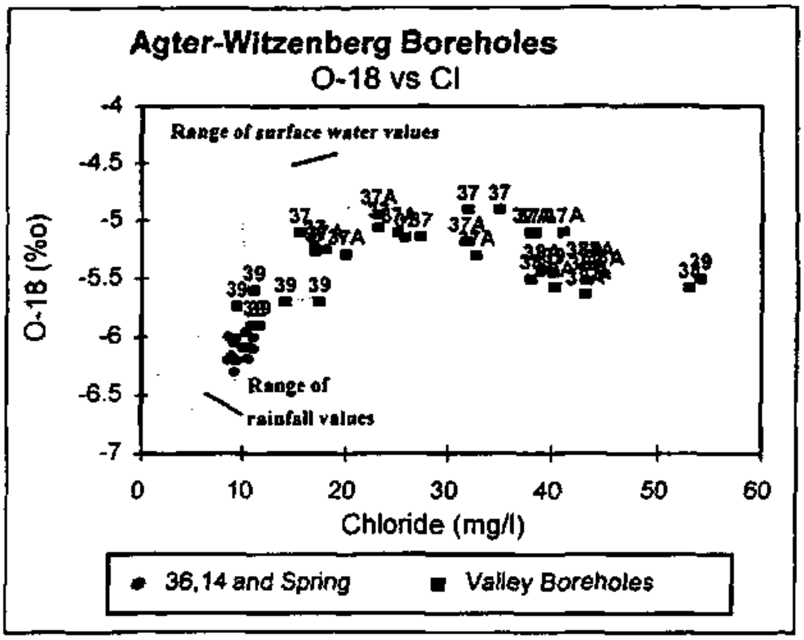

FIGURE DISCUSSION

$\delta^{18}O$ values provide the basis for three groupings:

- *G39936, 311/14 and the spring at the foot of the mountain have low $\delta^{18}O$ (~-6.2‰).*
- *Valley waters have higher $\delta^{18}O$ (~-5.2‰). There is a slight difference between the valley quartzite (G39937, G39937A) and shale (G39938, G39938A) samples.*
- *G39939 drilled into the deep quartzites shows a mixture of the two water types.*

Comparing the mountain borehole grouping to the rainfall values, two aspects can be seen: Firstly, the ^{18}O signature is the same, implying direct infiltration from rain and no recharge from evaporated surface ponds of water. Secondly, the chloride concentration in the groundwater is approximately twice that in the rainfall, which implies that transpiration has reduced the recharge to 50 % of the rainfall. Comparing the valley borehole grouping to the surface water data also reveals interesting correlations. The boreholes closest to the stream, ie G39937 and G39937A show similar $\delta^{18}O$ and similar chloride to that of the surface water. However, the boreholes further away show lower $\delta^{18}O$ than that of the surface water, but also higher chloride content. This indicates that G39937 and G39937A are recharged directly by surface water, whereas G39938 and G39938A have mixed water sources. The higher chloride values encountered for the boreholes in the Bokkeveld group reflect the greater amount of leachable chloride in the shales than in the Table Mountain quartzites.

Figure 3.31

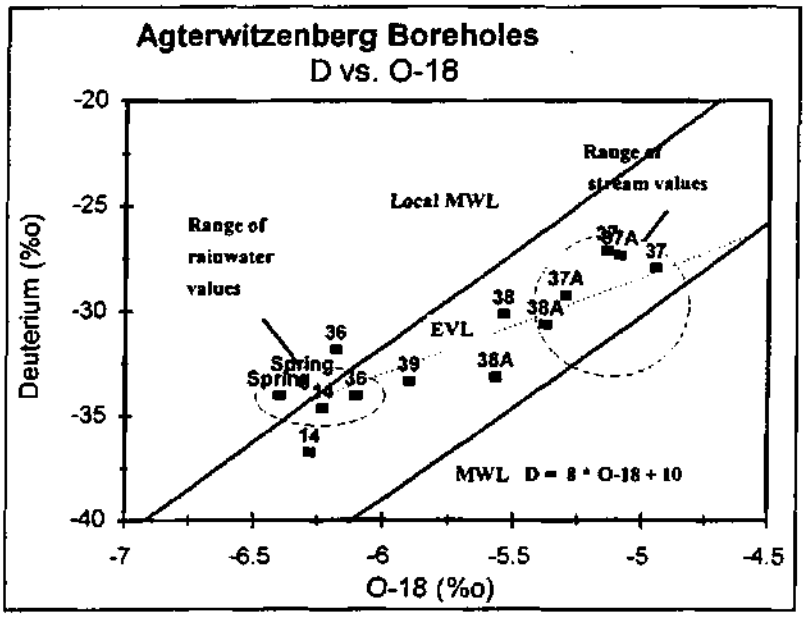

FIGURE DISCUSSION

All the points lie close to the local meteoric water line (Local MWL). The spring and mountain waters are closer to the local MWL than the other samples which could show some minor evaporation effects. G39939 and G39938 lie along an apparent mixing line and could be mixtures of mountain (rainfall) and valley (surface water) recharge.

Figure 3.32

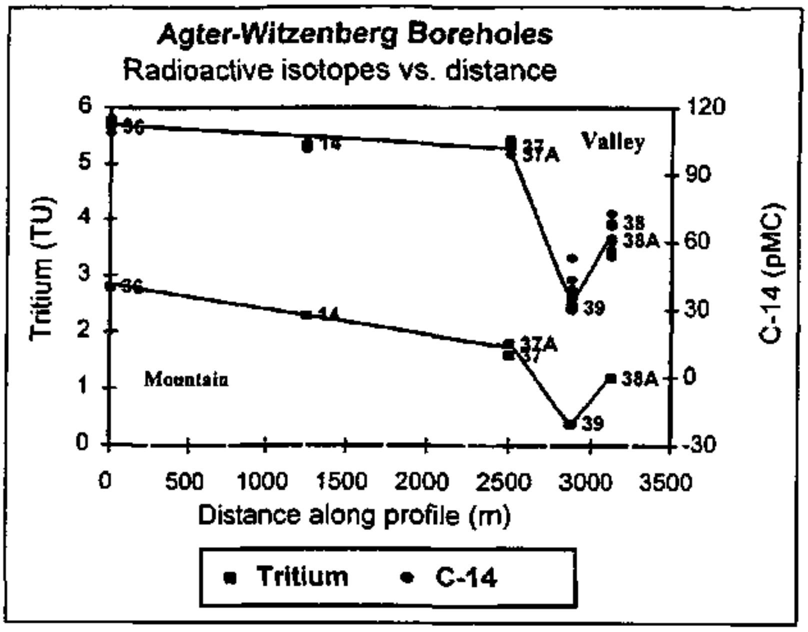

FIGURE DISCUSSION

Both age-related parameters show recharge in the mountain (G39936, 311/14), where ^{14}C exceeds 100 pmc and tritium is greater than 0 TU, and "older" water in the valley. The valley Table Mountain samples (G39937 and G39937A) also show a high ^{14}C content, but slightly lower tritium. Valley Bokkeveld samples have low ^{14}C values with a greater variability. The low ^{14}C in G39938A is a reflection of both carbonate addition to the water and old age. This is confirmed by the fact that there is still measurable tritium left in the water and the water is undersaturated with respect to calcite (Table 3.6). This precludes absolute dating of the water using ^{14}C since there is obviously mixing of water types and variable carbonate dissolution. Once again, G39939 stands out as an exception on the distance line. Note the variation of C^{14} of about 25 % for G39939 and G39938. This implies a large degree of mixing of waters.

Figure 3.33

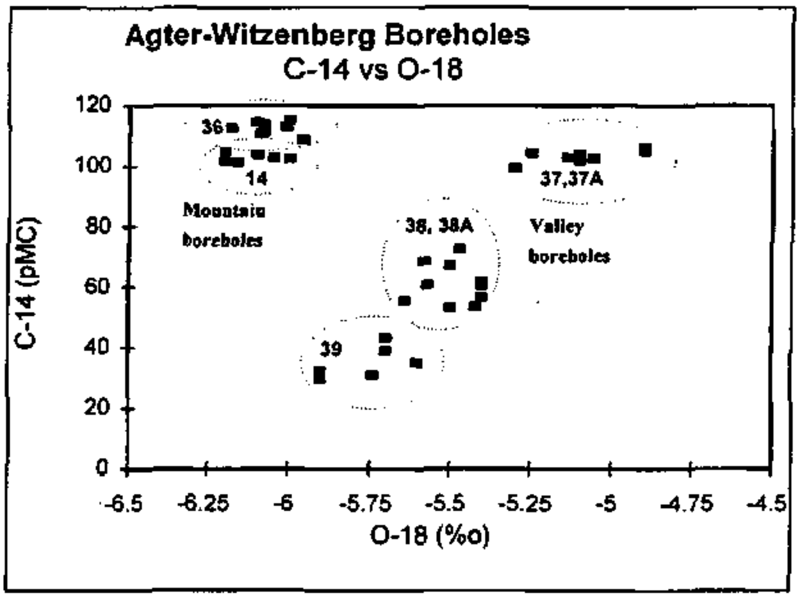

FIGURE DISCUSSION

This plot characterises the young mountain (G39936, 311/14), young valley (G39937, G39937A) and "old" valley (G39939) waters. The graph suggests possible mixing of water types for the valley boreholes (G39938/ G39938A) between end members G39939 and G39937/ G39937A).

Figure 3.34

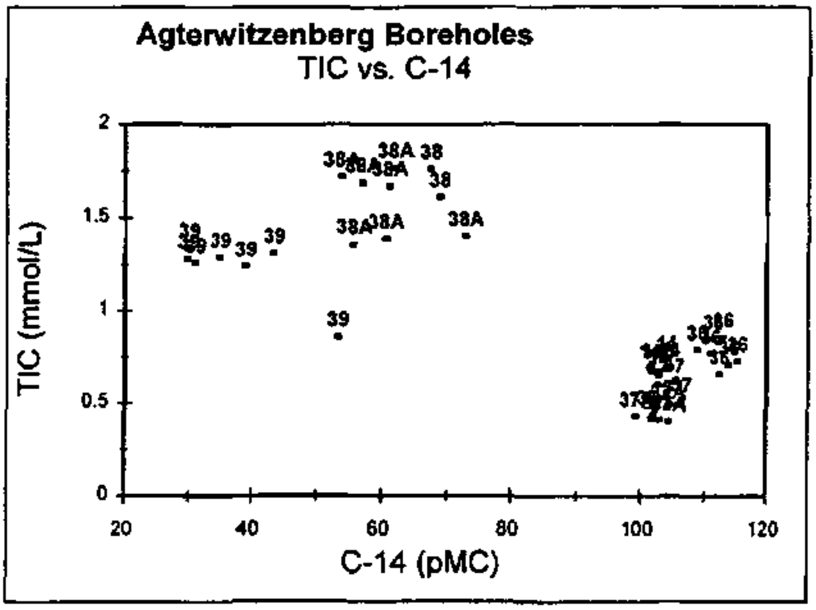

FIGURE DISCUSSION

There is a clear grouping of the different sample groups in the TMG and in the BV group.

The boreholes in the Table Mountain Group (G39937, G39937A, 311/14 and G39936) cluster together indicating young age (^{14}C > 100 pmc). Low TIC (total inorganic carbon) follows from the absence of carbonate in the TMG and little vegetation to introduce carbon dioxide in the groundwater.

Borehole G39939 shows variable amounts of ^{14}C and less variable amounts of TIC. This suggests that each seasons' water consists of several packets of water recharged under the same regime but reaching the borehole at different times. The single sample with high ^{14}C content and lower TIC was the first one sampled at this borehole and is probably contaminated with drilling fluid. G39938 and G39938A also show seasonal ^{14}C variations but TIC variations as well. In this case the water reaching the boreholes is a mixture of different ages and chemical composition. These low ^{14}C results indicate underground residence times of the water up to 8000 years (Table 3.8).

Figure 3.35

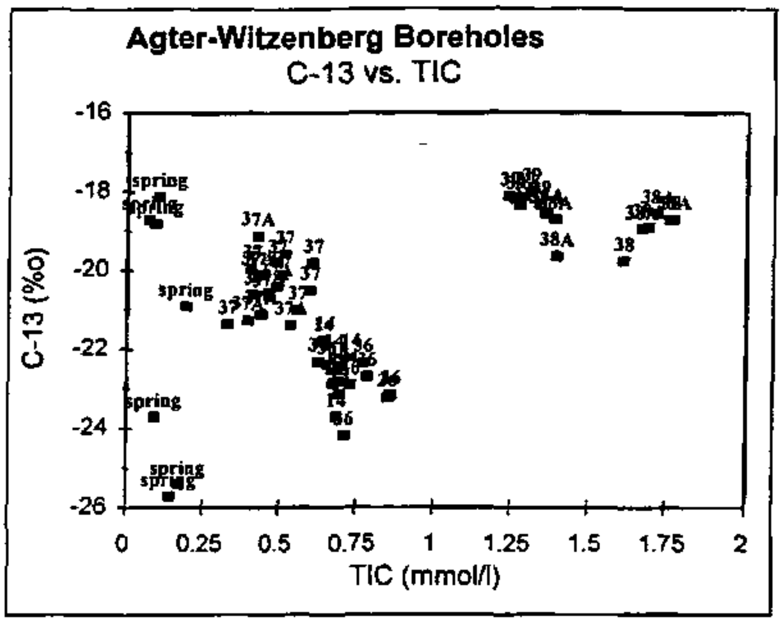

FIGURE DISCUSSION

^{13}C results identify the process that contributes alkalinity to the water. The small ^{13}C difference of only a few per mille between the recharge water and the water with the lowest ^{14}C content in the Bokkeveld indicates that there is very little additional carbon in the form of carbonate ($\delta^{13}C=0$ ‰) being added to the water. The alkalinity in the water is therefore generally the result of silicate weathering reactions such as:

$$CaAl_2(SiO_4)_2 + 2CO_2 + H_2O = Ca^{++} + 2HCO_3^- + Al_2O_3 + 2SiO_2$$

(Vogel & Ehhalt 1963). Reactions of this type cause the pH to increase without the addition of carbonate to the water. The small increase of ^{13}C from -23 to -18 ‰ is caused by small amounts of carbonate being dissolved. These quantities can be calculated from the ^{13}C values and used in the age calculation from radiocarbon analyses.

Figure 3.36

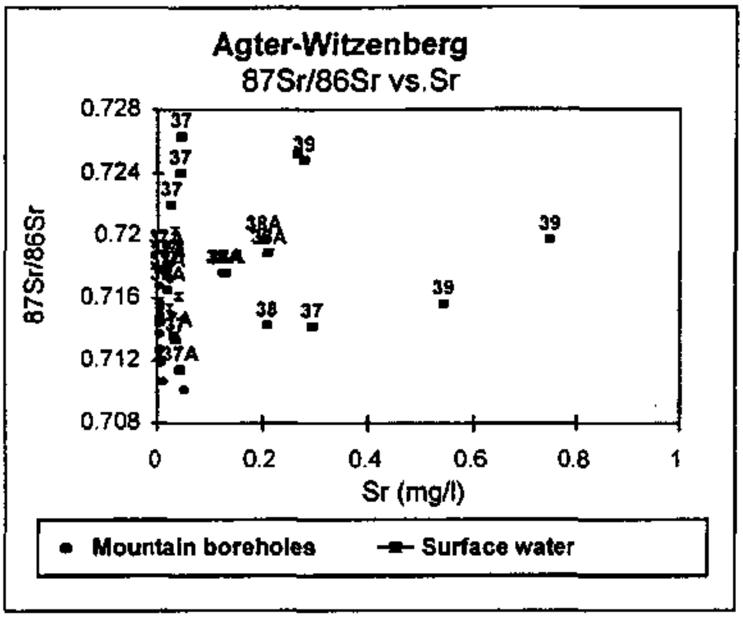

FIGURE DISCUSSION

Strontium isotope ratios vary considerably from a baseline close to seawater (ratio of 0.7092) to higher values representing the addition of strontium from aquifer materials. Strontium values are low in the quartzite rocks and higher in the Bokkeveld (G39938/A) where more time and opportunity exists for Sr dissolution. The former show some patterning. The latter do not, and neither do the stream waters, indicating more than a two-component mixing in these cases.

Figure 3.37

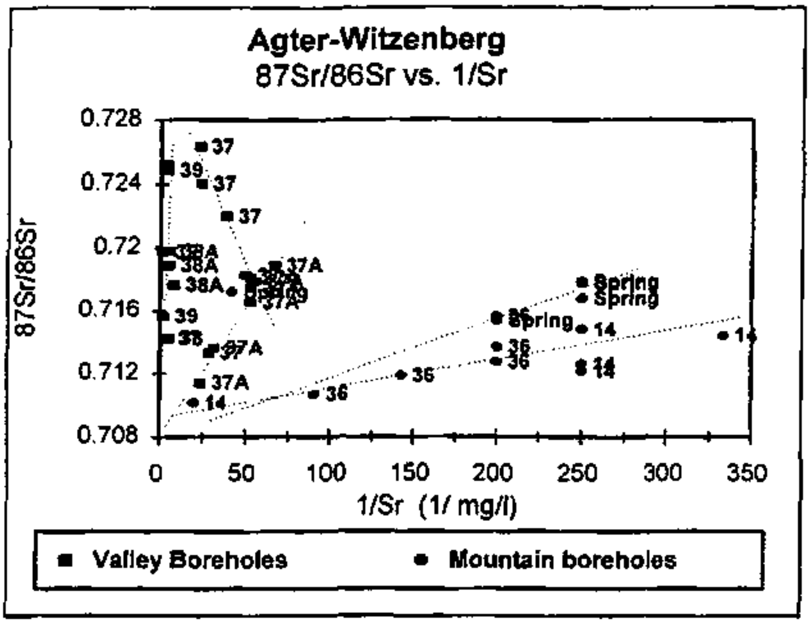

FIGURE DISCUSSION

Straight lines on a plot of Sr isotope ratio as function of the inverse of the concentration indicate the mixing of two components, i.e. water mixing in the boreholes or a single water mass gradually acquiring strontium from another source. This is clearly seen in the group representing the mountain (quartzite) water (311/14, G39936 and also Spring) which suggests the mixing between a water with a seawater isotope ratio and a higher ratio/low Sr water type. None of the other parameters have shown this variation in the mountain waters. In the valley quartzite waters linearity is also observed but one borehole (G39937A) trends towards the high isotope ratio while the other (G39937:deep) trends towards a lower ratio. This suggests different additional strontium sources for both boreholes. This is the only parameter set indicating a difference between this borehole pair.

Two of the samples collected during the course of the project were also analysed for nitrogen isotopes. Variations in the ratio of $^{15}N/^{14}N$ are primarily produced by biological processes. The $\delta^{15}N$ ratio can thus be used for tracing the effects of water interaction with fertilizers, sewage effluent and animal or human waste (Heaton 1986). The results from the Agter-Witzenberg samples appear in Table 3.7.

Table 3.7 : Nitrogen isotope results.

Sample	Date	$\delta^{15}N$ (‰ air)	NO_x-N (mg/l)
G39937	1996/01/15	5.5	1.63
G39937A	1996/01/15	5.9	2.13

These samples show no evidence of contamination by fertilizers or other nitrogen-bearing pollutants, supporting the evaluation of the Agter-Witzenberg groundwaters as uncontaminated by cultural influences. The small amount of nitrate present is probably attributable to soil organic compounds.

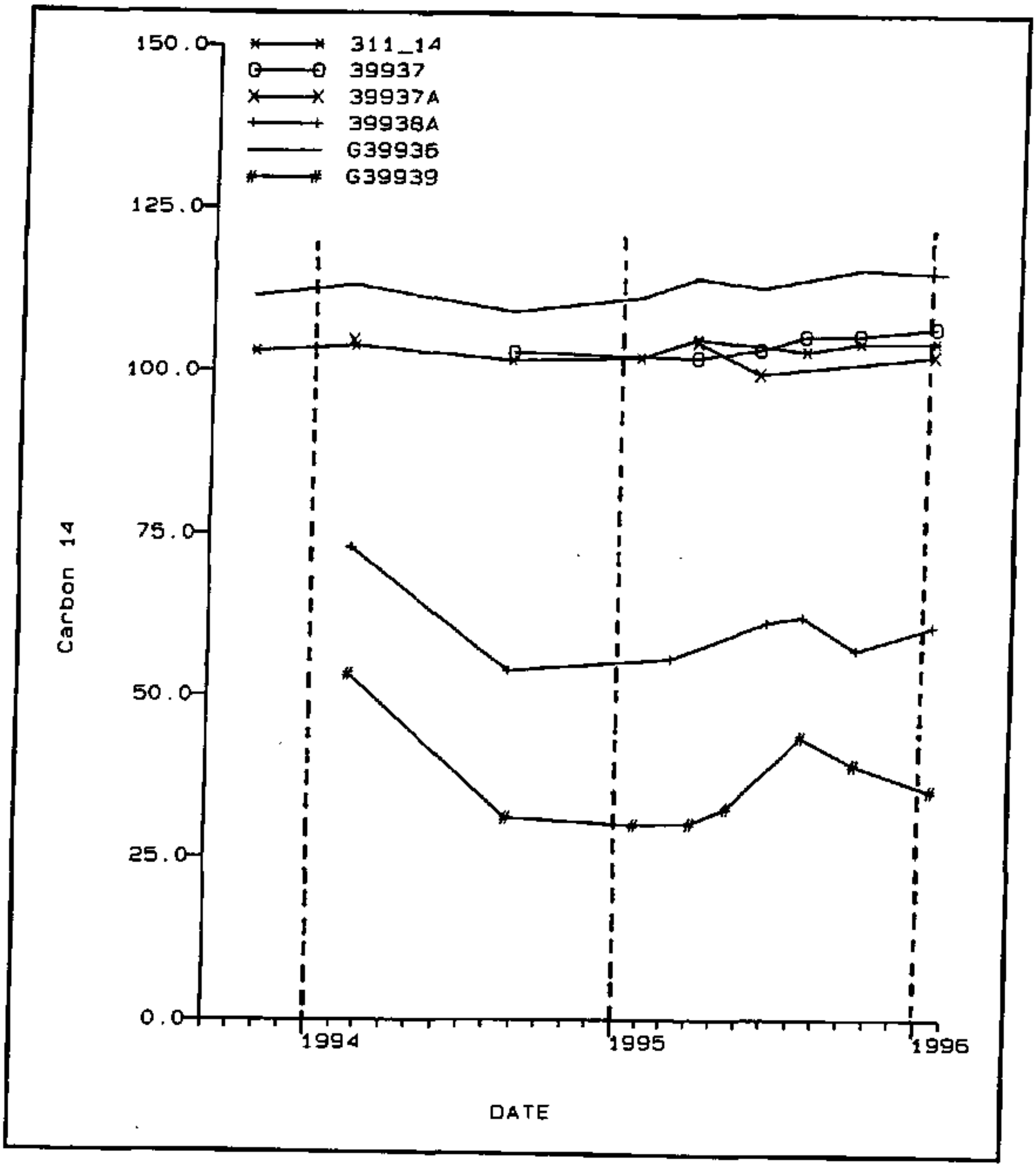

Figure 3.38 : Agter-Witzenberg Boreholes. $\delta^{14}C$ Time Series.

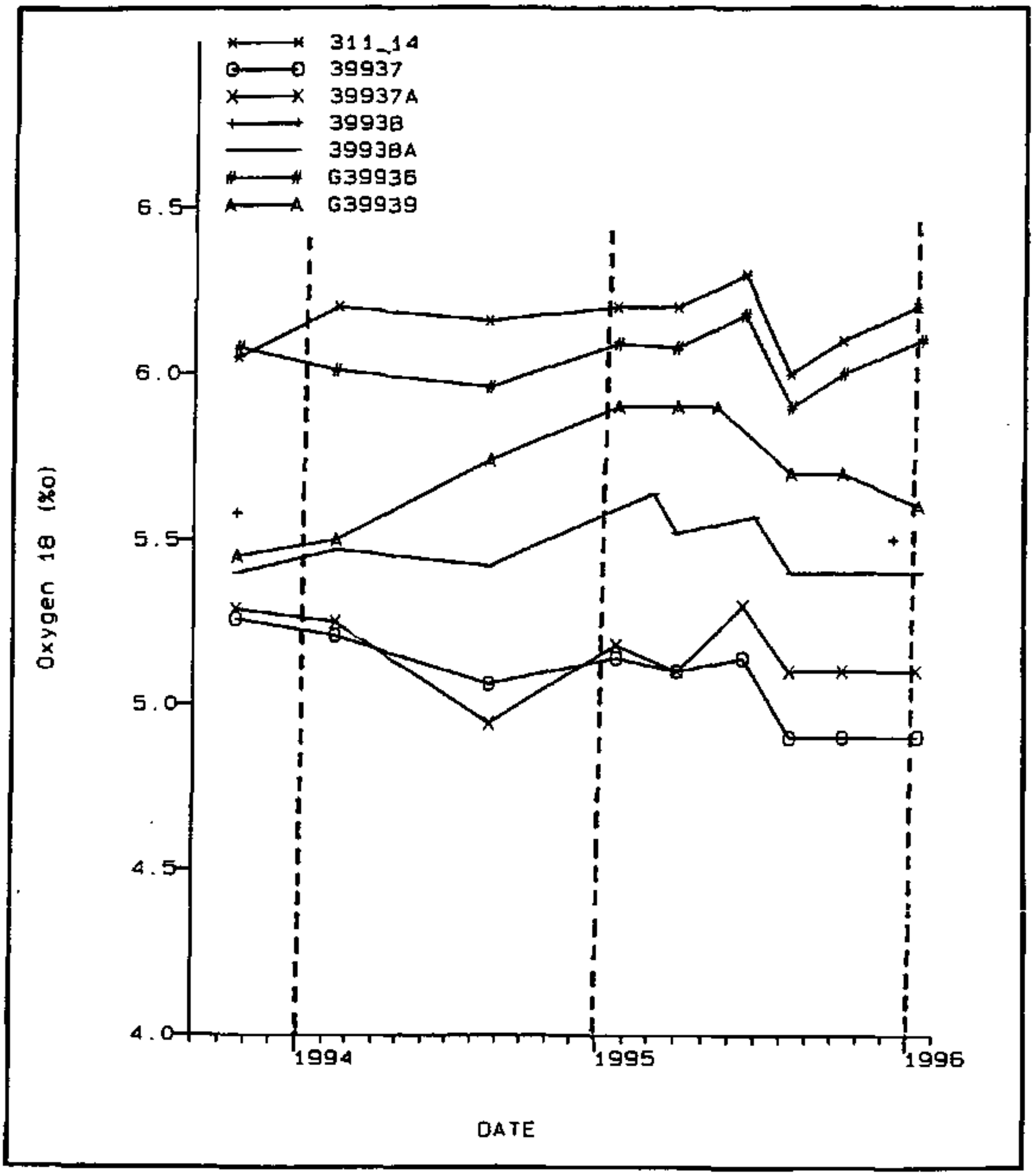

Figure 3.39 : Agter-Witzenberg Boreholes. $\delta^{18}C$ Time Series.

Time variations

FIGURE DISCUSSION

The boreholes in the Table Mountain quartzites show some periodicity of ^{14}C with high values occurring in the late summer and low ^{14}C in the winter, although this is not uniquely defined.

Variations in the samples with low ^{14}C concentrations (G39939, G39938 and G39938A) do not appear to be regular (Figure 3.38).

There are no obvious seasonal or long-term trends on the $\delta^{18}O$ time series graph (Figure 3.39) Whatever mixing of different water types may be occurring, their effects do not show up in the small $\delta^{18}O$ difference between the types.

3.7.3.4 Groundwater dating and chlorofluorocarbons

To calculate groundwater ages (i.e. the time that the water has been underground) using radiocarbon, the flow pattern and the sources of carbon should be known. The flow pattern is uncertain in this area. In fact the data indicate that there is a fair amount of mixing between younger and older water, either in the aquifer or in the boreholes during sampling. The ages calculated from the ^{14}C content are therefore intermediates between those of the end-members of the mixing pattern. The sources of the TIC in the water can very well be identified by ^{13}C in this area: soil carbon dioxide with $\delta^{13}C$ of -23‰ and aquifer carbonate with $\delta^{13}C=0‰$. From these two inputs the relative contribution of the two sources can be determined and appropriate ages calculated (Pearson 1965). Radiocarbon contents greater than 100 pmc show the presence of bomb-^{14}C and indicate ages less than 40 years (post 1960 AD) The results are shown in Table 3.8. Also shown in this table are the tritium analysis results analysed at Witwatersrand University (Prof B Verhagen).

As part of another WRC project investigating the application of CFC's in groundwater for the purpose of age-dating in fractured rock aquifers (Weaver & Talma 1997), a set of samples was collected at Agter-Witzenberg for CFC analysis. Table 3.8 below shows the interpreted dates for the three CFC tracers and compares these with the ^{14}C and tritium measured from the same boreholes.

Table 3.8: Date calculations, tritium and CFC data

Borehole Number	^{14}C (pmc) range	Tritium (TU) Jan 1997	$\delta^{13}C$ PDB	CO_2 added %	^{14}C age range	Derived age of recharge		
						F-11	F-12	F-113
G39936	109-115	2.8±0.3	-22.9	0	0-40	1979	1984	1987
311/14	102-105	2.3±0.3	-22.5	1.7	0-40	1975	1974	1981
G39937	102-106	1.6±0.3	-20.4	11	0-40	1970	1971	1976
G39937A	99-104	1.8±0.3	-20.5	10	0-40	1970	1972	1978
G39938	67-69	-	-19.2	16	1630-1800	-	-	-
G39938A	54-73	1.2±0.3	-19.3	16	1200-3730	1952	1956	<1955
G39939	30-53	0.4±0.3	-18.3	20	3360-8130	<1950	<1950	<1955

As can be seen from these data, there is a general correspondence between the CFC, tritium and ^{14}C trends. It is important to note that the tabulated CFC 'dates' are based purely on the model of CFC concentration projected on the atmospheric CFC growth curve (Weaver and Talma 1997) and do not take the mixing of waters into account. The CFC dates for the first four boreholes (in the TMG) could well be correct, but those in the Bokkeveld (G39938A, G39939) are close to the background value of CFC and therefore only indicate 'old' water with a trace of modern influence. This mixing of young and old water has a different effect on the different dating isotopes, hence the discrepancy between 'dates'.

The three dating tools, radiocarbon, tritium and CFC therefore provide a consistent picture of groundwater flow within the limitations of having to quantify mixing in the valley boreholes.

3.7.3.5 Temperature Profiles

Temperature profiles were measured by Barry Venter of DWAF for the boreholes in this study. The results for the deep boreholes are shown in the following graphs:

Figure 3.40

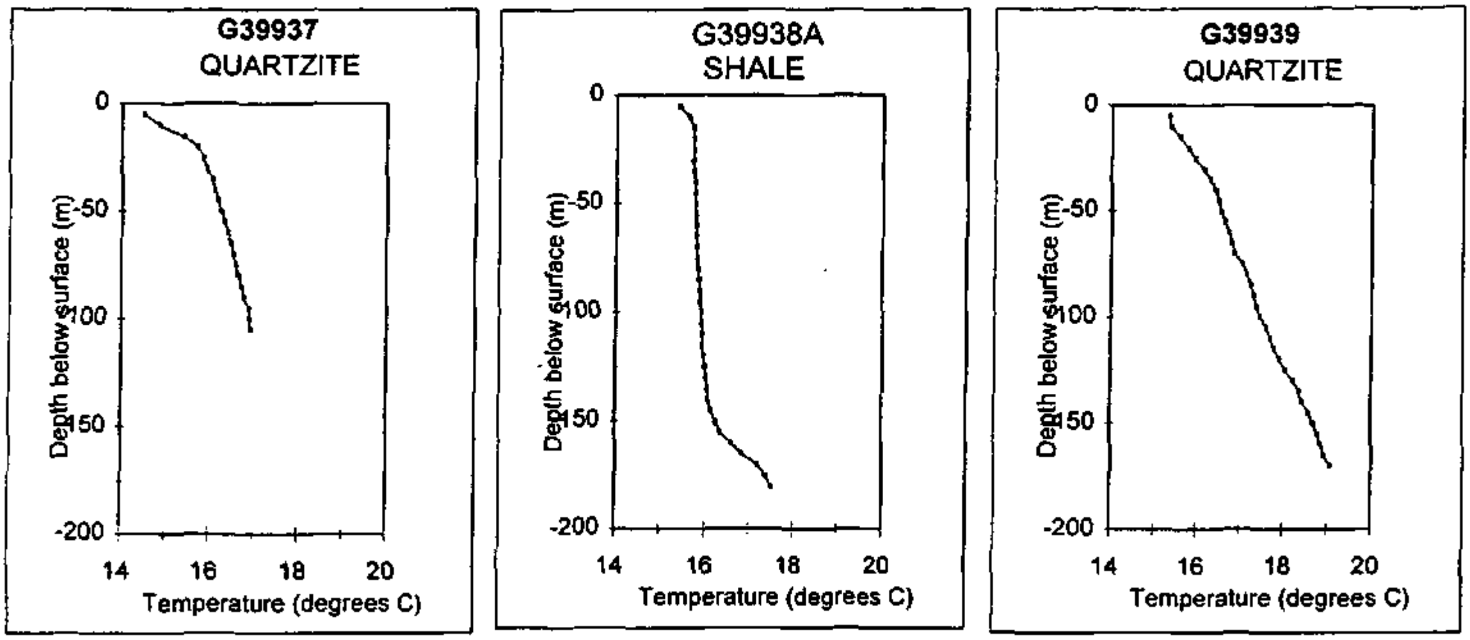

FIGURE DISCUSSION

The lower temperatures (below 15°C) encountered over the first 20 m in borehole G39937 could be due to the recharge by cooler surface water, especially as this influence is not seen in G39938A and G39939.

The sudden temperature rise between 160 m and 180 m below surface in G39938A indicates a possible fracture zone where hotter water from depth has penetrated . Slow heat conduction in the shales leads to a localised zone of higher temperature close to the fracture zone. The water samples from this borehole do not reflect this higher temperature zone, because the water originates from an upper fracture at around 120 m which has much higher hydraulic conductivities. The upper fracture contains cooler shallow groundwater influenced by rain and surface water recharge.

The expected temperature response is that the gradient in the shales would be higher than in the quartzites. This is because quartzite has a higher thermal conductivity than shale. However, as shown in the graphs, the reverse is true for Agter-Witzenberg. Borehole G39937 in the quartzites has a gradient of 1.3°C per 100 m whereas G39938A in the shales has one of 0.3°C per 100 m. The temperature gradient of G39939 is even steeper at 2.2°C per 100 m. The average for the Cape Fold Belt is about 1.5°C per 100 m. The low temperatures and temperature gradient in G39938A can be explained if the influence of cooler shallow water dominates in the rock around the borehole.

The unusually steep gradient for G39939 is regarded as further evidence of deep seated flow of groundwater. Referring to the chemistry database it can be seen that the field measured temperature confirms these profiles, with the average for G39939 being 19.6°C and 17.3°C for G39938A.

3.8 Flow Model for the Agter-Witzenberg Aquifer

A conceptual flow model for the Agter-Witzenberg Valley aquifer is summarised on Figures 3.41 and 3.42.

Winter

Winter rainfall causes 50 % recharge in the mountain areas. Rainfall recharge also occurs in the valley, but to a lesser extent. The rainfall infiltrates below the ground surface before evaporation takes place and recharges the aquifer, elevating the water levels. The aquifer fills up at this stage and excess groundwater seeps out as springs along the mountain slopes. Surface runoff predominates in the valley where minimal recharge occurs.

Summer

There is little recharge by rainfall at this time of year so the recharge mound below the mountain shrinks. Together with the large volumes withdrawn by farmers' pumping in the valley this accounts for the general drop in water levels. The farmers' pumping leads to a drop of over 30 metres in the water level in G39938A. The heavy pumping sets up a strong hydraulic gradient from the mountain towards the valley which accelerates the movement of water from the Table Mountain Group across the contact into the Bokkeveld Group rocks. Old, deep water from the Table Mountain Group is fed up the contact zone (which has a high hydraulic conductivity) and mixes with shallow water in borehole G39939. The lowering of the valley water table by pumping also encourages recharge by the perennial stream during summer as supported by the same $\delta^{18}O$ isotopic signature in G39937 and the surface water.

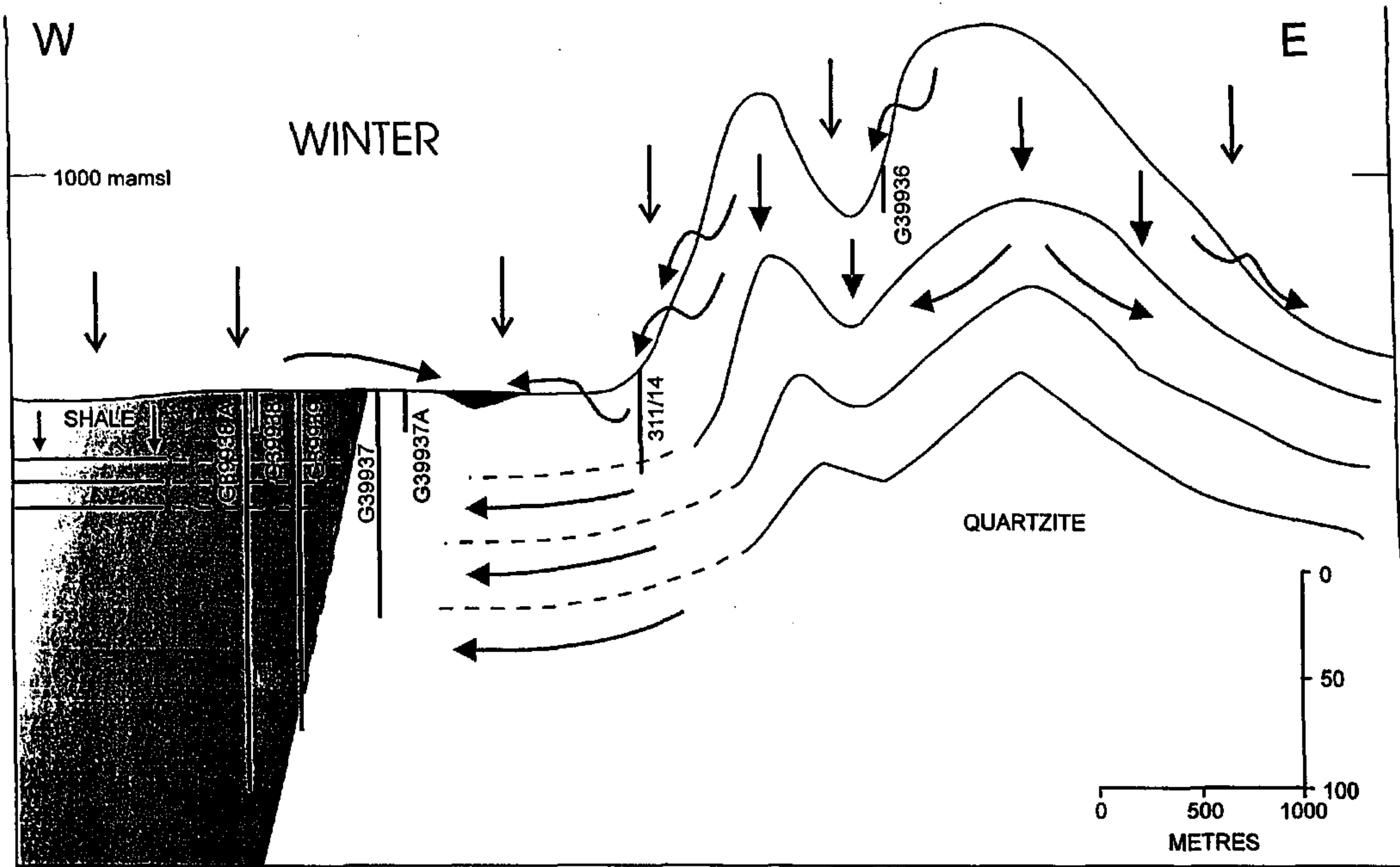

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Figure 3.41 : Groundwater flow patterns in the Agter-Witzenberg aquifer
Winter model.

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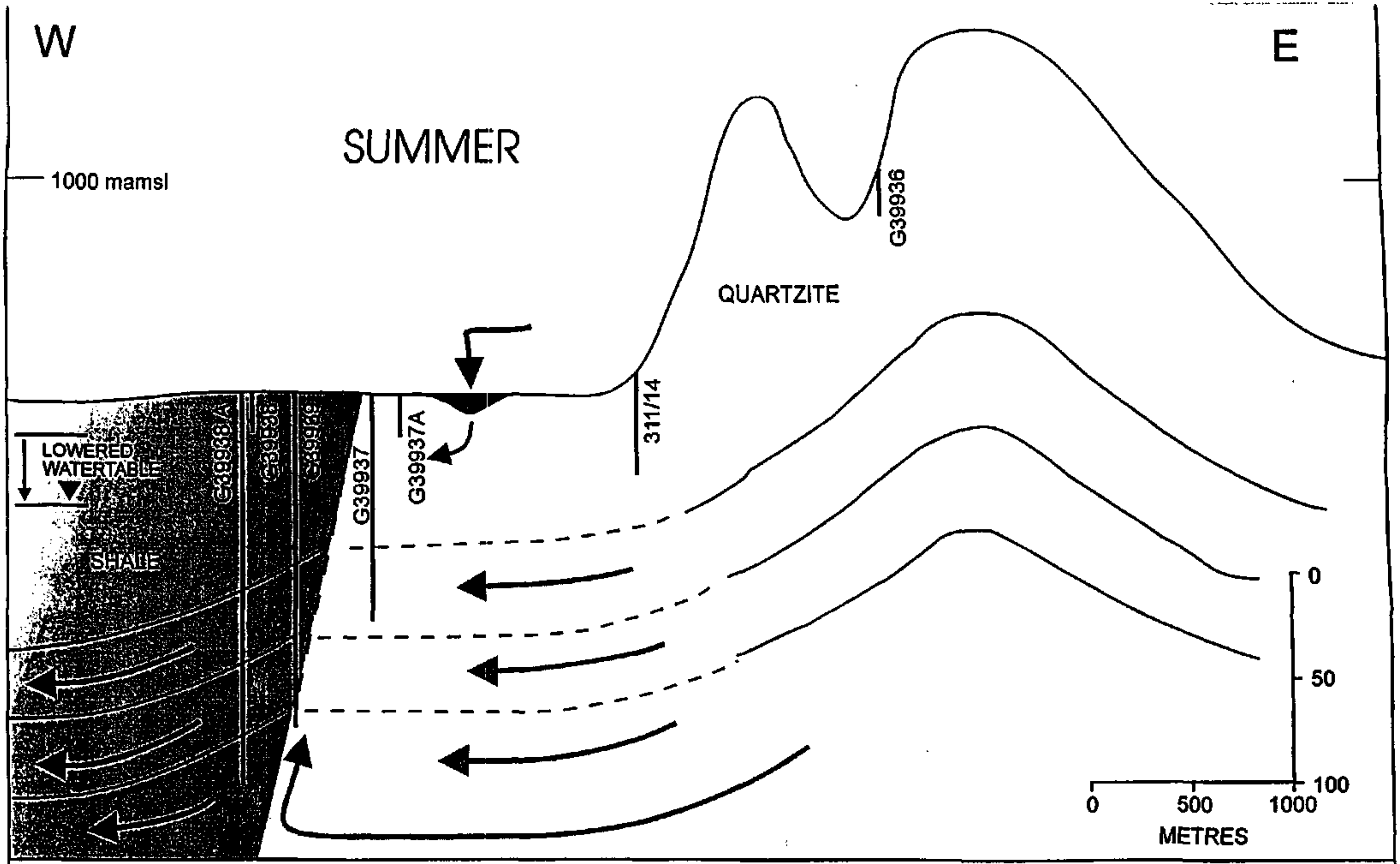

GEOCHEMISTRY AND ISOTOPES

Figure 3.42 Groundwater flow patterns in the Agter-Witzenberg aquifer
Summer model

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Evidence

The conceptual flow model is supported by the following:

- G39936, 311/14 and the spring show the isotopic character of direct rain recharge and subsequent concentration of the recharged water by transpiration, leading to a net recharge of 50 % of precipitation.
- Under undisturbed conditions, the water table is higher than the river level, so the river water "floats" over the water table. Evaporated water from the river (with higher $\delta^{18}O$ than the rainfall) would not be found in the boreholes when these conditions apply. Instead all the boreholes would show $\delta^{18}O$ similar to the rainfall. During these times the aquifer would be discharging into the river.
- However, heavy pumping by the farmers in the valley causes water levels to drop by over 30 metres in summer in the shales, thus inducing a hydraulic response. The consequence of the pumping is that the river in summer becomes a recharge source, with boreholes G39937 and G39937A in the Quartzites showing the same evaporated ^{18}O signature as the river.
- The contact between the Bokkeveld shales and Table Mountain Quartzites is a zone of relatively high hydraulic conductivity providing a mixing conduit for the deep seated older groundwater (which has the ^{18}O signature of the rainfall recharge in the high mountain areas) and the recharged stream water. This accounts for some of the anomalous chemistry in borehole G39939.
- Significant chemical and isotopic variations are evident in Bokkeveld shale boreholes (G39938 and G39938A) due to the different seasonal mixing regimes. These are obviously mixtures with the end members representing young (< 10 years) stream recharge water and older (50-200 years) deeper water.
- Very rapid vertical mixing occurs in the Table Mountain Quartzites in the valley. This is evident from the similarity of the chemical and isotope properties of the shallow (G39937) and deep borehole (G39937A) there.
- Extensive gain of sodium, and pH increase, can be seen in G39939, the borehole drilled through the Bokkeveld shales into the quartzites. The nature and location of the process responsible for this is not known at this stage, but it could develop into a useful geochemical marker if properly identified.

3.9 Mathematical flow modelling

3.9.1 *Reason for modelling*

The detailed study of hydrochemistry and isotopes has provided a model of groundwater flow for the Table Mountain Group quartzites of Agter-Witzenberg. This model supports the view that groundwater flow in the Table Mountain Group quartzites can be deep seated. The very important consequence of this conceptual flow model is that there is a huge reservoir of groundwater. Such a reservoir allows the aquifer manager a large number of additional exploitation stratagems not normally available to the South African wellfield manager.

However, this deep-seated model is one that is proposed on "gut-feel" and is now, following this investigation, strongly supported by isotopes and geochemistry.

The remaining "proof" that is required is to test the aquifer hydraulically. This should be by water balance methods, stream flow gauging, drilling of deep boreholes and pump testing.

To quote Wood (Pers. comm. 1995), "Geochemistry can be used to gain some qualitative insight independently of flow, but it will not stand the scrutiny of the hydrologic community without coupling it to flow. The first step is to develop a computer flow-model based on the conceptual model."

3.9.2 *The model*

The software used for the computer model is MODFLOW (McDonald and Harbough, 1988). MODFLOW is a single porosity model more suited to primary aquifers. However, it must be realized that this is a "first-time look-see" exercise. With the second phase of this project which will be a detailed monitoring of hydraulic data in order to develop a water-balance for the valley it will be in order to use a dual-porosity model more suited to the fractured-rock environment.

The main pumping in the valley occurs some three to four kilometres west of G39938A. Initially this was modelled as a single borehole pumping 1000 L/s. This however had almost no effect on the water levels in the study boreholes and thus a pumping borehole was positioned 500 metres west of G39938A and set to pump at 50 L/s.

The initial hydraulic conductivities used were based on general experience of Table Mountain Group rocks and discussions with the farmers regarding borehole success rates. Calibration showed the above values to be high and after a number of runs (45), the values shown in Figure 3.43 were used.

The model grid that was used measures 50 metres horizontally across each cell increasing to between 75 and 150 metres for those along the western edge of the study area. The top layer of cells is 80 metres deep, and the others below measure 200m each in the vertical direction. The total thickness used was 2000 metres which is less than the total thickness of the aquifer. The width of the modelled area was 5200 metres.

After calibration of the flow-model was achieved the software package PATH3D was used for particle tracking. The purpose of particle tracking is to understand the path that a water molecule would follow and its rate of movement along that path. Particles (100) were injected at 3 points, namely borehole G39936 in the mountain, in the stream and in G39938A at a point 40 metre below surface. The model was then run and the positions of the particles at various time intervals were plotted. The time taken to reach the discharge point is shown in Table 3.9 below. Figure 3.43 shows the position of the particles at various time intervals along the flow-path.

Table 3.9 : Groundwater modelling particle tracking results.

Injection point	Time taken to reach Discharge point
G39938A	2 yrs 2 months
the stream	20 years
G39936	53 years

Examining these results some observations are made:

- In the Bokkeveld Group which has the higher hydraulic conductivity and lower recharge the tracers essentially move horizontally from the injection to discharge point.
- In the Table Mountain Group the lower hydraulic conductivity and higher recharge induces the tracer to move downwards in the aquifer, up to 200 metres before being induced to move up to the pump inlet.
- At the start of injection at G39936 the tracers do not move uniformly, some are seen to discharge at surface.

The results from this modelling exercise support the model derived from the isotope and geochemistry studies. There are, however, some discrepancies. The age of the water from the deeper boreholes has been shown by ^{14}C to be much older than the 50-odd years indicated by the modelling studies. The depth to which the particles move for the TMG are less than are expected, the conceptual flow model would imagine 500 to 1000 metres as being probable. However, accepting the limitations of the input data for the model it is encouraging that the model does show both that the water recharged from the mountains will be old by the time of discharge and also that it will tend to follow a deep flow path.

It is important to note that the mathematical model has been used as a conceptualisation tool and is not proof that flow occurs exactly as predicted. Nevertheless it does provide strong and exciting supporting evidence.

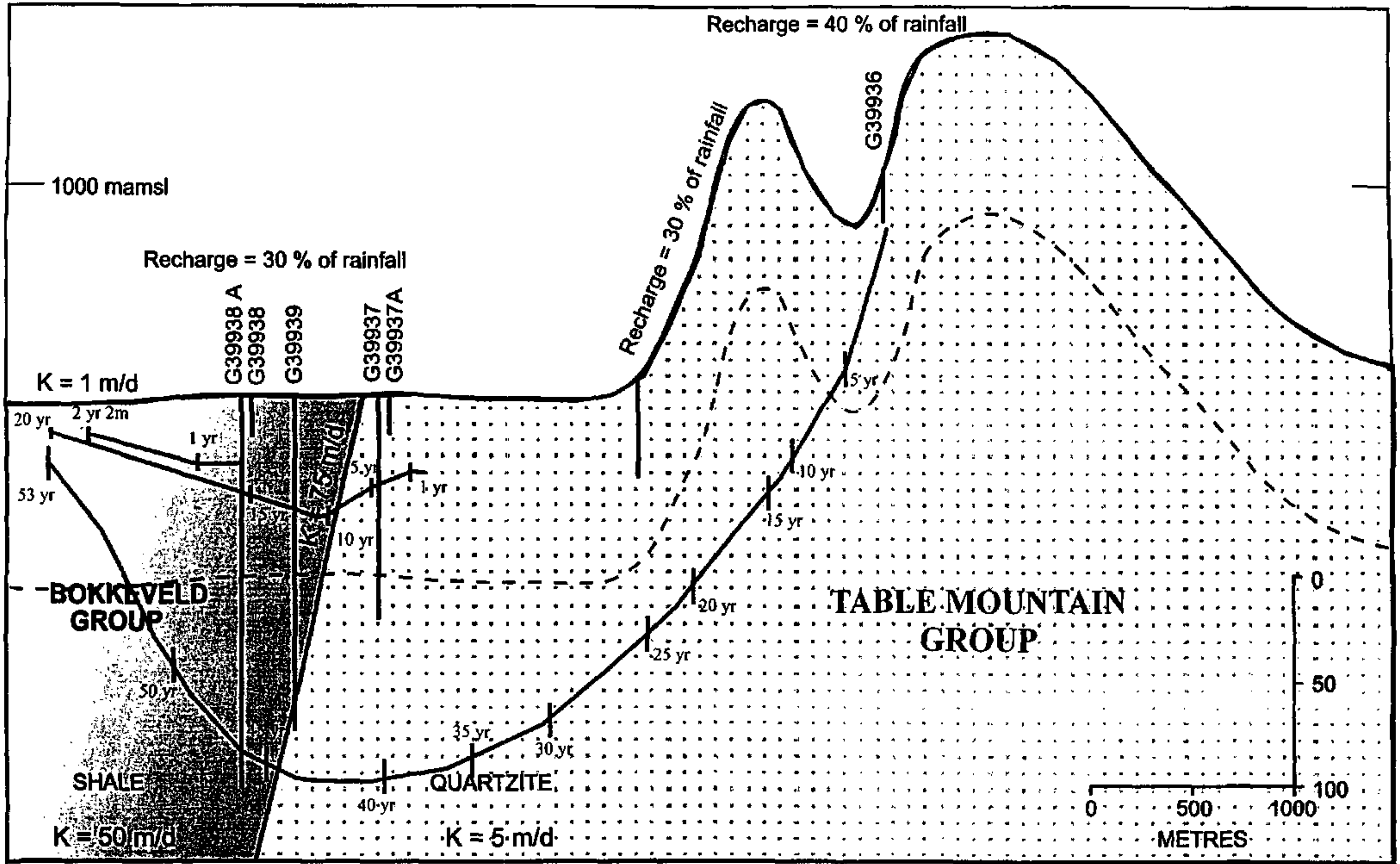

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Figure 3.43 Cross section along Agter-Witzenberg valley profile showing model parameters

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CHAPTER 4.

Conclusions

4. CONCLUSIONS

4.1 TMG quartzites and medium-seated groundwater flow

The quartzites of the TMG are recognised as being one of the top three aquifers in South Africa in terms of yield and wide areal distribution. The other two are the dolomites of the Malmani Subgroup and the sands and gravels of the Cenozoic. These TMG quartzites have a high potential for regional water-supply projects in the Western and Southern Cape.

The relevance and potential for development have been further enhanced by the embargo on further dam-building by Minister Kadar Asmal "until all alternate water-supplies have been investigated and developed". In the past the TMG has not been hydrogeologically investigated to the same extent as has been the other two aquifers, consequently there are shortcomings in our understanding of these aquifers which in turn has inhibited large-scale development of the aquifers.

One of the major obstacles is quantification of the available groundwater resource. In theory this is a vast resource. The area covered is tens of thousands of square kilometres and with the Peninsula Formation being 1500 m thick and the Nardouw being 1000 m thick the aquifer volume is enormous. Furthermore, as quartzite is highly competent, fractures at depth will tend to remain open, as opposed to granite (and most of South African hard rocks) for which fractures at depths greater than 200 m will close with time. Added to the above is that the TMG quartzites have undergone intense tectonic activity resulting in areas which have extensive fracturing.

Of particular relevance to the question of quantification is proof of the existence of groundwater from the medium-seated zone of the aquifer. There is abundant evidence of an extensive shallow-seated aquifer. Many boreholes in the 10 to 200 metre depth exist and they pump large quantities of water. The high-yielding hot-water springs are proof that deep-seated flow occurs.

Knowledge that medium-seated groundwater flow does occur makes resources available to the water-supply manager that previously could not be calculated nor relied upon. In addition it makes available the possibility of a method of optimum exploitation of the TMG aquifers.

This method complements the Mediterranean climate of the Western Cape of no rain in summer when water-demand is highest. The method is to "over-pump" the aquifer in summer and lower the water-table tens and up to hundreds of metres. In winter when there is excess recharge this aquifer is allowed to fill up. However, in order to implement such a method, knowledge must be available and confidence must exist for medium-seated flow. The results of this project provide the first set of data that prove that medium-seated flow does occur.

The deep quartzite borehole (G39939) exhibits a number of chemical and isotopic signatures which indicate that it intersects groundwater from deeper levels of the aquifer than either the shallow quartzite boreholes (G39937) or the shale boreholes (G39938).

The graph of $\delta^{18}O$ versus Cl shows that the deep water is a mixture of mountain water and valley water. Tritium and ^{14}C show that this is much older water than encountered in boreholes tapping shallow mountain and valley waters. The graph of $\delta^{18}O$ versus ^{14}C shows that the shallow mountain and shallow valley boreholes are the youngest water with the valley waters showing an evaporative signature. The two deeper boreholes show older water with the deep quartzite borehole having an $\delta^{18}O$ signature close to the mountain recharge water signature and the deep shale having a signature closer to the valley recharge. Significantly, however, is that the two end members are shallow water. The weight of evidence shown by interpretation of these graphs is that a portion of the recharge occurring in the mountains circulates through the deeper layers before mixing with shallower recharge water from the valley. It is thus concluded that both chemistry and isotopes show that medium-seated groundwater flow does occur.

Down-the-hole geophysical logging showed that the temperature gradient for the deep quartzite borehole was steeper than for the other boreholes and also steeper than expected. This is further evidence that this water has travelled via deeper levels than currently encountered.

4.2 Summer pumping and winter-recharge aquifer management

This method of exploitation has been proposed by Prof A Issar of Ben Gurion University who is an advisor to DWAF. This method, for various reasons, has not been adopted as a method of exploitation. Hydrographs from the Agter Witzenberg show that this method of exploitation is indeed being used in the valley by the farmers. The closest pumping borehole is more than 500 metres away, yet water-levels for the deep valley boreholes dropped by 30 metres during the 94/95 pumping season. Elsewhere water-level drops of 80 metres were recorded. At the end of the following winter recharge season water-levels had recovered. This shows that this TMG groundwater management method does work.

4.3 Recharge in the TMG quartzites

The very rugged nature of the outcrop together with the coarse sandy soil developed from weathering of the TMG quartzites indicates a high recharge potential. If this can be proved this will be further support for the summer-pumping winter-recharge aquifer management method. For most of South African aquifers recharge is taken to be less than 10 %. Very rarely are double figures mentioned, with the Cenozoic sands being regarded as exceptional at 15 % to 20 %.

Comparing Cl and $\delta^{18}O$ for the two mountain boreholes and the spring with values obtained from five cumulative rainfall samplers the indicated recharge is 50 %. This is an extraordinarily high figure which means that if this potential recharge can be recovered in summer, then the sustainable yield of these aquifers is much higher than has been previously assumed.

Recharge in the past would have been taken to be 8 % to 15 % which is $^1/_6$ to $^1/_3$ of the observed value. The excess recharge is lost to the aquifer due to the aquifer being "full" and the excess recharged groundwater discharges as base-flow. Investigations in the Jonkershoek Valley (Midgeley and Scott, 1994) have shown that even in winter river highflow conditions most of the riverwater is groundwater. It is this excess groundwater which should be captured by summer-pumping winter-recharging management.

4.4 Cumulative rainfall sampler

The cumulative rainfall samplers have proved to be very useful in collecting a representative annual sample of rainfall quality. Some refinement is needed to prevent insects and bird droppings from contaminating the sample. However, the consistent volume of sample collected for the 8 samplers installed at five sample stations (two were rejected), the consistent chloride and the consistent $\delta^{18}O$ show that these samplers will be very useful for future groundwater studies where aquifer input chemistry and oxygen isotope values are needed.

4.5 Achievements and the aims of the project

The original aims of the project were:

- To relate hydrochemical variations and hydrographs to recharge and resource evaluation of the Cape Rocks.
- To relate groundwater isotopes to the hydrochemical variations and hydrographs for the estimation of groundwater residence time and groundwater recharge source areas.

Together these aims have been achieved. The hydrograph and hydrochemical variations suggested distinctions between the aquifers in the area and seasonal changes. It required the addition of the groundwater isotope data and then the rain and surface water measurements to be able to relate the components to each other. The fractured nature of the aquifer causes water in the boreholes to be mixtures from different sources each with its own residence time. A range of residence times is therefore possible for each component of the water balance.

The study of the Agter Witzenberg aquifer has become a good example of the integrated approach to ground water studies in the Cape Rocks. To the authors' knowledge such a wide range of data on a single site has not been attempted either in South Africa or elsewhere. The characterisation of different water sources contributing to an aquifer is only possible by a holistic view of all the data.

CHAPTER 5.

Recommendations

5. RECOMMENDATIONS

- The establishment of the Agter-Witzenberg aquifer as a test site of Cape Fractured Rocks is recommended. This area has now shown itself as a useful testing ground for concepts regarding flow in the Cape Rocks, for which other applications are likely to exist elsewhere in the province. Continuation of some form of monitoring at the boreholes of this site will therefore allow its later availability for other similar studies. On the one hand more data from the site would enable one to confirm or amplify the conclusions reached during the present project. On the other hand it would be a good testing area for techniques or ideas that might develop at a later stage. For such later potential use, it would be useful to continue monitoring water levels, rainfall and to collect rainfall, stream and groundwater samples on a regular basis for analysis of some components. The existence of the research boreholes here and the keen interest of the local farmers will form a good basis for continued operation of such an establishment.

- A detailed proposal for the establishment of the Cape Aquifer Test Site (CATS) is presented as Appendix F.

- The determination of a proper water balance for the valley would be a useful continuation of this project. This would entail stream flow gauging on a regular basis, some monitoring of farmers' water comsumption and estimates of the likely recharge in the agricultural parts of the valley. Analyses of some of the parameters measured in the present study should be continued. Attention should also be given to the water situation further west into the valley and extended towards the south and north where larger water level variations have been reported.

- The applicability of the approach developed in the AgterWitzenberg Valley needs to be tested elsewhere now. Locations where this could be done would be in the Cape Rocks, preferably in contact with other rocks, where large seasonal ground water level variations occur. One would firstly determine whether concurrent chemical and isotopic variations exist at all and then look for likely sources thereof.

- A more detailed groundwater and tracer modeling exercise than the one presented here, would be a useful addition to attempt quantification of the ideas developed here.

- These can yield information on the chemical character that water can assume when in contact with specific rocks or minerals and possibly set limits to the reaction rates involved. Such studies can include ^{13}C and ^{87}Sr. They are also likely to yield some data on the transient chemical effects when a freshly drilled borehole is exploited. The results obtained from water/rock interaction for Struisbaai have provided valuable insight into the origins of the groundwater salinity. Further studies for a variety of rock types have the potential to develop into a useful chemical/isotopic fingerprinting technique.

- Cumulative rainfall sampling is a viable, cheap method to characterize rainfall isotopically, though not quite as effective for hydrochemical measurements. These should be used more often in groundwater investigations where either recharge estimations are made, or where the geochemical input into a catchment is studied.

CHAPTER 6.

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Appendix A.

Rainfall Data

ANALYTICAL DATA FOR CUMULATIVE RAINFALL COLLECTORS

Collector	A	B	C	D	E	F	G	H	I	J
Date	960510	960510	960510	960510	960510	960510	960510	960510	960510	960510
K	3.6	1.8	12.4	3	16.7	8.8	5.4	12.3	9.5	10.1
Na	3.3	1.9	5.4	3.2	6.1	3.3	3.1	5.1	4.2	4.3
Ca	5.7	3.9	1	4.9	1.5	3.3	5.2	8.4	5.3	5.3
Mg	0.9	0.5	0.7	0.9	3.2	2.4	1.1	2.1	1.3	1.4
NH4-N	4.1	3.4	5.2	5.1	29	0.3	0.4	5.2	5	6.1
SO4	5	2.4	1.9	5.9	0.7	7.5	6.1	19.1	22.7	26.1
Cl	3.3	2.5	6.6	4.2	11	4	3.8	6.5	4.8	5.4
Alk(CaCO3)		1.5	24.5	1.5	127.5	12.3	13.3	2	6.5	10
NOx-N	8	5.3	0.2	6.9	0.3			8	5.6	6
P	2.2	1	4.5	2.1	5.2	6	4.1	10	5.5	5.7
Si	0.9	1.9	1.4	0.6	0.9	0.2	0.3	2.2	0.3	0.2
DOC	3.6	3	17.1	6.7	41.9	12.1	5.7	7.6	13.7	11.5
EC	14.2	8.5	12.2	12	35	8.5	7.4	18.5	14.5	16
pH	4.2	5.8	7.3	5.4	7.8	6.7	6.8	5.2	6.1	6.3
Hardness	18	12	5	16	17	18	18	30	19	19
Zn	0.2	0.06	0.1	0.59	0.11	0.04	0.03	0.12	0.11	0.09
O-18	-6.53	-6.41	-6.33	-5.3	-5.7	-6.06	-6.13	-6.26	-6.2	-6.27
Deuterium	-35.8	-34.7	-33.6	-29.0	-32.6	-34.5	-34.6	-32.7	-29.4	-35.6

VOLUME DATA FOR CUMULATIVE RAINFALL COLLECTORS

Collector	A	B	C	D	E	F	G	H	I	J
Vol (l)	5	4.46	4.48	1.87	6.76	5.92	6.21	4.84	6.58	6.12
Vol (mm)	612	546	548	229	827	724	760	592	805	749

ANALYTICAL DATA FOR OBSERVATION POINT : AWR1

Date (YYMMDD)	931022	940609	940623	940628	940824	940915	941011	941117	950309	950405	950620	950818	950922	951017	951219	960115	960510
K mg/L	0.60	1.30	0.20	0.10	0.10	1.30	0.10	0.80	0.70	1.90	0.10	0.70	0.10	0.10	0.20	0.30	0.20
Na mg/L	1.10	1.10	2.20	4.10	0.70	3.50	2.00	1.90	3.10	1.10	2.70	8.10	2.50	3.30	1.00	0.80	0.40
Ca mg/L	5.70	19.30	1.40	1.60	1.30	30.50	0.60	8.10	101.00	14.20	0.90	3.70	1.50	0.50	2.40	1.90	3.60
Mg mg/L	0.30	0.70	0.40	0.60	0.10	1.50	0.20	0.60	2.60	0.80	0.30	1.50	0.40	0.40	0.20	0.20	0.10
NH4-N mg/L	0.13	1.87	1.07	<0.10	<0.10	0.70	<0.10	<0.10	0.73	4.15	<0.10	<0.10	0.50	<0.10	<0.10	0.11	<0.10
SO4 mg/L	3.40	3.70	1.10	1.50	0.60	6.70	0.70	1.90	7.00	8.00	1.00	5.00	1.20	1.00	1.00	0.00	<1.00
Cl mg/L	5.40	31.60	6.20	10.00	2.90	59.00	3.60	17.90	175.00	29.00	6.00	14.60	7.30	7.00	5.00	6.00	8.20
Alk (CaCO3) mg/	5.30	11.30	4.00	0.50	1.00	0.80	0.50	-	10.00	4.70	0.50	9.00	-	-	-	-	
NOx-N mg/L	0.52	0.33	<0.10	<0.10	<0.10	2.15	0.20	0.40	<0.10	1.73	<0.10	<0.10	0.57	<0.10	<0.10	<0.10	<0.10
P mg/L	<0.05	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	0.16	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
Si mg/L	0.20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	<0.10
D O C mg/L	8.10	3.80	0.50	0.30	0.30	13.90	<1.00	3.80	13.50	8.40	<1.00	<1.00	0.60	-	1.80	2.00	1.70
E.C. mS/m (Lab)	5.00	16.00	3.90	4.80	2.00	26.00	1.80	8.60	66.00	15.50	2.90	1.60	4.90	3.10	3.00	4.00	4.60
pH (Lab)	6.40	6.10	6.30	5.30	5.00	5.10	5.60	4.80	6.40	6.60	5.10	5.20	4.50	4.80	4.80	4.40	4.60
TDS (Calc) mg/L	32.00	-	25.00	31.00	13.00	166.00	12.00	55.00	422.00	99.00	19.00	10.00	31.00	20.00	20.00	28.00	29.00
Hardness as CaC	15.00	51.00	5.00	6.00	4.00	82.00	2.00	23.00	263.00	39.00	4.00	2.00	6.00	3.00	7.00	5.00	10.00
% Balance	3.18	1.74	1.30	4.28	7.72	4.94	3.28	2.94	3.42	4.33	4.17	5.19	2.92	2.87	3.75	5.16	
Cations meq/L	0.38	1.24	0.28	0.31	0.11	1.88	0.14	0.56	5.46	1.17	0.19	0.11	0.26	0.20	0.18	0.17	0.22
Anions meq/L	0.37	1.22	0.28	0.32	0.11	1.97	0.14	0.57	5.28	1.22	0.20	0.11	0.27	0.21	0.17	0.18	0.23

ANALYTICAL DATA FOR OBSERVATION POINT : AWR2

Date (YYMMDD)	940915	941011	941117	950125	950405	950622	950815	950922	951017	951219	960116	960510
K mg/L	2.70	0.10	0.20	0.70	0.20	0.10	0.15	0.10	0.10	0.10	0.10	0.10
Na mg/L	5.50	1.90	0.80	4.60	0.60	2.30	0.90	1.90	3.30	1.00	0.30	0.40
Ca mg/L	12.00	0.70	1.50	64.00	34.50	1.90	1.50	3.90	2.40	14.20	4.50	10.50
Mg mg/L	1.00	0.20	0.20	1.80	1.00	0.30	0.20	0.30	0.40	0.40	0.10	0.40
NH4-N mg/L	1.20	<0.10	<0.10	<0.10	0.49	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
SO4 mg/L	10.10	0.70	1.20	6.70	3.50	0.80	0.40	0.90	1.00	1.00	<1.00	1.40
Cl mg/L	11.50	3.60	2.40	111.00	60.50	6.80	4.40	10.30	11.00	28.00	10.00	19.90
Alk (CaCO3) mg/	17.50	1.00	1.50	11.30	4.30	1.30	0.40	1.50	0.50	1.00	0.30	0.80
NOx-N mg/L	2.35	<0.10	0.20	0.32	1.12	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
P mg/L	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10	<0.10
Si mg/L	-	-	-	-	-	-	-	-	-	-	-	<0.10
D O C mg/L	9.00	<1.00	2.50	8.70	5.00	<1.00	<1.00	0.90	-	2.80	1.50	1.60
E.C. mS/m (Lab)	13.20	1.80	1.70	42.50	24.50	3.10	2.00	4.70	4.20	12.00	4.00	8.40
pH (Lab)	6.90	6.10	5.70	6.60	6.20	5.80	5.80	5.60	5.50	5.90	5.60	5.60
TDS (Calc) mg/L	84.00	12.00	11.00	272.00	157.00	20.00	13.00	30.00	27.00	74.00	28.00	54.00
Hardness as CaC	34.00	3.00	5.00	167.00	90.00	6.00	5.00	11.00	8.00	37.00	12.00	28.00
% Balance	2.06	0.34	4.38	1.13	3.97	4.87	4.58	1.37	10.14	2.68	2.35	
Cations meq/L	1.07	0.14	0.13	3.56	1.87	0.22	0.13	0.33	0.30	0.81	0.28	0.61
Anions meq/L	1.05	0.14	0.14	3.52	1.94	0.23	0.14	0.34	0.30	0.83	0.29	0.61

Appendix B.

Surface Water Data

FLOW GAUGING AT AGTER WITZENBERG RIVERS ON 26/3/96

AGTER WITZENBERG RIVER EAST

Measured flow using a 20 litre bucket
Average 7.03 seconds per 20 litre
Flow rate **0. 00284 metres cubed per second**

AGTER WITZENBERG RIVER SOUTH

Measured by flow meter in a constructed channel 170mm wide by 105mm deep

SET PULSES	ACTUAL PULSES	SECONDS
5	8	3
50	52	36 / 42
100	101	52 / 59
200	200	198 / 257

A range of measurements were taken with a significant error in some of the ranges. I judged the flow to be about 5 litres per second. An average of the 50 and 100 pulse measurements gives a flow reading of **0. 0031 metres cubed per second**

AGTER WITZENBERG RIVER WATER NORTH

Measured by flow meter in a constructed channel spanning 1.140 metres

Spacing of measurements	1000mm	900	800	700	600	500	400	300	200	100
Depth to base	100mm	120	120	150	180	180	170	90	100	100
Average flow measurements across channel - time measured for 50 pulses set	0	0	0	49.2	8.6	9.7	11.8	20.5	41	41

Flow at 10cm = 0.00153 Meters cubed per second
20 cm = 0.00153
30 cm = 0.002628
40 cm = 0.008279
50 cm = 0.010548
60 cm = 0.011826
70 cm = 0.00201

Total flow = 0.038351 Meters cubed per second

Alan J. Hon

Appendix C.

Water Level Data

WATERLEVEL DATA

G39937		G39937A		G39938		G39938A	
DATE	LEVEL (mamsl)	DATE	LEVEL (mamsl)	DATE	LEVEL (mamsl)	DATE	LEVEL (mamsl)
22/10/93	882.700	22/10/93	882.710	22/10/93	883.350	22/10/93	882.900
15/02/94	880.770	15/02/94	880.790	23/08/94	880.090	15/02/94	868.460
23/08/94	882.760	23/08/94	883.000	01/10/94	884.200	23/08/94	880.230
01/10/94	882.270	01/10/94	882.160	16/08/95	876.395	27/01/95	857.550
17/11/94	881.420	17/11/94	881.510	22/09/95	879.170	09/03/95	853.830
27/01/95	879.320	27/01/95	879.340	18/10/95	880.460	04/04/95	852.550
09/03/95	878.240	09/03/95	878.375	01/10/94	884.200	04/07/95	873.150
04/04/95	878.925	04/04/95	878.900	22/09/95	879.170	16/08/95	874.725
04/07/95	881.380	04/07/95	881.510			22/09/95	878.630
16/08/95	882.270	16/08/95	882.340			18/10/95	879.970
22/09/95	882.240	22/09/95	882.290			18/01/96	869.460
18/10/95	882.480	18/10/95	882.530			10/05/96	872.730
15/01/96	882.880	15/01/96	882.570				
10/05/96	880.630	10/05/96	880.710				

WATERLEVEL DATA

G39936		**G39939**	
DATE	LEVEL (mamsl)	DATE	LEVEL (mamsl)
22/10/93	1059.09	22/10/93	883.070
17/02/94	1058.33	15/02/94	865.700
22/08/94	1059.57	23/08/94	880.050
01/10/94	1059.47	01/10/94	883.200
26/01/95	1058.38	27/01/95	858.200
09/03/95	1058.11	09/03/95	854.600
06/04/95	1057.67	04/04/95	853.350
22/06/95	1058.80	04/07/95	866.680
15/08/95	1059.60	16/08/95	870.970
22/09/95	1059.39	22/09/95	873.910
18/10/95	1059.52	18/10/95	874.590
16/01/96	1058.82	18/01/96	865.950
10/05/96	1058.10	10/05/96	866.310

Appendix D.

Groundwater Data

GROUNDWATER CHEMISTRY DATA

311/14

DATE	12/09/92	10/22/93	02/17/94	08/22/94	01/25/95	04/05/95	06/22/95	08/15/95	10/18/95	01/16/96
K (mg/L)	0.1	0.1	0.1	0.1	0.2	0.3	0.2	0.2	0.1	0.2
Na (mg/L)	5.0	4.9	5.4	5.0	5.1	5.2	5.0	5.3	5.1	4.0
Ca (mg/L)	0.2	0.0	0.4	0.2	0.3	0.2	0.2	0.4	0.3	0.3
Mg (mg/L)	0.7	0.6	0.6	0.7	0.6	0.6	0.6	0.6	0.6	0.6
NH4 (mg/L)	<0.05	<0.05	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
SO4 (mg/L)	0.8	0.5	<0.5	0.8	0.8	0.5	0.9	0.8	<1	<1
Cl (mg/L)	10.0	9.0	9.0	8.8	9.5	9.5	9.1	8.5	10.0	9.0
Alk (mg/L CaCO3)		0.5	2.5	1.5	0.8	1.0	0.5	2.5	0.3	
NOX-N (mg/L)	0.05	0.05	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
P (mg/L)	<0.05	<0.05	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Si (mg/L)	3.0	3.1	3.4	3.1	3.0	3.5	2.9	3.4	3.2	3.1
Cu (mg/L)	<0.02	<0.02	<0.03	0.04	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Fe (mg/L)	0.02	<0.03	<0.03	0.27	<0.05	<0.05	0.11	0.25	<0.05	<0.05
Mn (mg/L)	<0.02	<0.02	<0.03	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Zn (mg/L)	<0.01	<0.02	<0.03	0.27	<0.03	<0.03	<0.05	<0.05	<0.05	<0.03
Sr (mg/L)			<0.05	0.00	<0.1	<0.1	<0.05	<0.05	<0.05	<0.05
Li (mg/L)		<0.005	<0.005		<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Rb (mg/L)				<0.03	<0.03	<0.03	<0.05	<0.05	<0.01	<0.01
Ba (mg/L)				<0.1	<0.25	<0.25	<0.5	<0.5	<0.25	<0.1
DOC (mg/L)	<0.5	<0.5	0.60	<0.5	<1	<1	<1	<1		<1
EC - lab (mS/m)	4.5	4.2	4.4	4.5	4.3	4.4	4.3	4.2	4.3	4.0
pH - field	5.7	4.8	3.9	4.9	4.0	4.0	4.5	4.9	4.7	
Cations (meq/L)	0.29	0.27		0.11	0.29	0.29	0.29	0.30	0.29	0.24
Anions (meq/L)	0.30	0.28		0.11	0.30	0.30	0.29	0.31	0.28	0.25
% balance	3.79	4.40		7.72	2.01	2.53	1.48	0.47	2.74	4.75
Carbon-13 (%o PDB)		-22.86	-22.53	-22.38	-23.70	-23.12	-21.80	-21.80	-22.20	-22.20
TIC (mmol/L)		0.676	0.681	0.694	0.686	0.697	0.640	0.650	0.730	0.680
Carbon-14 (pmc)		103.0	103.8	101.5	101.9	104.7	-999.0	102.8	104.1	104.2
Oxygen-18 (%o SMOW)		-6.05	-6.20	-6.16	-6.20	-6.20	-6.30	-6.00	-6.10	-6.20
87-Sr/86-Sr		0.714436	0.712164	0.712635	0.710159	0.714837				

GROUNDWATER CHEMISTRY DATA

G39936

DATE	10/23/93	02/15/94	08/23/94	01/26/95	04/05/95	06/22/95	08/16/95	10/19/95	01/22/96
K (mg/L)	0.1	0.1	0.1	0.1	0.3	0.1	0.1	0.2	0.2
Na (mg/L)	5.3	5.2	5.5	5.6	5.8	6.0	6.0	5.9	4.8
Ca (mg/L)	1.5	1.3	1.5	1.4	0.9	0.8	0.9	0.8	0.6
Mg (mg/L)	0.7	0.6	0.7	0.7	0.6	0.7	0.8	0.6	0.7
NH4 (mg/L)	<0.05	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
SO4 (mg/L)	0.8	0.8	1.2	1.6	1.0	1.1	1.1	1.0	
Cl (mg/L)	10.0	9.3	10.3	10.7	10.6	10.5	10.8	11.0	11.0
Alk (mg/L CaCO3)	3.5	3.0	2.5	2.3	2.3	0.8	1.3	1.0	
NOX-N (mg/L)	<0.05	<0.1	0.15	<0.1	<0.1	<0.1	0.30	<0.1	<0.1
P (mg/L)	<0.05	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Si (mg/L)	2.0	2.4	2.2	2.2	2.5	2.4	2.6	2.4	2.3
Cu (mg/L)	<0.02	<0.03	0.04	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Fe (mg/L)	<0.03	0.03	0.37	0.08	<0.05	<0.05	<0.05	<0.05	<0.05
Mn (mg/L)	<0.02	<0.03	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Zn (mg/L)	<0.02	<0.03	0.05	<0.03	<0.03	<0.05	<0.05	0.04	<0.03
Sr (mg/L)	<0.05	<0.05	<0.05	<0.1	<0.1	<0.05	<0.05	<0.05	<0.05
Li (mg/L)	<0.005	<0.005		<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Rb (mg/L)				<0.03	<0.03	<0.05	<0.05	<0.01	<0.01
Ba (mg/L)				<0.25	<0.25	<0.5	<0.5	<0.25	<0.1
DOC (mg/L)	0.5	1.6	<0.5	<1	<1	<1	<1		<1
EC - lab (mS/m)	5.0	5.0	5.2	5.1	4.8	4.7	5.4	5.0	5.0
pH - field	4.9	4.9	5.1	5.1	4.9	4.7	5.0	4.9	
Cations (meq/L)	0.36		0.37	0.37	0.36	0.34	0.37	0.35	0.30
Anions (meq/L)	0.37		0.92	0.38	0.37	0.34	0.37	0.37	0.30
% balance	1.26	2.93	1.25	1.24	2.68	1.45	0.18	4.42	0.31
Carbon-13 (%o PDB)	-23.21	-23.15	-22.69	-22.34	-24.17	-22.37	-22.30	-22.90	-22.80
TIC (mmol/L)	0.854	0.862	0.785	0.773	0.711	0.657	0.630	0.730	0.690
Carbon-14 (pmc)	111.5	113.1	108.9	111.1	114.0	112.5		115.4	114.7
Oxygen-18 (%o SMOW)	-6.08	-6.01	-5.96	-6.09	-6.08	-6.18	-5.90	-6.00	-6.10
87-Sr/86-Sr	0.713724	0.712764	0.711885	0.710702	0.715691				

GROUNDWATER CHEMISTRY DATA

G39937

DATE	10/21/93	02/15/94	08/23/94	01/25/95	04/05/95	06/20/95	08/14/95	10/17/95	01/16/96
K (mg/L)	1.3	1.7	0.8	1.0	1.7	1.1	0.8	0.8	0.5
Na (mg/L)	12.8	12.1	15.5	15.8	10.4	16.0	18.5	19.0	18.0
Ca (mg/L)	0.6	1.3	0.8	1.3	2.2	1.6	1.9	2.3	0.9
Mg (mg/L)	3.4	5.0	0.7	3.0	3.6	3.1	3.1	3.3	3.0
NH4 (mg/L)	<0.05	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
SO4 (mg/L)	0.6	<0.5	1.4	1.2	1.0	2.3	3.8	4.0	1.9
Cl (mg/L)	17.0	16.9	23.2	25.9	15.4	27.4	31.9	35.0	32.0
Alk (mg/L CaCO3)	1.1	1.5	2.3	2.3	2.8	1.3	2.5	1.3	3.0
NOX-N (mg/L)	5.80	7.20	2.65	3.35	5.40	3.01	1.90	1.70	1.63
P (mg/L)	<0.05	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Si (mg/L)	4.1	4.4	4.1	4.0	4.2	4.2	4.2	4.1	3.7
Cu (mg/L)	-0.02	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Fe (mg/L)	0.04	0.04	0.23	<0.05	<0.05	<0.05	<0.05	0.05	<0.05
Mn (mg/L)	<0.02	<0.03	<0.05	<0.05	<0.05	<0.5	<0.05	<0.05	<0.05
Zn (mg/L)	<0.02	<0.03	<0.03	0.03	<0.03	<0.05	<0.05	<0.03	<0.03
Sr (mg/L)	0.30	0.05	0.30	<0.1	<0.1	<0.05	<0.05	<0.05	<0.05
Li (mg/L)	<0.005	<0.005		0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Rb (mg/L)				<0.03	<0.03	<0.05	<0.05	<0.01	<0.01
Ba (mg/L)				<0.25	<0.25	<0.5	<0.5	<0.25	<0.1
DOC (mg/L)	<0.5	1.2	<0.5	<1	<1	<1	<1		<1
EC - lab (mS/m)	11.7	13.4	12.4	13.0	11.4	13.2	15.0	16.0	14.0
pH - field	5.0	5.1	5.1	5.2	5.0	5.1	5.0	4.9	
Cations (meq/L)	0.90		0.94	1.02	0.90	1.05	1.18	1.23	1.09
Anions (meq/L)	0.93		0.92	1.04	0.89	1.06	1.16	1.23	1.12
% balance	3.24	2.45	2.41	1.54	0.98	0.78	0.90	0.19	2.40
Carbon-13 (%o PDB)	-21.00	-21.35	-20.50	-19.57	-20.60	-19.94	-19.80	-19.80	-21.10
TIC (mmol/L)	0.560	0.328	0.601	0.516	0.414	0.408	0.490	0.610	0.510
Carbon-14 (pmc)			102.7		101.8	103.1	105.1	105.3	106.4
Oxygen-18 (%o SMOW)	-5.26	-5.21	-5.06	-5.14	-5.10	-5.14	-4.90	-4.90	-4.90
87-Sr/86-Sr	0.714235	0.724047	0.718310	0.722001	0.726384			0.713344	

GROUNDWATER CHEMISTRY DATA

G39937A

DATE	10/21/93	02/15/94	08/23/94	01/25/95	04/05/95	06/20/95	08/14/95	10/17/95	01/15/96
K (mg/L)	0.8	0.9	1.3	0.8	0.9	0.8	0.8	0.8	1.6
Na (mg/L)	15.0	15.0	16.3	19.5	16.3	18.0	21.9	21.0	22.6
Ca (mg/L)	1.1	1.8	1.9	2.2	1.6	5.4	5.2	3.6	1.9
Mg (mg/L)	3.4	3.1	3.2	3.4	3.6	3.4	4.0	4.0	3.8
NH4 (mg/L)	<0.05	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
SO4 (mg/L)	1.4	<0.5	1.9	1.9	1.1	5.9	9.0	4.0	2.4
Cl (mg/L)	20.0	18.0	23.2	31.8	25.2	32.7	38.4	38.0	41.0
Alk (mg/L CaCO3)	2.9	3.7	2.8	4.3	3.5	5.3	4.7	4.5	4.0
NOX-N (mg/L)	4.50	6.80	4.32	3.69	4.20	2.49	3.20	2.70	2.13
P (mg/L)	<0.05	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Si (mg/L)	3.8	4.0	3.9	3.7	3.9	3.1	3.9	3.8	3.7
Cu (mg/L)	<0.02	<0.03	<0.03	<0.03	<0.03	<0.03	0.03	<0.03	<0.03
Fe (mg/L)	<0.03	0.04	0.15	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Mn (mg/L)	<0.02	<0.03	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Zn (mg/L)	<0.02	<0.03	<0.03	0.04	<0.03	<0.05	<0.05	0.03	<0.03
Sr (mg/L)	<0.02	0.05	0.02	<0.1	<0.1	<0.05	0.06	<0.05	<0.05
Li (mg/L)	<0.005	<0.005		<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Rb (mg/L)				<0.03	<0.03	<0.05	<0.05	<0.01	<0.01
Ba (mg/L)				<0.25	<0.25	<0.5	<0.5	<0.25	<0.1
DOC (mg/L)	<0.5	1.6	<0.5	<1	<1	<1	<1		<1
EC - lab (mS/m)	12.0	12.4	13.9	15.5	13.6	17.0	19.5	18.0	18.0
pH - field	5.3	5.3	5.4	5.4	5.2	4.9	5.6	5.4	
Cations (meq/L)	0.97		1.10	1.26	1.10	1.37	1.56	1.46	1.43
Anions (meq/L)	0.97		1.06	1.28	1.10	1.33	1.59	1.44	1.43
% balance	0.72	4.71	3.74	2.03	0.13	2.98	2.01	1.15	0.20
Carbon-13 (%o PDB)	-21.37	-21.25	-20.55	-20.12	-20.66	-19.10	-20.10	-20.40	-21.10
TIC (mmol/L)	0.540	0.397	0.464	0.447	0.466	0.427	0.430	0.490	0.440
Carbon-14 (pmc)		104.5			104.3	99.4			102.2
Oxygen-18 (%o SMOW)	-5.29	-5.25	-4.94	-5.18	-5.10	-5.30	-5.10	-5.10	-5.10
87-Sr/86-Sr	0.718900	0.718124	0.717491	0.716576	0.717943	0.713638	0.711417		

GROUNDWATER CHEMISTRY DATA

G39938

DATE	10/22/93	12/19/95
K (mg/L)	0.4	0.7
Na (mg/L)	28.9	23.0
Ca (mg/L)	13.5	18.5
Mg (mg/L)	7.3	7.6
NH4 (mg/L)	<0.05	<0.1
SO4 (mg/L)	10	15
Cl (mg/L)	52.9	38.0
Alk (mg/L CaCO3)	45	60
NOX-N (mg/L)	<0.05	<0.1
P (mg/L)	<0.05	<0.1
Si (mg/L)	14.9	
Cu (mg/L)	<0.02	<0.03
Fe (mg/L)	0.38	<0.05
Mn (mg/L)	0.20	0.17
Zn (mg/L)	<0.02	<0.03
Sr (mg/L)	0.12	0.13
Li (mg/L)	0.031	0.030
Rb (mg/L)		0.080
Ba (mg/L)		
DOC (mg/L)	1.1	0.5
EC - lab (mS/m)	29.0	28.0
pH - field	5.6	
Cations (meq/L)	2.54	
Anions (meq/L)	2.60	
% balance	2.14	
Carbon-13 (%o PDB)	-19.77	-18.70
TIC (mmol/L)	1.61	1.76
Carbon-14 (pmc)	68.8	67.4
Oxygen-18 (%o SMOW)	-5.58	-5.50
87-Sr/86-Sr	0.714277	

GROUNDWATER CHEMISTRY DATA

G39938A

DATE	10/23/93	02/17/94	08/24/94	03/09/95	04/05/95	07/04/95	08/16/95	10/19/95	01/18/96
K (mg/L)	0.8	0.7	0.6	0.6	0.7	0.8	0.8	0.6	0.5
Na (mg/L)	36.5	25.1	28.0	26.0	25.8	26.0	29.3	27.0	25.3
Ca (mg/L)	19.0	14.5	20.8	16.7	16.1	21.3	25.6	21.1	17.4
Mg (mg/L)	8.9	5.8	8.7	5.0	4.8	7.9	11.1	9.2	6.3
NH4 (mg/L)	<0.05	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
SO4 (mg/L)	7.7	0.6	12.6	9.3	9.7	12	25	15	10
Cl (mg/L)	76.5	44.8	39.0	43.0	43.2	40.2	44.0	44.0	43.0
Alk (mg/L CaCO3)	46	47	75	47	48	70	86	73	53
NOX-N (mg/L)	<0.05	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
P (mg/L)	<0.05	0.12	<0.1	0.10	0.13	<0.1	<0.1	<0.1	<0.1
Si (mg/L)	14.9	18.4	13.4	17.0	16.6	14.4	13.3	14.5	15.5
Cu (mg/L)	<0.02	<0.03	<0.03	0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Fe (mg/L)	0.19	0.38	0.20	0.16	0.11	<0.05	0.14	0.05	0.06
Mn (mg/L)	0.31	0.23	0.24	0.28	0.28	0.25	0.20	0.19	0.18
Zn (mg/L)	0.06	<0.03	<0.03	<0.03	<0.03	<0.05	0.05	0.03	<0.03
Sr (mg/L)	0.20	0.19	0.19	0.12	0.13	0.16	0.22	0.19	0.15
Li (mg/L)	0.030	0.032		0.027	0.020	0.030	0.039	0.003	0.029
Rb (mg/L)				<0.01	<0.03	<0.05	<0.05	<0.01	<0.01
Ba (mg/L)				<0.25	<0.25	<0.5	<0.5	<0.25	<0.1
DOC (mg/L)	1.0	1.9	0.8	<0.5	<1	<1	<1		<1
EC - lab (mS/m)	37.5	26.0	32.5	26.0	25.5	21.0	37.0	32.0	28.0
pH - field	5.8	6.2	6.9	6.5	6.4	6.7	7.1	6.9	
Cations (meq/L)	2.54		2.99	2.37	2.33	2.85	3.49	2.98	2.50
Anions (meq/L)	2.60		2.85	2.35	2.39	2.77	3.48	3.02	2.48
% balance	1.54	3.74	4.70	1.16	2.50	2.65	0.28	1.26	0.68
Carbon-13 (‰ PDB)	-20.81	-19.64	-18.55	-18.52	-18.56	-18.96	-18.70	-18.90	-18.70
TIC (mmol/L)	1.503	1.397	1.719	1.364	1.360	1.668	1.770	1.690	1.390
Carbon-14 (pmc)	-999.0	72.8	53.7	55.5		61.1	62.0	56.9	60.5
Oxygen-18 (‰ SMOW)	-5.40	-5.47	-5.42	-5.64	-5.52	-5.57	-5.40	-5.40	-5.40
87-Sr/86-Sr	0.714279	0.719805	0.718945	0.717665	0.717676				

GROUNDWATER CHEMISTRY DATA

G39939

DATE	10/22/93	02/16/94	08/24/94	01/26/95	04/05/95	05/20/95	08/16/95	10/18/95	01/18/96
K (mg/L)	1.7	2.1	1.4	2.5	1.2	1.2	1.2	1.3	1.4
Na (mg/L)	26.4	28.9	23.2	25.9	25.4	26.0	25.6	24.0	23.3
Ca (mg/L)	16.5	20.8	11.2	12.2	10.1	9.6	9.4	11.2	11.6
Mg (mg/L)	2.6	3.3	1.8	1.4	1.5	1.4	1.4	1.6	1.6
NH4 (mg/L)	<0.05	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
SO4 (mg/L)	8.8	10.9	3.9	4.3	3.6	4.6	5.7	6.0	4.9
Cl (mg/L)	40.1	54.0	9.3	11.5	11.0	10.1	17.4	14.0	11.0
Alk (mg/L CaCO3)	50	45	67	75	71	69	59	65	67
NOX-N (mg/L)	<0.05	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
P (mg/L)	<0.05	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Si (mg/L)	13.2	16.1	12.3	10.3	10.0	8.6	10.2	11.3	11.5
Cu (mg/L)	<0.02	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Fe (mg/L)	0.45	0.61	0.33	0.20	0.11	0.13	0.30	0.18	0.20
Mn (mg/L)	0.15	0.19	0.13	<0.05	<0.05	0.07	0.07	0.08	0.08
Zn (mg/L)	<0.02	<0.03	<0.03	<0.03	<0.03	<0.05	<0.05	0.04	<0.03
Sr (mg/L)	0.42	0.51	0.26	0.54	0.38	0.25	0.26	0.31	
Li (mg/L)	0.025	0.029		0.005	0.050	0.050	<0.050	<0.004	0.038
Rb (mg/L)				<0.03	<0.03	<0.05	<0.05	<0.01	<0.01
Ba (mg/L)				<0.25	<0.25	<0.5	<0.5	<0.25	<0.1
DOC (mg/L)	0.8	<0.5	<0.5	<1	<1	<1	1.0		<1
EC - lab (mS/m)	25.2	29.0	19.0	19.0	18.0	17.5	18.5	18.0	18.0
pH - field	5.8	7.8	7.6	8.6	8.1	7.6	7.9	7.9	
Cations (meq/L)	2.23		1.76	1.92	1.77	1.77	1.73	1.76	1.76
Anions (meq/L)	2.31		1.67	1.90	1.80	1.77	1.79	1.80	1.75
% balance	3.38	1.19	4.90	0.67	2.20	0.27	3.53	2.46	0.60
Carbon-13 (%o PDB)	-19.55	-20.29	-18.18	-18.34	-18.32	-17.90	-18.00	-18.10	-18.10
TIC (mmol/L)	0.906	0.860	1.261	1.277	1.341	1.320	1.310	1.240	1.290
Carbon-14 (pmc)		53.2	31.0	29.9	30.0	32.4	43.3	39.1	35.1
Oxygen-18 (%o SMOW)	-5.45	-5.50	-5.74	-5.90	-5.90	-5.90	-5.70	-5.70	-5.60
87-Sr/86-Sr	0.724549	0.722370	0.724878	0.715674	0.719766			0.725238	

GROUNDWATER CHEMISTRY DATA

	311/10	**311/11**	**311/15**
DATE	12/09/92	12/09/92	12/09/92
K (mg/L)	1.9	0.8	2.5
Na (mg/L)	21.4	35.3	18.8
Ca (mg/L)	7.6	15.6	6.1
Mg (mg/L)	6.5	7.3	3.5
NH4 (mg/L)	<0.05	0.10	<0.05
SO4 (mg/L)	15	22	15
Cl (mg/L)	35.0	52.1	31.0
Alk (mg/L CaCO3)	27	53	18
NOX-N (mg/L)	1.27	<0.05	<0.05
P (mg/L)	<0.05	<0.05	<0.05
Si (mg/L)	10.0	14.9	20.2
Cu (mg/L)	0.02	<0.02	<0.02
Fe (mg/L)	0.03	1.13	2.46
Mn (mg/L)	0.03	0.10	0.15
Zn (mg/L)	0.04	0.01	<0.01
DOC (mg/L)	<0.5	<0.5	<0.5
EC - lab (mS/m)	22.0	32.0	20.0
pH - field	5.7	6.1	5.4
Cations (meq/L)	1.89	2.94	1.48
Anions (meq/L)	1.93	2.99	1.54
% balance	2.22	1.72	3.85

CSIR DIVISION OF WATER TECHNOLOGY 10 OCTOBER 1995
ANALYTICAL SERVICES (STELLENBOSCH LABORATORY)
PRECISION AND RECOVERY DATA

	n	Avg mg/L	Addn mg/L	Std dev	CV %	Rec %	n	Avg mg/L	Adcn mg/L	Std dev	CV %	Rec %
Potassium as K mg/L	10	1.7	1.5	0.02	0.9	95	10	5.4	4.5	0.03	0.6	101
Sodium as Na mg/L	10	23.6	5	0.22	0.9	105	10	69.6	15	0.32	0.5	96
Calcium as Ca mg/L	10	12.5	5	0.21	1.7	102	10	37.2	15	0.75	2.0	100
Magnesium as Mg mg/L	10	3.6	1.5	0.04	1.1	108	10	10.7	4.5	0.12	1.1	104
Ammonia as N mg/L	10	1.0	0.25	0.01	1.3	100	10	4.6	1.5	0.09	1.9	105
Sulphate as SO4 mg/L	10	17.1	5	0.74	4.3	114	10	228	200	3.68	1.6	103
Chloride as Cl mg/L	10	53.6	10	1.51	2.8	115	10	488	400	7.32	1.5	101
Alkalinity as CaCO3 mg/L	10	25.1	5	0.44	1.8	101	10	250	50	0.82	0.3	97
Nitrate as N mg/L	10	1.0	0.25	0.04	3.6	90	10	4.6	1.5	0.05	1.1	109
Phosphate as P mg/L	10	1.0	0.25	0.01	1.0	109	10	4.5	1.5	0.02	0.0	96
Conductivity mS/m	10	-	-	-	-	-	10	88.3	-	0.75	0.9	-
Dissolved Organic Carbon as C mg/L	10	-	-	-	-	-	10	10.2	2.5	0.24	2.4	97
Fluoride as F mg/L	10	0.50	0.25	0.03	5.2	98	10	2.0	0.5	0.07	3.4	100
Aluminium as Al mg/L	10	0.35	0.25	0.02	4.8	102	10	1.25	0.25	0.02	1.8	90
Copper as Cu mg/L	10	0.35	0.25	0.01	3.0	100	10	1.25	0.25	0.01	0.7	98
Iron as Fe mg/L	10	0.35	0.25	0.01	2.5	101	10	1.25	0.25	0.01	1.1	95
Manganese as mn mg/L	10	0.35	0.25	0.01	2.7	104	10	1.25	0.25	0.01	1.0	95
Zinc as Zn mg/L	10	0.35	0.25	0.01	4.0	98	10	1.25	0.25	0.01	1.1	93
Chemical Oxygen Demand mg/L	10	75	25	1.8	2.4	100	10	525	25	6.5	1.2	102

ICP-MS Microchemistry Data (concentrations in ppb)

Borehole G39936

Date	15/02/94	23/08/94	Date	15/02/94	23/08/94
Li		3.143	I	1.515	0.351
Be	359.014	5.921	Te	56.869	0.998
B	56.911		Cs	0.069	1.345
Al		55.197	Ba	26.271	1.295
Sc	0.259	1.097	La	0.028	
Ti	2.304	4.070	Ce		0.083
V	114.324	1.388	Pr		1.348
Cr		0.593	Nd	226.529	0.087
Mn	26.002	13.029	Sm		0.007
Fe	268.849	24.541	Eu	78.076	2.657
Co	1.827	0.774	Gd	0.108	
Ni	0.472	0.418	Tb	0.149	0.301
Cu	2.607	2.875	Dy		1.222
Zn	7.273	22.297	Ho		
Ga			Er		0.902
Ge		0.063	Tm		
As	61.381	0.000	Yb		
Se	4.133	20.079	Lu	47.527	
Br	0.336	35.492	Hf	0.316	
Rb	1.299		Ta		
Sr	45.946	7.870	W	1.090	1.220
Y			Re	0.083	
Zr	4.885	0.798	Os		3.551
Nb			Ir	43.425	
Mo	227.774		Pt	0.144	0.006
Ru	112.581		Au	0.037	
Rh			Hg	1.334	6.113
Pd	1.004	1.145	Tl	0.107	
Ag		0.621	Pb	0.145	0.847
Cd	2.155		Bi		
In			Th		2.538
Sn	160.134	0.525	U	0.029	
Sb		0.063			

ICP-MS Microchemistry Data (concentrations in ppb)

Borehole 311/14

Date	17/02/94	22/08/94	Date	17/02/94	22/08/94
Li		7.552	I	0.500	0.280
Be			Te	1.282	1.664
B		13.361	Cs	0.169	0.046
Al	102.106	36.794	Ba	3.555	1.750
Sc	3.515	1.435	La	0.197	0.861
Ti			Ce	0.085	0.033
V	117.066	1.110	Pr	54.621	0.288
Cr		0.473	Nd	214.756	0.108
Mn	26.748	8.482	Sm		0.012
Fe		20.932	Eu	0.279	0.000
Co		0.515	Gd		0.016
Ni	3.115	0.595	Tb	59.973	0.959
Cu		4.786	Dy	243.673	0.036
Zn	46.171	229.261	Ho	0.301	
Ga			Er		0.025
Ge		0.106	Tm	0.613	0.543
As	0.087	0.265	Yb		
Se		9.082	Lu		1.006
Br	5.190	40.132	Hf	165.970	
Rb	74.990		Ta		1.343
Sr	4.436	3.741	W	88.585	0.036
Y	0.058		Re	37.914	
Zr	4.247	0.855	Os		0.011
Nb	0.170		Ir	0.230	1.665
Mo	142.644		Pt	0.462	8.399
Ru	51.003		Au	0.368	1.753
Rh	33.430		Hg	0.668	
Pd		1.090	Tl	0.081	0.201
Ag		0.039	Pb	109.992	1.303
Cd	0.787		Bi	28.996	
In			Th	0.050	
Sn		0.420	U		0.005
Sb		0.495			

ICP-MS Microchemistry Data (concentrations in ppb)

Borehole G39937

Date	15/02/94	23/08/94
Li		3.402
Be	5.262	
B		
Al		12.326
Sc	67.463	1.620
Ti	18.537	1.581
V	108.293	3.106
Cr		0.508
Mn	24.598	9.306
Fe	508.712	9.079
Co	2.429	0.649
Ni	10.209	0.849
Cu		2.000
Zn	11.235	11.064
Ga	7.778	
Ge		
As		
Se		0.681
Br	9.460	550.564
Rb	8.921	1.310
Sr	62.340	27.661
Y		
Zr		0.531
Nb		
Mo		
Ru		
Rh		
Pd	0.103	0.058
Ag	81.519	3.698
Cd	2.846	
In		
Sn	2.158	5.091
Sb		0.005
I	0.886	2.926
Te		0.756
Cs	0.338	2.128
Ba	73.919	25.445
La	42.560	
Ce	0.123	0.961
Pr		0.011
Nd		
Sm	81.796	3.885
Eu	43.332	
Gd	0.765	
Tb	0.190	0.314
Dy	93.389	
Ho	0.054	
Er		0.031
Tm	0.196	
Yb	0.225	0.023
Lu		0.328
Hf	292.741	
Ta		0.326
W		0.049
Re		
Os		
Ir	*0.310*	*1.822*
Pt	0.184	0.015
Au	0.124	1.522
Hg		0.015
Tl	46.517	
Pb		
Bi		
Th		
U	91.595	0.099

ICP-MS Microchemistry Data (concentrations in ppb)

Borehole G39937A

Date	15/02/94	23/08/94	Date	15/02/94	23/08/94
Li		3.473	I	2.162	1.397
Be			Te	0.920	0.863
B			Cs	19.345	0.927
Al		12.959	Ba	25.323	22.015
Sc	50.237	1.510	La	0.308	
Ti		0.998	Ce		0.002
V	105.515	2.708	Pr	121.362	0.017
Cr		0.119	Nd		
Mn	25.221	5.181	Sm		1.012
Fe	32.701		Eu	0.091	
Co		0.723	Gd	1.700	0.015
Ni			Tb	132.914	0.937
Cu		1.336	Dy	815.790	2.458
Zn	2.543	9.369	Ho		
Ga			Er		1.829
Ge			Tm	0.118	
As	0.186	1.345	Yb		0.017
Se		0.574	Lu		
Br	10.735	436.169	Hf		
Rb	5.680	1.304	Ta	307.638	
Sr	25.348	26.144	W	1.395	0.035
Y	18.837		Re		
Zr		0.760	Os		0.022
Nb			Ir		
Mo	0.232		Pt		0.884
Ru			Au	0.046	
Rh		0.606	Hg	0.058	
Pd		1.064	Tl		
Ag		0.577	Pb		0.086
Cd	144.388		Bi		
In			Th		0.342
Sn		4.513	U	0.315	0.099
Sb		0.035			

ICP-MS Microchemistry Data (concentrations in ppb)

Borehole G39938A

Date	15/02/94	23/08/94	Date	15/02/94	23/08/94
Li		3.473	I	2.162	1.397
Be			Te	0.920	0.863
B			Cs	19.345	0.927
Al		12.959	Ba	25.323	22.015
Sc	50.237	1.510	La	0.308	
Ti		0.998	Ce		0.002
V	105.515	2.708	Pr	121.362	0.017
Cr		0.119	Nd		
Mn	25.221	5.181	Sm		1.012
Fe	32.701		Eu	0.091	
Co		0.723	Gd	1.700	0.015
Ni			Tb	132.914	0.937
Cu		1.336	Dy	815.790	2.458
Zn	2.543	9.369	Ho		
Ga			Er		1.829
Ge			Tm	0.118	
As	0.186	1.345	Yb		0.017
Se		0.574	Lu		
Br	10.735	436.169	Hf		
Rb	5.680	1.304	Ta	307.638	
Sr	25.348	26.144	W	1.395	0.035
Y	18.837		Re		
Zr		0.760	Os		0.022
Nb			Ir		
Mo	0.232		Pt		0.884
Ru			Au	0.046	
Rh		0.606	Hg	0.058	
Pd		1.064	Tl		
Ag		0.577	Pb		0.086
Cd	144.388		Bi		
In			Th		0.342
Sn		4.513	U	0.315	
Sb		0.035			

ICP-MS Microchemistry Data (concentrations in ppb)

Borehole G39939

Date	16/02/94	24/08/94	Date	16/02/94	24/08/94
Li		336.874	I		0.327
Be			Te		0.628
B		2.572	Cs	0.873	0.722
Al		22.754	Ba	42.986	21.269
Sc	28.509	5.452	La	0.267	
Ti	25.340	12.138	Ce		1.062
V	114.192	1.403	Pr		0.286
Cr		0.707	Nd	108.396	
Mn	843.318	167.614	Sm		
Fe		403.327	Eu	0.520	
Co		0.041	Gd	0.077	6.507
Ni	157.857		Tb	0.019	
Cu		0.278	Dy	80.862	5.187
Zn		1.375	Ho	0.078	
Ga	174.219		Er		
Ge		0.267	Tm	0.394	
As	0.760		Yb		
Se	247.106	0.541	Lu		0.999
Br	10.328	74.084	Hf		
Rb	7.245	1.249	Ta	23.346	
Sr	856.190	458.241	W		0.009
Y	17.297	3.036	Re		
Zr		0.716	Os		0.017
Nb	0.033		Ir	42.061	0.010
Mo	1.791		Pt	0.476	
Ru			Au	53.618	
Rh			Hg	0.497	
Pd	0.639	0.008	Tl		
Ag		0.033	Pb	0.346	1.269
Cd	2.502		Bi		
In			Th		0.348
Sn	2.084	1.373	U	0.084	
Sb		1.071			

ICP-MS Microchemistry Data (concentrations in ppb)

Borehole 313/1

Date	16/02/94	Date	16/02/94
Li		I	2.366
Be	3.858	Te	0.622
B		Cs	0.198
Al		Ba	22.230
Sc	88.907	La	86.121
Ti	31.905	Ce	
V	91.863	Pr	
Cr		Nd	
Mn	25.245	Sm	
Fe	449.636	Eu	0.515
Co	53.334	Gd	94.106
Ni	20.605	Tb	0.057
Cu		Dy	
Zn	19.927	Ho	49.045
Ga	161.220	Er	
Ge		Tm	
As	0.954	Yb	
Se		Lu	
Br		Hf	
Rb	4.385	Ta	0.182
Sr	47.761	W	1.512
Y		Re	90.711
Zr		Os	
Nb	0.234	Ir	0.206
Mo	0.880	Pt	
Ru		Au	93.359
Rh		Hg	0.427
Pd	0.185	Tl	94.288
Ag		Pb	0.618
Cd		Bi	
In		Th	
Sn	2.467	U	0.134
Sb			

Appendix E.

Borehole Logs and Construction Details

Construction material specifications for G39936, G39937, G39937A, G39938, G39938A and G39939:

Construction Materials		
Screens		
	Inner diameter	166 mm
	Outer diameter	186 mm
	Slot width	2 mm (5 rows of slots with 10 mm gap between horizontal slots)
Casing		
	Inner diameter	166 mm
	Outer diameter	186 mm
Gravel pack		
	Thickness	10 mm

The boreholes were developed by air purging each hole for approximately 6 hours using compressed air. During this time a V-notch weir was used to measure the blow yield:

Borehole	**V-notch (mm)**	**Flow rate (L/s)**
G39936	30	0.2
G39937A	80	2.6
G39937	105	5.0
G39938	10	0.02
G39938A	>203	>39
G39939	118	6.7

The following figures show the borehole construction design.

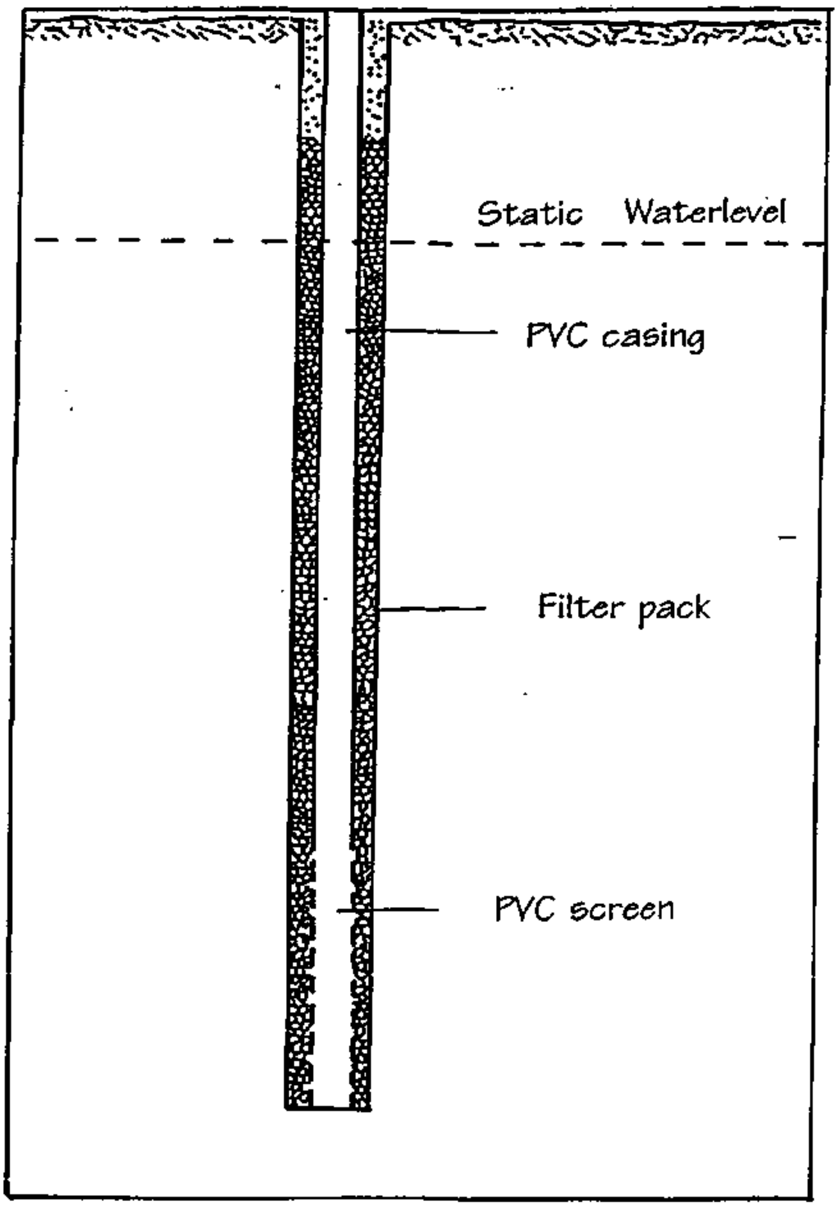

Figure 1 : Design of G39936, G39937A and G39938 (After Driscoll 1986)

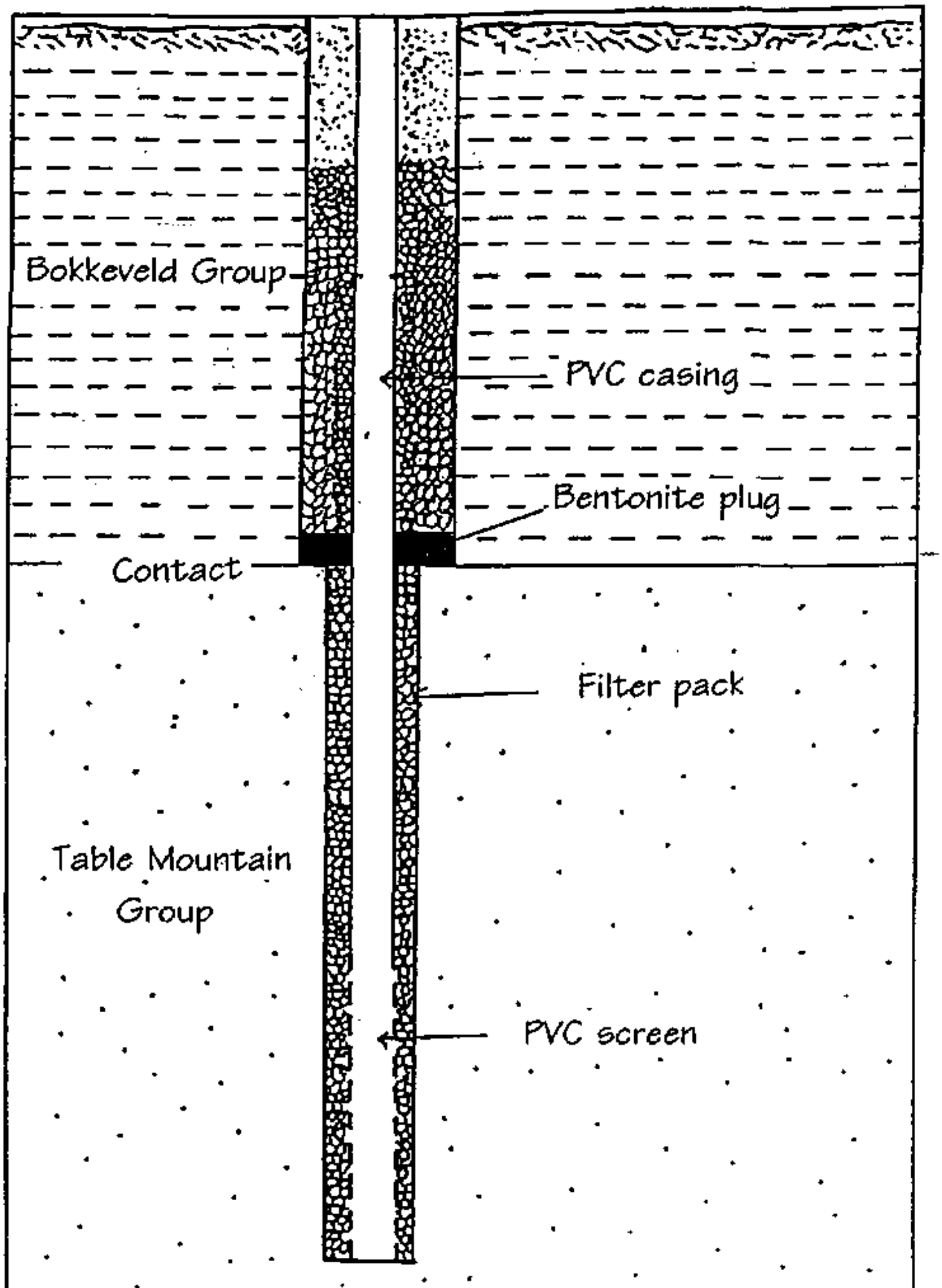

Figure 2 : Design of G39939 (After Driscoll 1986)

GEOLOGICAL PROFILE OF BOREHOLES

G39936

E-W coordinate	-28366.2 m	
N-S coordinate	3678602.1 m	
Elevation	1064.8 m	
Total Depth	21.6 m	
Water Intersections	Depth	Blow-out yield (L/s)
	21 m	0.2
Geology	0-1 m	unconsolidated medium to coarse grained sand
	1-15 m	fine to medium grained sandstone
	15-16 m	clay
	16- 21.6 m	fine to coarse grained sandstone

G39937A

E-W coordinate	-25499.4 m	
N-S coordinate	3679507.8m	
Elevation	884 m	
Total Depth	21. m	
Water Intersections	Depth	Blow-out yield (L/s)
	19 m	0.7
Geology	0-2 m	unconsolidated medium to coarse grained sand
	2-4 m	fine grained sandstone
	4-8 m	fine to coarse grained sandstone
	8-21 m	medium to fine grained sandstone

G39937

E-W coordinate	-25509.2 m	
N-S coordinate	3679505.4m	
Elevation	884 m	
Total Depth	109 m	
Water Intersections	Depth	Blow-out yield (L/s)
	17 m	0.2
	26 m	0.6
	32 m	1
	56 m	2
	72 m	3
	98 m	4
Geology	0-2 m	unconsolidated medium to fine grained sand
	2-109 m	fine to coarse grained sandstone

G39938

E-W coordinate	-24690.9 m	
N-S coordinate	3679173.6m	
Elevation	888.2 m	
Total Depth	17 m	
Water Intersections	Depth	Blow-out yield (L/s)
	16.5 m	0.5
Geology	0-11.5 m	clay
	11.5- 17 m	black shale

G39938A

E-W coordinate	-24679.8 m	
N-S coordinate	3679164.0m	
Elevation	887.7 m	
Total Depth	181 m	
Water Intersections	Depth	Blow-out yield (L/s)
	12 m	-
	26 m	3
	84 m	-
	88 m	-
	95 m	5.7
	98 m	10.5
	110.5 m	14.2
	118 m	22.2
	146 m	-
Geology	0-8.8 m	yellow/brown clay
	8.8-181 m	black shale

G39939

E-W coordinate	-24882.8 m	
N-S coordinate	3679276.3m	
Elevation	886.3 m	
Total Depth	171 m	
Water Intersections	Depth	Blow-out yield (L/s)
	27 m	-
	38 m	-
	51 m	-
	67 m	-
	84 m	>16
	124 m	(solid casing installed- water cut off)
	169.5 m	0.571
	170.5 m	0.75
	170.8 m	3.41
	170.9 m	5.61
	171 m	6.67
Geology	0-7.5 m	clay
	7.5-169.5 m	black shale
	169.5-171 m	quartzite sandstone

Appendix F.

Proposal to develop the Cape Aquifer Test Site (CATS)

PROPOSAL TO DEVELOP THE CAPE AQUIFER TEST SITE (CATS)

1 Purpose of the research project

The quartzites of the TMG are recognised as being one of the top three aquifers in South Africa in terms of yield and wide areal distribution. The other two are the dolomites of the Malmani Subgroup and the sands and gravels of the Cenozoic. These TMG quartzites have a high potential for regional water-supply projects in the Western and Southern Cape.

The relevance and potential for development have been further enhanced by the embargo on further dam-building by Minister Kadar Asmal "until all alternate water-supplies have been investigated and developed". In the past the TMG has not been hydrogeologically investigated to the same extent as has been the other two aquifers. Consequently there are shortcomings in our understanding of these aquifers which in turn has inhibited large-scale development of the aquifers.

One of the major obstacles is quantification of the available groundwater resource. In theory this is a vast resource. The area covered in tens of thousands of square kilometres and with the Peninsula Formation being 1500 m thick and the Nardouw being 1000 m thick the aquifer volume is enormous. Furthermore, as quartzite is highly competent, fractures at depth will tend to remain open, as opposed to granite (and most of South African hard rocks) for which fractures at depths greater than 200 m will close with time. Added to the above is that the TMG quartzites have undergone intense tectonic activity resulting in areas which have extensive fracturing.

Of particular relevance to the question of quantification is proof of the existence of groundwater from the medium-seated zone of the aquifer. There is abundant evidence of an extensive shallow-seated aquifer. Many boreholes in the 10 to 200 metre depth exist and they pump large quantities of water. The high-yielding hot-water springs are proof that deep-seated flow occurs. Knowledge that medium-seated flow does occur makes resources available to the water-supply manager that previously could not be calculated nor relied upon.

This WRC project "Geochemistry and Isotopes for Resource Evaluation in the Fractured Rock Aquifers of the Table Mountain Group" has developed some strong evidence using geochemistry and isotopes that this medium-seated flow does occur.

What is now needed is to confirm this evidence with a hydro-climatic model and a physical-mathematical model. This view is supported by both Professor Arie Issar of Ben Gurion University, Israel (e-mail to Siep Talma, CSIR, April 1998) and by Warren Wood, Principal Research Hydrogeologist, United States Geological Survey. Professor Issar remarked: "Regarding the Agter Witzenberg area, I am of the opinion that the area of investigation should be enlarged and deepened, because I can see in there an important case study for understanding the regional hydrogeological regime of the TMG. Yet I think that on top of the isotopic-hydrochemical study that you are carrying out one should also apply other methods, comprising a hydro-climatic model as well as physical-mathematical modelling. I know that it is rather complicated in the fractured TMG, but I think that attacking the puzzle from three directions, will enable a better evaluation of the potential of groundwater in the TMG of this region."

Should these two additional areas of investigation indeed confirm that medium-seated flow does occur then there will have been proved an immense additional groundwater resource. For the Western and Southern Cape this will be of great benefit for the future. Currently this future is one of water shortages in the near future.

2 Why Agter Witzenberg for CATS?

The establishment of the CATS in Agter Witzenberg has three major ADVANTAGES over other sites. FIRSTLY there is at present major stressing of the aquifer due to the pumping by farmers. This is more so than in all other TMG sites. During the previous investigation water-level drops of over 80 metres were recorded. In the one borehole being monitored the water-level dropped 28 metres despite the nearest pumping borehole being a few kilometres distant. SECONDLY there already exists a set of monitoring boreholes from the previous investigation. THIRDLY the cost of establishing the weirs for water balance calculations will not be too great as one is already constructed, a second has been constructed for the Arch Dam and for the third an existing farmers weir can be modified.

3 Aims

3.1 Short-term aims

- to establish three monitoring weirs on the streams flowing out of the Agter Witzenberg Valley to establish water balance outflow;
- to establish a suitable network of groundwater water-level recorders to measure water-table fluctuations both natural and due to farmers pumping;
- to identify weather stations owned by local farmers for which the data is suitable;
- *to establish a network of input and output water chemistry and water isotope monitoring* stations;

- to drill one or more deep monitoring boreholes through the Cedarberg Formation shales into the underlying confined aquifer of the Peninsula Formation to measure hydraulics and chemistry;
- to identify research projects and the suitable researchers (for post-graduate purposes) who will contribute towards the long-term aims described below.

3.2 Long-term aims

- to develop for the Agter Witzenberg Valley a hydro-climatic model and a physical-mathematical model to complement the recently developed isotopic-hydrogeochemical model (WRC project K5/481);
- to understand the groundwater-surface water interactions on a catchment scale for the quartzites of the Table Mountain Group so that the groundwater resources can be properly evaluated and exploited to their fullest extent.

Appendix G.

Salinity in the Struisbaai Aquifer

SALINITY IN THE STRUISBAAI AQUIFER

by

JOHN M C WEAVER

THESIS

Submitted in the fulfilment of the requirements for the degree of

MAGISTER SCIENTIAE

in the

Faculty of Science
Department of Geohydrology
University of the Orange Free State
Bloemfontein

Supervisor: Prof G van Tonder MSc., PhD.

May 1998

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SUMMARY

SALINITY IN THE STRUISBAAI AQUIFER

The water-supply for Struisbaai has a historical reputation for its high salinity. Like most of the coastal holiday resorts along the Cape South Coast there are a number of permanent residents. For Struisbaai these comprise owners of small businesses servicing the holiday trade, fishermen and their families and retired folk. However, unlike other coastal resort-towns, Struisbaai is notable for the lack of houses with attractive gardens. This is a direct reflection of the relatively high salinity of the water-supply which in the past was not suitable for irrigation, having salinities of over 100 mS/m and sometimes over 500 mS/m. For example a sample of town water-supply was collected in June 1990 from a tap at Struisbaai Hotel and the EC was found to be 658 mS/m (4150 mg/L of dissolved salts). In 1990 a replacement wellfield was developed which has an EC of about 90 mS/m. With this relatively low salinity attractive gardens may become a feature of the future for Struisbaai.

Three previous groundwater investigations have taken place, and in all of these the high salinities have been ascribed to over-pumping with resulting seawater intrusion. However, none of these authors gave any conclusive evidence for their theories. All of these reports gave field observations and then formulated theories for the origin of the salinity but in none of these reports were the two linked by logical arguments. This thesis thus considered the various possible sources of salinity and made conclusions as to the most likely source.

The three sources of salinity that were considered are:

- Salinity derived from sea-spray causing high salinity recharge.
- Geological factors which yield high salinity groundwater.
- Hydrogeological factors which result in sea-water intrusion.

Field work consisted of drilling of four new boreholes, geophysical down-hole logging of six boreholes, establishing rainwater sampling points, collecting of groundwater samples and processing water samples for isotopic analysis.

The methodology used to analyse the data was to closely consider the water quality of rainwater and groundwater samples as well as the isotopic composition of the groundwater. By considering ratios of the chemical composition, ratios of isotopic composition and using graphical plots the conclusion made was that the source of salinity is due to sea-spray which causes rain recharging to the aquifer to have a high salinity. This rain was measured to have a salinity of 10.5 and 12.5 mS/m respectively for the two rain collector stations. When a recharge to the aquifer of about 10% is allowed the resultant salinity is similar to that measured for groundwater at that site.

Using the same methodology it was concluded, except for two individual boreholes, that geological and hydrogeological factors are not the source of salinity. For these two individual boreholes it was shown that over-pumping and seawater intrusion was the probable cause of salinity.

The decision to replace the old wellfield with the new wellfield has been a fortuitous decision. By doing so two positive effects have occurred. Firstly the wellfield is now in an area where the local recharge is less saline due to it being further away from the sea and thus receiving less sea-spray. Secondly the possibility of over-pumping and inducing seawater intrusion is minimal.

This thesis has contributed to South African hydrogeology in that as far as can be ascertained this is the first documentation of the contribution that sea-spray makes towards causing salinity in South African coastal aquifers.

OPSOMMING

SOUTGEHALTE VAN DIE STRUISBAAI AKWIFEER

Struisbaai se watervoorsiening is histories van n hoë soutgehalte. Soos die meeste vakansie oorde langs die Kaapse Suid Kus, is daar 'n aantal permanente inwoners. Struisbaai se permanente inwoners is eienaars van klein besighede, vissemanne en afgetredenes. In teenstelling met die ander vakansie dorpies langs die Suid Kus is daar nie erwe met mooi tuine nie. Die rede hiervoor is die relatiewe hoë soutgehalte van die dorpswater. In die verlede was die water se soutgehalte meer as 100 mS/m en in sommige gevalle was die soutgehalte selfs hoër as 500 mS/m. 'n Monster wat in Junie 1990 in die Struisbaai Hotel geneem is, het 'n elektriese geleiding van meer as 658 mS/m gehad (dit is gelykstaande aan 4150 mg/L se opgeloste soute). In 1990 is 'n nuwe grondwaterbron ontwikkel. Die water van hierdie bron het 'n elektriese geleiding van omgeveer 90 mS/m. Hierdie verbetering in die soutgehalte van die watervoorsiening mag dalk daartoe lei dat mooi tuine in Struisbaai nog 'n algemene verskynsel sal word.

In die verlede is drie onafhanklike geohidrologiese ondersoeke op Struisbaai uitgevoer. In al drie die ondersoeke is die hoë soutgehalte van die grondwater toegeskryf aan seewater indringing as gevolg van te hoë pomptempos. Nie een van hierdie skrywers het oortuigende bewyse gelewer van hierdie teorie nie. Al drie verslae het veldwaarnemings voorgelê, waarvandaan gevolgtrekkings gemaak is. Geeneen kon die twee logies verbind nie. Hierdie tesis kyk na al die moontlike bronne van versouting en verwys daarvolgens na die mees waarskynlikste bron.

Die drie moontlike oorsake van versouting wat in ag geneem is:

- Versouting as gevolg van seesproei wat daartoe lei dat afloopwater wat die grondwaterbron aanvul 'n hoë soutgehalte het.
- Geologiese faktore wat grondwater van 'n hoë soutgehalte lewer.
- Hidrogeologiese faktore wat gelei het tot seewater indringing.

Vir die ondersoek is vier addisionele boorgate geboor, geofisise waarnemings is uitgevoer in ses boorgate, reënwater monsterneming punte is opgestel en grondwater monsters is ingesamel vir chemiese en radio-isotoop analiese.

Die metodiek vir hierdie ondersoek was om die watergehalte van die reën met die van die grondwater te vergelyk en te kyk na die isotoop samestelling van die grondwater. Deur die verhoudings van die chemiese samestelling asook die verhoudings van die isotoop samestellings grafies te vergelyk kon die gevolgtrekking gemaak word dat die seesproei die bron van versouting is deurdat die reënval afloopwater aanvullingswater met n hoë soutgehalte lewer. Die chemiese analise van die reënwatermonsters het bewys dat die soutgehalte van die reën by die monsterpunte wissel van 10.5 mS/m tot 12.5 mS/m. As 'n 10% aanvullingsyfer in ag geneem word is die soutgehalte van die grondwater dus gelykstaande aan die gekonsentreerde soutgehalte van die reënwater.

Deur van dieselfde metodiek gebruik te maak, kon die gevolgtrekking gemaak word dat behalwe vir twee van die boorgate, die geologiese en geohidrologiese faktore nie die bron van versouting is nie. In die geval van die twee boorgate is seewater indringing as gevolg van 'n te hoë pompontrekkings tempo waarskynlik die bron van versouting.

Die besluit om die produksieveld met 'n nuwe een te vervang het gely tot twee goeie resultate. Eerstens is die watervoorsieningsbron verder van die see geleë in 'n area waar die soutgehalte van die afloopwater wat as aanvullingswater dien baie laer is. Tweedens is die waarskynlikheid van seewater indringing as gevolg van verhoogde pomptempo minimaal.

Hierdie tesis het 'n bydrae gelewer tot die Suid Afrikaanse hidrologie in die sin dat sover moontlik vasgestel kon word is dit die eerste skrywe wat die rol van seesproei verbind met 'n verhoogde soutgehalte in Suid Afrikaanse kusakwifere.

CHAPTER 1

STRUISBAAI: INTRODUCTION, WATER-SUPPLY AND PROBLEMS OF HIGH SALINITY

1.1 PREAMBLE

Struisbaai is 170 kilometres east of Cape Town (Fig. 1.1). The name Struisbaai is derived from the Dutch name Vogelstruijsbaai recorded in 1672, meaning bay of ostriches. The bay provides the only protected harbour for 60 km to the west and 25 km to the east. In addition to the holiday resort population there is also a small commercial handline fishery.

The permanent population is 1700 of whom about half are fisher-folk. The summer population is estimated at about 9,000. This population variation is reflected in the water consumption as shown in Figure 1.2. This data was supplied by the municipality.

The water-supply for Struisbaai has a historical reputation for its high salinity. Like most of the coastal holiday resorts along the Cape South Coast there are a number of permanent residents. For Struisbaai these comprise owners of small businesses servicing the holiday trade, fishermen and their families and retired folk. However, unlike other coastal resort-towns, Struisbaai is notable for the lack of houses with attractive gardens. This is a direct reflection of the relatively high salinity of the water-supply which in the past was not suitable for irrigation, having salinities of over 100 mS/m and sometimes over 500 mS/m. For example a sample of town water-supply was collected by McLea (1990) from a tap at Struisbaai Hotel and the EC was found to be 658 mS/m (4150 mg/L of dissolved solids). In 1990 a replacement well field was developed which has EC of about 90 mS/m so attractive gardens may become a feature of the future for Struisbaai.

1.2 OBSERVATIONS BY PREVIOUS WORKERS REGARDING THE ORIGIN OF THE SALINITY OF STRUISBAAI GROUNDWATER

Figure 1.3 shows the study area and the positions of the various monitoring points.

Previous workers Meyer (1986a and 1986b), Levin (1988) and Toens (1991) have ascribed the salinity to various factors including seawater intrusion.

Meyer (1986a) was surprised by the high observed TDS values (870 - 1000 mg/L) for the boreholes drilled into the Table Mountain Group (TMG) quartzites. He would have been more familiar with values of 50 - 200 mg/L as is obtained from boreholes elsewhere (inland) in the TMG. He said (1986) that "one possible explanation is that water from the overlying Bredasdorp Formation in one or another manner mixes with water in the sandstones". This is a theme also followed by Toens (1991). Also mentioned by Meyer (1986a) was borehole 9A which was drilled into Bokkeveld shales and which had poor quality (high salinity) water.

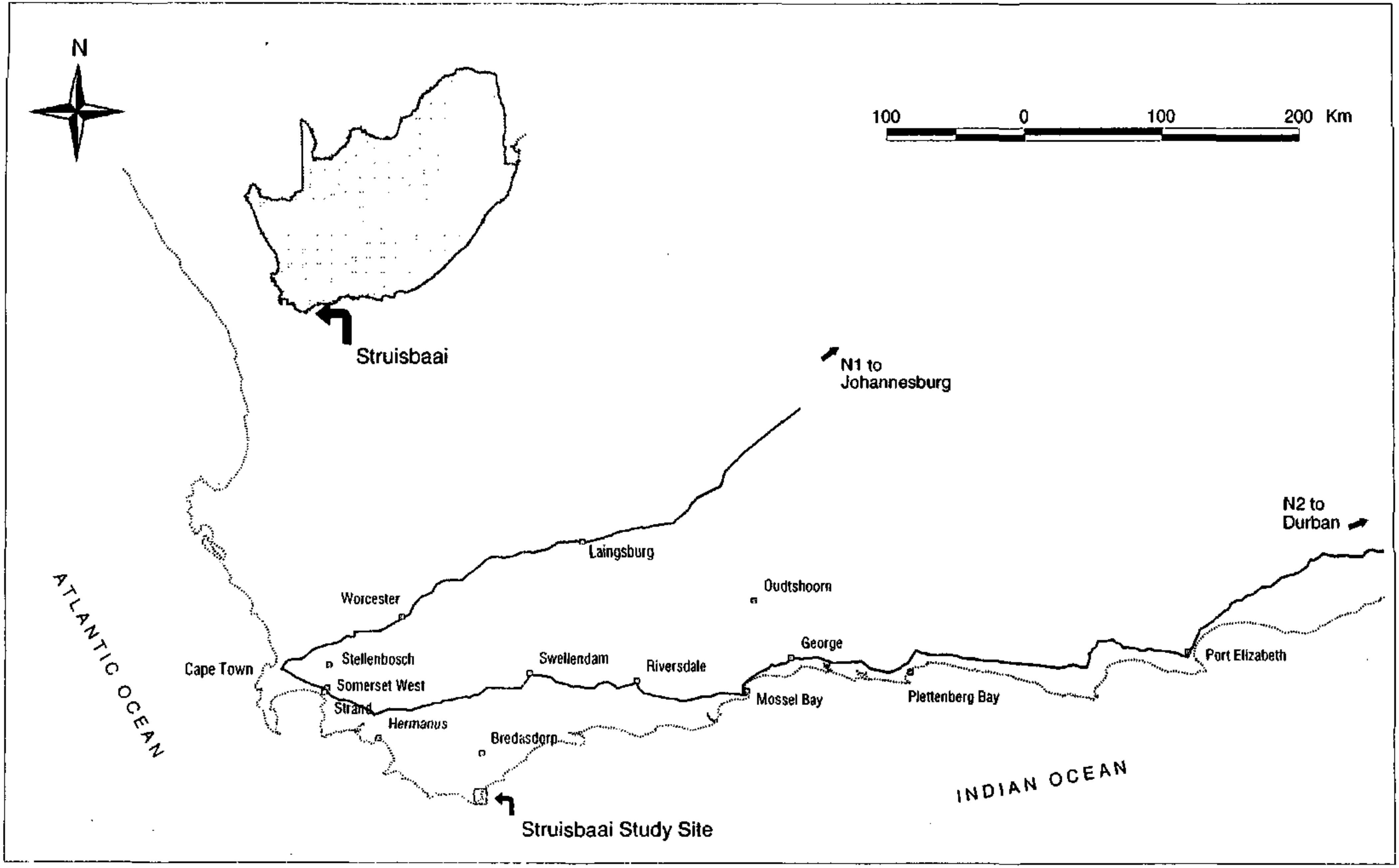


FIGURE 1: STRUISBAAI LOCALITY MAP

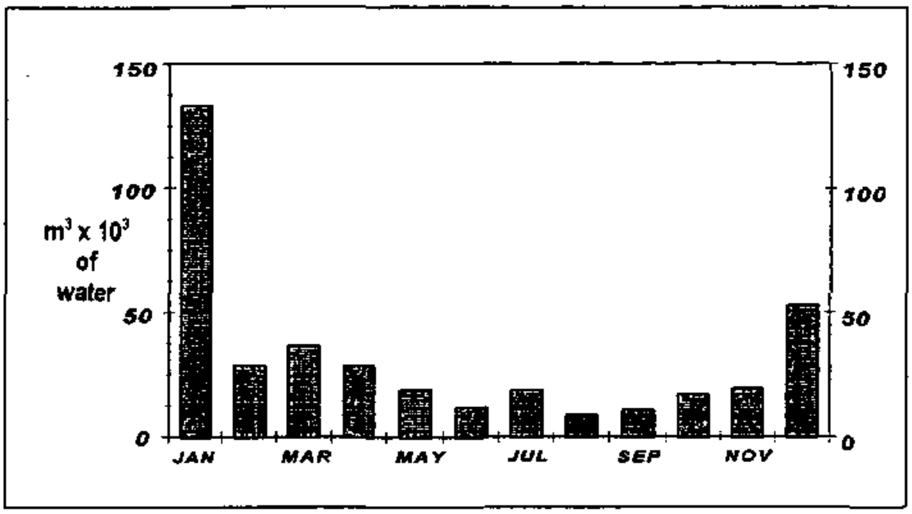


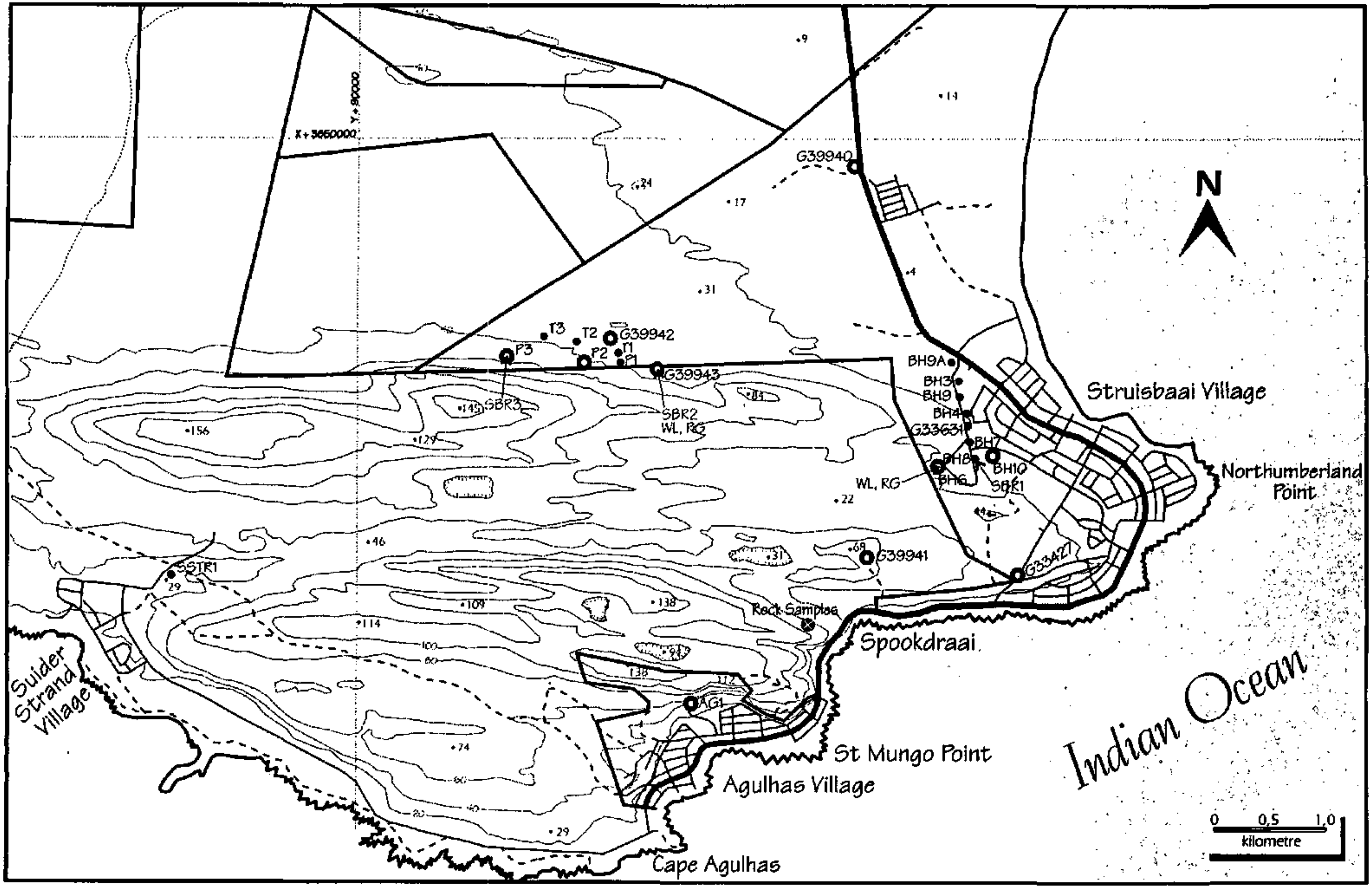
Figure 1.2 Struisbaai water consumption for 1996. The metering period is 15 to 15 of following month, thus the 133560 m³ consumption of January is for the peak holiday season of December/January (Data from Municipal Records)

Meyer (1992 pers comm) later developed the theme that the high salinity is due to sea water intrusion during periods of high pumpage. This is based on two sets of data. The first data-set used for developing the theme is the TDS measured in borehole G33427 during a test-pumping exercise (Figure 1.4). This borehole was sited by Meyer in 1986 on a NNE striking fracture which was mapped in the quartzites below the high water mark. The borehole is about 400 metres inland. Seven hours after pumping (rate not known) started the salinity increased rapidly and continued to increase at a lower rate. He regarded this as seawater intrusion. The second data-set used is the hydrograph (Figure 1.5) of G33631 which is located in the original well field. This shows a steep drop of water-levels by some 8 - 12 metres every summer season when the water demand is very high due to the holiday-maker influx. The graph indicates the water level drops up to 14 m below sea-level. Also shown on Figure 1.5 is the measured conductivities of 3 water-supply boreholes.

Levin (1988) concluded that the TMG holds the best potential as a groundwater source and that boreholes should be drilled to 150 metres. This would place the water-strikes below sea-level. He reports a deterioration of water quality with increasing depth which he ascribed to factors such as:

➡ salt concentration due to the flat groundwater gradient
➡ effect of Bokkeveld shales
➡ possible seawater intrusion

Toens (1991) carried out a regional assessment of groundwater potential. A total of 53 groundwater analyses were collated (23 collected and 30 from previous work). He notes that strata underlying the Bredasdorp are characterised by high salinities, which is particularly evident in the low lying areas near the coast. Analyses from boreholes and springs south of the Sandberg have EC's more than 130 mS/m which he ascribes to the water occurring at the base of the Bredasdorp.



GEOCHEMISTRY & ISOTOPES **WRC K5/481/0/1**

Figure 1-3

Struisbaai study site locality and positions of monitoring points

Legend

Tracks
•74 Spot Elevation
•BH8 Borehole
Farm Boundaries
Contours (20m interval)
P3 Sampled Boreholes

SBR1 = Rain sampler
WL = Water level recorder
RG = Automatic Raingauge

Groundwater Group
Cape Water Programme
CSIR

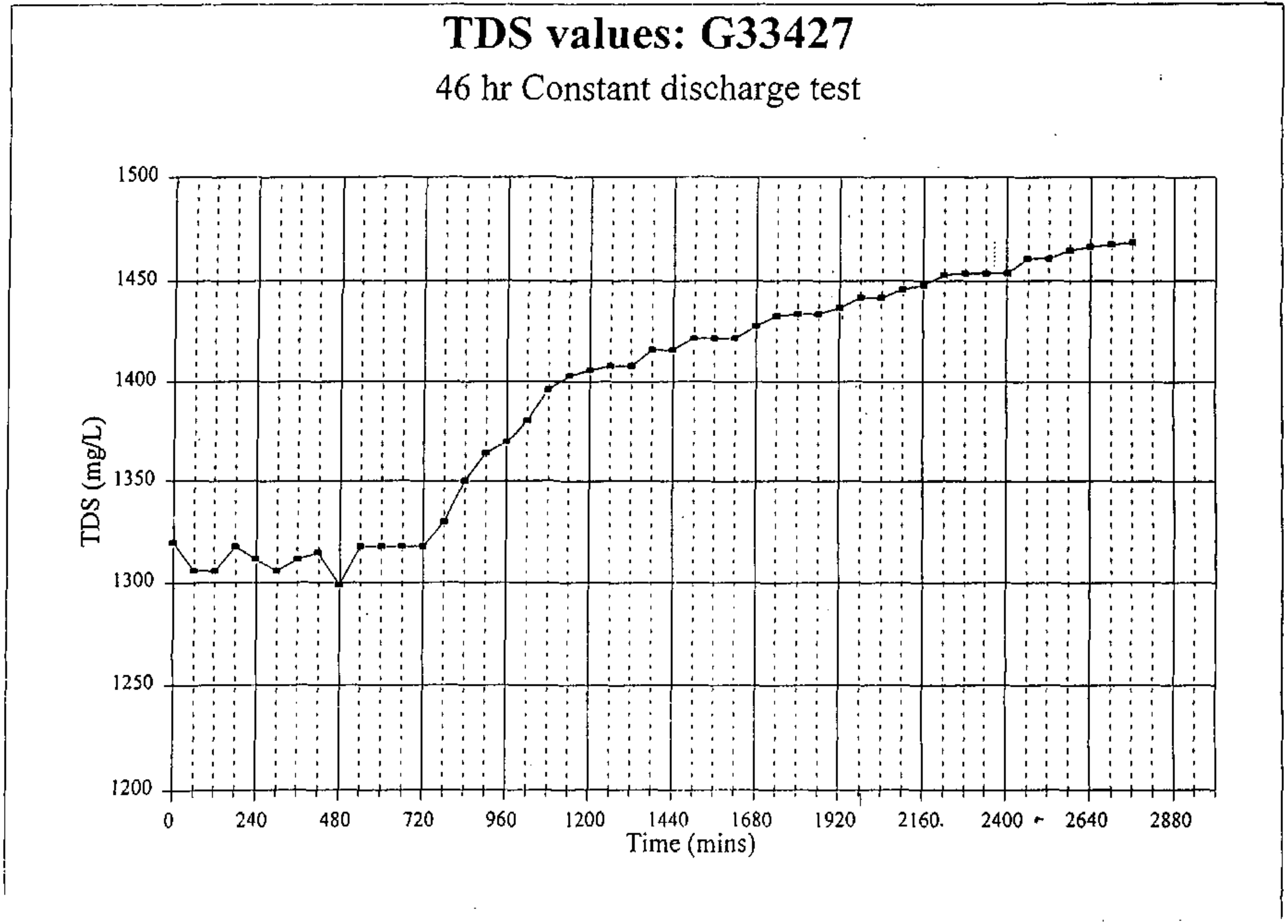


Figure 1-4 Struisbaai : Graph showing the increase of salinity observed in borehole G33427 during a 46-hour constant discharge test (from Meyer 1992)

STRUISBAAI

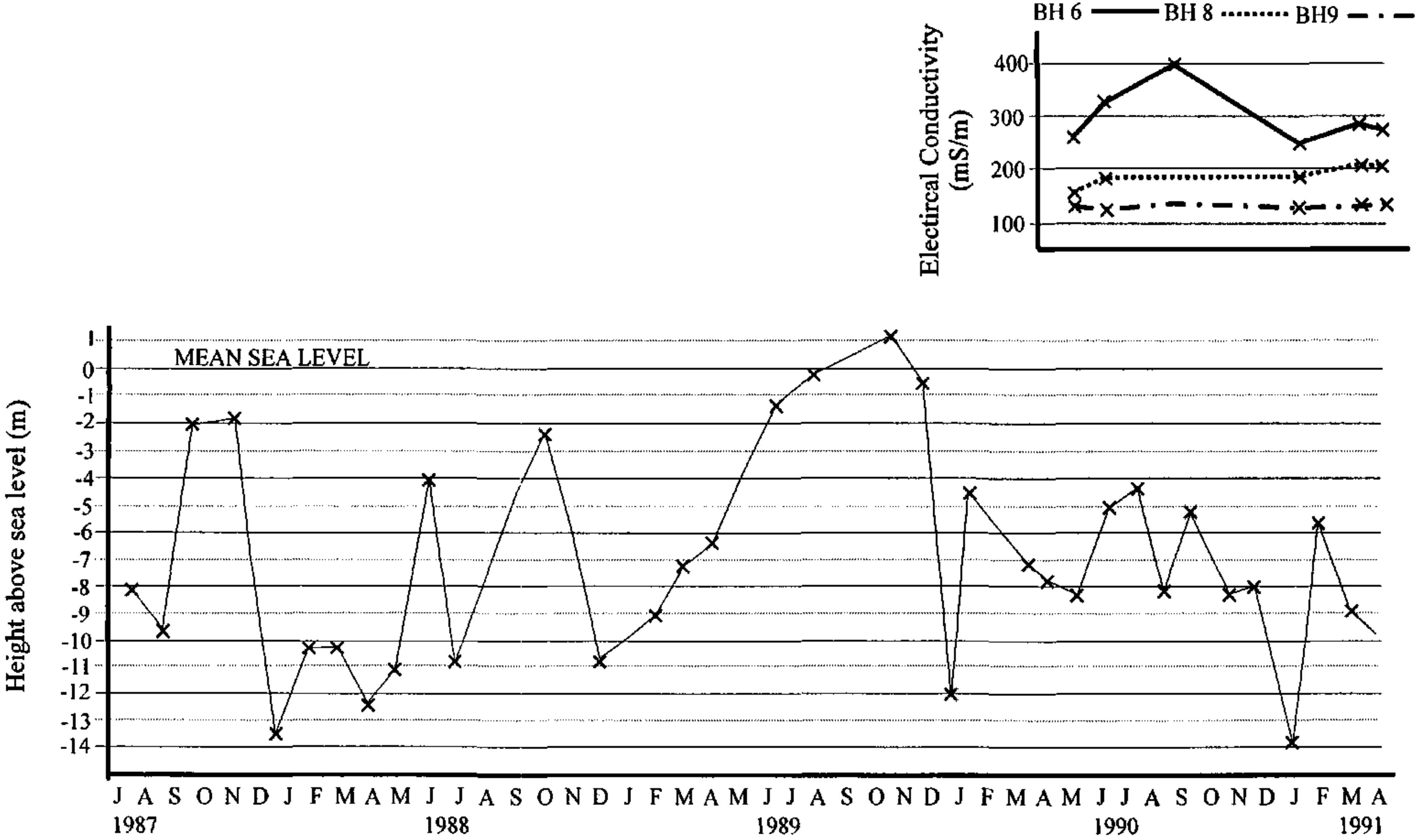


FIGURE 1-5 **Struisbaai: Observed water-level fluctuations in monitoring borehole G33631 which is in the "old wellfield" (from Meyer, 1992). The water quality graph shows the EC for the corresponding dots.**

For boreholes in the TMG where there is no Bredasdorp cover Toens (1990) found EC's of 80 mS/m and ascribes the increased EC of 100 mS/m for P_1, P_2 and P_3 (new water supply boreholes for Struisbaai as due to the Bredasdorp cover. He ascribes the high EC's encountered in the old Struisbaai boreholes to be a result of seawater intrusion drilled into the TMG.

None of these authors gave any conclusive evidence for their theories. All of these reports gave field observations and then made theories but in none of these reports were the two linked by logical arguments.

1.3 THE AIM OF THIS THESIS

The investigation of the hydrogeology at Struisbaai was carried out as part of a Water Research Commission research project titled "Geochemistry and Isotopes for Resource Evaluation in the Fractured Rock Aquifers of the Table Mountain Group" (Weaver *et al.*, 1997). After drilling of additional sampling boreholes and completion of the final few sampling runs the project team realised that this site was not suitable as a research site for the objectives of that research project and further work was discontinued.

It was, however, recognised that the information could be used towards solving the source of salinity in the groundwater supply. This would then constitute a useful case-study, because as far as the author has been able to ascertain no similar work has been carried out in South Africa. There are three sources of salinity which are considered to possibly be the cause of groundwater at Struisbaai having a higher than expected dissolved salt content. These are:

➠ Salinity derived from sea-spray causing high salinity recharge.
➠ Geological factors which yield high salinity groundwater.
➠ Hydrogeological factors which result in seawater intrusion.

Salt fallout from sea-spray is a phenomenon experienced by all inhabitants along the coast. House windows that need regular cleaning and motorcars that rust faster than do inland cars are two examples of this phenomenon. This sea-spray also affects groundwater quality (Martin and Harris, 1982). The effect is most marked along the coastal strip and lessens the further inland one goes.

There are two geological factors which are possible contributors of salinity. The first is connate salinity, which is seawater trapped in rock-pores from periods of marine transgression when groundwater was replaced by seawater. The second is salinity derived from shales of marine origin. In the Western Cape shales from the Malmesbury Supergroup and from the Bokkeveld Group are well known for having saline groundwater.

The third possible source of salinity is hydrogeological and is man-induced. This is saline intrusion which is caused by over-pumping of boreholes. This lowers the water-table to below sea-level, thus inducing seawater to flow towards the pumping borehole which then pumps a mixture of seawater and groundwater.

This thesis will examine the field data in terms of these possible sources of salinity and makes conclusions as to which of these factors is responsible.

The aim of the thesis is to identify the cause of the high salinity of the groundwater at Struisbaai.

★★★

CHAPTER 2

FIELD INVESTIGATION: METHODS AND PROCEDURES

The original project was directed towards an examination of variations of chemical and isotopic composition of groundwater with time as an aid to estimating groundwater reservoir capacity. Only after research work was stopped at Struisbaai was it realised that the data could be used to identify the sources of the high salinity in the groundwater. Some minor additional field work was done.

2.1 PREVIOUS INVESTIGATIONS

Previous investigations at Struisbaai and Agulhas were directed towards water supply. Meyer (1986a and 1986b) summarized previous drilling at Agulhas, a total of 9 boreholes, and at Struisbaai, a total of 9 boreholes. At Agulhas boreholes 1 and 2 of Meyer (1986b) are still in use for water-supply. This borehole 1 is marked AG1 on Figure 1.3. The Struisbaai boreholes (Meyer 1986a) have been replaced by a well field located further from the sea. Figure 1.3 shows the old Struisbaai well field BH3 to BH10 located adjacent to the village and the replacement well field boreholes P1, P2 and P3 which are 4 kilometres west of Struisbaai. This well field was established by the Engineering Consultants VKE (McLea, 1990) to supply water for a township development north of Struisbaai. Due to the good quality of the water from this well field all Struisbaai's water is obtained from this well field, with the old well field now being used as a standby to supply peak summer holiday season demand.

Other workers, Joubert (1973), Levin (1988) and Toens (1991) carried out investigations and made recommendations for water-supply but did not carry out any drilling.

2.2 PRELIMINARY FIELD WORK

On 3rd and 4th March 1993 an initial field visit was made in order to establish which of the boreholes described in the various reports were available for sampling. The boreholes were AG1, BH8, BH10, P2 and P3 (Figure 1.3). Other boreholes were located but were not available for sampling, either because of blockages or they were collapsed or they were sufficiently close to the chosen boreholes and were thus considered to be duplicates.

2.3 DRILLING OF ADDITIONAL BOREHOLES

In order to obtain a sampling network with a wider areal coverage an additional four boreholes were drilled (G39940, G39941, G39942 and G39943). Borehole G39940 was drilled in order to obtain water samples from the Uitenhage Formation (Jurassic age). G39941 in order to obtain a sample further from the old well field. G39942 and G39943 in order to obtain water samples from the upper zone of the quartzites, as the production boreholes P1, P2 and P3 were deep boreholes obtaining water from fractures deeper than 70 m. Access to the central zone was impossible as the calcrete forms a very rugged topography with many cavernous weathering features on surface. Note the internal drainage feature 1.5 kilometres to the south of borehole P3. In addition the existing but damaged borehole G39427 was reconditioned. Borehole logs of existing boreholes and of the new boreholes are presented in Appendix 1.

The drilling method was air-percussion with a drill-foam being used to reduce side-wall collapse. Where collapsing conditions were particularly severe, mud-rotary drilling was used.

Collapsing conditions were encountered at the calcrete/quartzite contact where the calcrete was cavernous and weathered. For the boreholes drilled during this investigation a steel casing was inserted and seated into the quartzite below this contact, thus sealing off any water intersected in the calcretes. This was done as the water quality in the quartzites was being investigated. Drilling then continued until the first water strike with a yield sufficient for sampling was encountered. The positions of these boreholes plus all existing known boreholes is shown in Figure 1.3.

Down-the-hole geophysical logging of these boreholes was carried out by Mr Barry Venter of DWA&F. The logs and the interpretations are contained in Appendix 4.

Test pumping data is available only for existing boreholes P1, P2 and P3 (McLea, 1990 and 1991). These are presented in Appendix 2.

2.4 RAIN GAUGES

Rainwater samples were collected in order to compare chemistry and isotopes of recharge and groundwater. Three rainwater collectors were erected, namely at Bh10 - SBR1, at BhG3943 - SBR2 and at BhP3-SBR3. These rainwater collectors have a collecting funnel attached to a tube leading down into a sealed container. The other end of the tube is placed inside a sample bottle which stands upright in the bottom of the container. The water from each rainstorm collects in the inner sample bottle from which a chemistry sample is taken during each (monthly) field visit. The data for these samplers thus represents the cumulative rainfall composition since the preceding sampling date. With knowledge of the rainfall quantities of the same period, an estimate of the annual isotope and chemical input at each site can be made.

2.5 GROUNDWATER SAMPLING

Five sampling runs were carried out. The first in March 1993 was for the existing boreholes and for the full network of ten monitoring boreholes was in October 1993, April 1994, August 1994 and December 1994. The results are contained in Appendix 3. The sampling equipment was either the existing production pump or an electric submersible which has a yield of ~ 0.8 L/sec.

For the geochemistry and isotopes study, the following determinants were required:

Table 2.1 Physical and chemical determinants measured

Group	Determinants
Physical determinants	EC, pH, temperature
Major cations	K, Na, Ca, Mg
Major anions	Cl, SO_4
Aggregate determinants	Alkalinity, DOC, TIC
Other elements	P, Si, NO_2, NH_4
Metals	Cu, Fe, Mn, Zn
Micro constituents	Sr, Rb, Ba, Li
Isotopes	^{13}C, ^{18}O
	^{14}C, (radioactive)
	$^{87}Sr/^{86}Sr$ (radiogenic)

Field data sheets were prepared before each sampling exercise. Standard sampling and sample handling procedures as set out in Weaver (1992) were followed. Some of the environmental isotopes and chemical constituents required specialised sampling mechanisms or preservation measures. ^{14}C, for example required the processing of 20 litres of water.

Before collecting a sample, the static water level at each borehole was measured. The borehole was then pumped for a period long enough to purge the hole of stagnant water. This allows representative samples of the *in-situ* groundwater to be taken. During pumping the electrical conductivity was monitored continuously and sampling begun once the reading had stabilised, but after three time the volume of water standing in the borehole column had been removed.

Temperature, EC and pH were measured in the field for the following reasons:

- ➡ These are parameters which can change after removal of water from the sampling point and are best measured as soon as possible. EC and pH are temperature-dependent parameters and are influenced by precipitation of salts out of solution or sample degassing.
- ➡ These parameters provide a preliminary overview of the water quality which can be used to decide the extent of sample collection necessary.
- ➡ They provide a check on laboratory data. (Lloyd and Heathcote, 1985).

Water samples were collected in PVC plastic bottles which were acid washed prior to sampling to remove all leachable materials. Unfiltered samples were collected for major cations and anions, alkalinity, hardness and DOC. Each bottle was rinsed at least twice with the sampled water before filling.

For filtered samples a hand-held syringe was fitted with a 0.45 micron filter membrane and the collected sample filtered into a sample bottle containing enough nitric acid to adjust the pH to less than 2. These preservation measures are necessary to prevent the metal ions precipitating or forming complexes with organic or other ligands in the water before reaching the laboratory. The syringe and filter holder was also rinsed with the sample water before collecting filtered samples for metal analyses.

For environmental isotopes, two 250 ml samples in glass bottles were collected for ^{18}O and D, and one sample preserved with 1 ml $HgCl_2$ for ^{13}C. Tritium samples required at least a litre of water. The sampling procedure for ^{14}C was more complex. Because the isotope occurs at very low concentrations, suitable samples for transport and laboratory analysis require a large volume of sample and specialised treatment. Approximately 20 litres had to be acidified and the formed CO_2 expelled with air in a closed system. The CO_2 was trapped in an absorber filled with caustic soda solution in the field for later analysis of the precipitated carbonate in the laboratory (Vogel, 1967).

All samples were delivered to the laboratories as soon as possible after collection to minimise the possibility of sample deterioration.

2.6 LABORATORY ANALYSIS

Chemical analysis of water samples was undertaken by the CSIR laboratories in Stellenbosch. Methods used conformed to guidelines set out in *Standard methods for the examination of water and wastewater* (APHA, 1989). Ion balances were checked to be within 5% for data quality control. Isotope analyses were carried out at the Environmentek laboratories in Pretoria.

Selected samples were also sent for ICPMS analysis. The first batch were tested at the Anglo-American Research Laboratories and the later samples at the Pretoria laboratories of the Institute of Soil, Climate and Water (Agricultural Research Council). It was hoped that these low-concentration metals could provide additional or supporting information to that derived from the major ion chemistry. At this stage, however, no useful correlations have been found. The results of the exercise are nevertheless presented as a part of Appendix 3. ICPMS is a relatively inexpensive analytical method which can generate large amounts of data on microchemistry. The usefulness and applicability of this method to groundwater studies needs to be assessed in relation to traditional methods.

2.7 GENERAL DISCUSSION ON THE ANALYTICAL DATA

Detailed examination of the analytical data reveals some anomalous results. The analytical laboratory of the CSIR in Stellenbosch is in high repute for producing results with both high accuracy and precision. In the annual inter-laboratory comparison this laboratory is always placed in the first five out of 30-odd participating laboratories. In the light of the confidence in the quality of the analyses these anomalies are commented on.

➡ DOC (Dissolved Organic Carbon). Inspection of the results for the production boreholes AG1, P2 and P3 an apparent instrumentation calibration problem was observed. These boreholes are regularly pumped thus ensuring representative groundwater samples. AG1 is 3 kilometres from P2 and P3 and its overall chemistry is different to P2 and P3 which are 700 metres apart and have similar chemistry. The DOC analyses for each sample run are similar to each other, but different between each sampling run. Table 2.2 shows the DOC results as well as alkalinity and nitrate.

Table 2.2 Struisbaai. DOC, alkalinity and nitrate results for the production boreholes AG1, P2 and P3

Date	**4/3/93**	**28/10/93**	**14/4/94**	**28/8/94**	**7/12/94**
DOC					
AG1	4.4	6.9	3.0	1.7	0.79
P2	4.7	7.0	2.9	1.6	0.79
P3	4.1	7.2	2.9	1.4	0.79
ALKALINITY					
AG1	215	228	216	217	212
P2	222	230	213	213	211
P3	208	220	209	238	208
NITRATE					
AG1	2.35	4.74	3.12	2.34	2.32
P2	0.1	0.26	<0.1	0.28	<0.1
P3	0.05	0.1	<0.1	0.13	<0.1

There is no correlation between alkalinity and DOC. For nitrate and DOC there is some correlation for borehole AG1 in that the highest DOC result corresponds to the highest nitrate result, but no correlation between nitrate and DOC for P2 and P3. AG1 receives groundwater from a different stratigraphic elevation than do P2 and P3 but if this were the reason for the DOC/Nitrate partial correlation for AG1 and not P2 and P3 then the DOC for P2 and P3 should be different to AG1 and not virtually identical. From ^{14}C results AG1 is much older water than P2 and P3, thus should be well buffered from seasonal changes and also chemically (DOC) different to P2 and P3 . Geologically and hydrologically there is not an explanation.

These results were discussed with the analytical staff and in the time period of sampling and analysis there was neither an instrument nor an analytical method change which could have influenced the DOC results. The graphs from the auto-analyser were retrieved and re-examined. For all of these analyses standards of 20, 10 and 5 mg/L DOC were used, plus a control sample of groundwater from the Atlantis aquifer which has a similar, but less saline water. The standards and the control sample were consistent and the DOC's measured for these samples are correct in relation to the standards and control.

The mystery of the sampling run correlation and the trend for the period of sampling remains a mystery.

- The first set of analyses for the two newly drilled boreholes G39942 and G39943 appear to have residual effects from either the drilling mud used during the tricone rotary drilling of the calcretes or from drilling foam used with the air percussion used for drilling the quartzites. For example G39942 calcium increases from 57 mg/L to 74 mg/L, sulphate decreases from 61 mg/L to 21 mg/L and alkalinity increases from 72 mg/L to 172 mg/L. These two samples are not discarded, but in the ensuing discussions regarding the chemical and isotopic evaluation of the groundwater the influence of drilling mud is taken into account.

- The isotopes were analysed in a different laboratory from that which analysed the chemistry. These results show only two anomalies. The first samples from G39942 and G39943 which have TIC (total inorganic carbon) less than half of the subsequent samples which also resulted in a carbon-14 content not being able to be measured for G39943. This would appear to support the cause of the anomalies to be due to the organic drilling mud used.

- $\delta^{18}O$ of borehole P3 for 15/04/94 is -4.0 $^{o}/_{oo}$ whereas the other samples for this borehole range from -4.8 to -5.1 $^{o}/_{oo}$ which is the same range as for all the other boreholes (except G39940). This value is considered incorrect.

★★★

CHAPTER 3

MARITIME INFLUENCE ON RAINFALL AND RECHARGE QUALITY

3.1 GENERAL

Struisbaai falls in the winter rainfall region receiving most rain in winter, nevertheless there is substantial summer rain. The rain varies between 400 and 500 mm per annum, the long term average being 458 mm. The prevailing winds are west to southwest in winter and southeast in summer, reaching gale force from either direction. The average maximum temperature in summer is 28 °C and winter is 17 °C.

3.2 STRUISBAAI RAINFALL AND SALINITY

The South African Weather Bureau, Information Section was contacted for information regarding rainfall figures. The two closest weather stations are Agulhas lighthouse and Bredasdorp Police Station. For Agulhas lighthouse monthly rainfall is available from 1894 to 1997 and daily rainfall from 1902 to 1997. For Bredasdorp Police Station the same period but monitoring stopped in 1991.

Graphs of the long-term rainfall and the monthly average are shown in figure 3.1, 3.2, 3.3 and 3.4. The bulk of the rain is in winter with 67% of Agulhas' rain and 61% of Bredasdorps rain falling in winter. However, it is also obvious that there is an appreciable amount of rain that falls during the summer period. The winter rains are from cold frontal systems passing over the coast and the rain is from the west. During summer the low pressure fronts pass further to the south, but as they pass, south-west to south onshore winds are generated which produces the relatively high summer rains.

Rainfall collectors SBR1 and SBR2 were installed 12 October 1993 and a third SBR3 on 15 April 1994. A veld-fire on 10-11 January 1995 destroyed SBR1 and SBR2. Lack of co-operation in sample collecting resulted in the samples being collected at long intervals rather than after each rainfall. Consequently combining the rain analyses with the historical rainfall data (figure 3.1) to produce a weighted average rainfall chemistry figure must be regarded as an indicator of rain chemistry rather than the actual rain chemistry. For each sample analysed this is taken to represent the chemistry of the total rain between the date of collection and the previous sampling run. Thus SBR1 of 16 April 1994 is taken to be the chemistry of all the rain between 23 Nov 1993 and 16 April 1994.

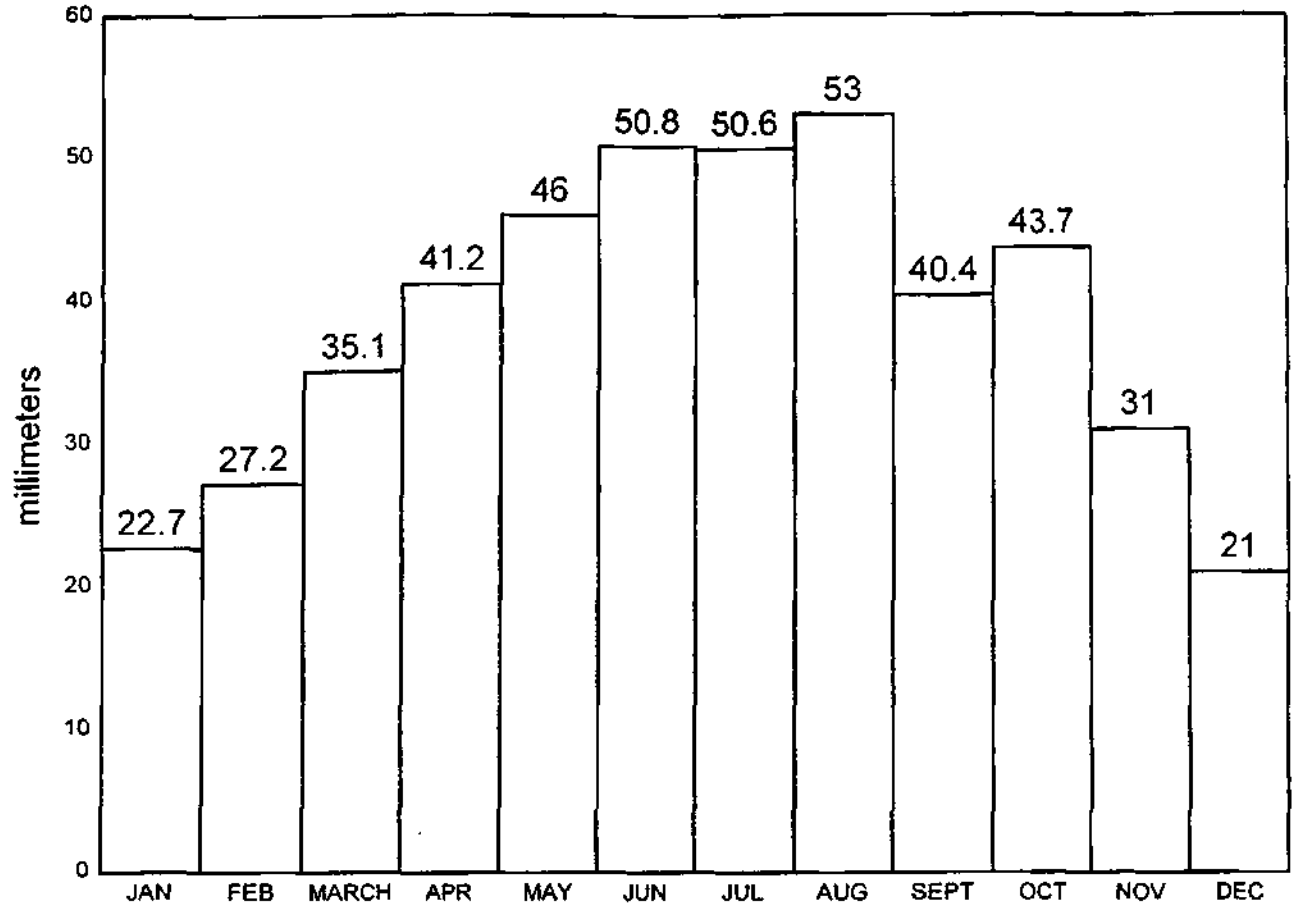


Figure 3.1 Monthly average rainfall for Bredasdorp. Note that the maximum rain is during the winter months nevertheless there is appreciable summer rain

Data from Weather Bureau
Department of Environmental affairs

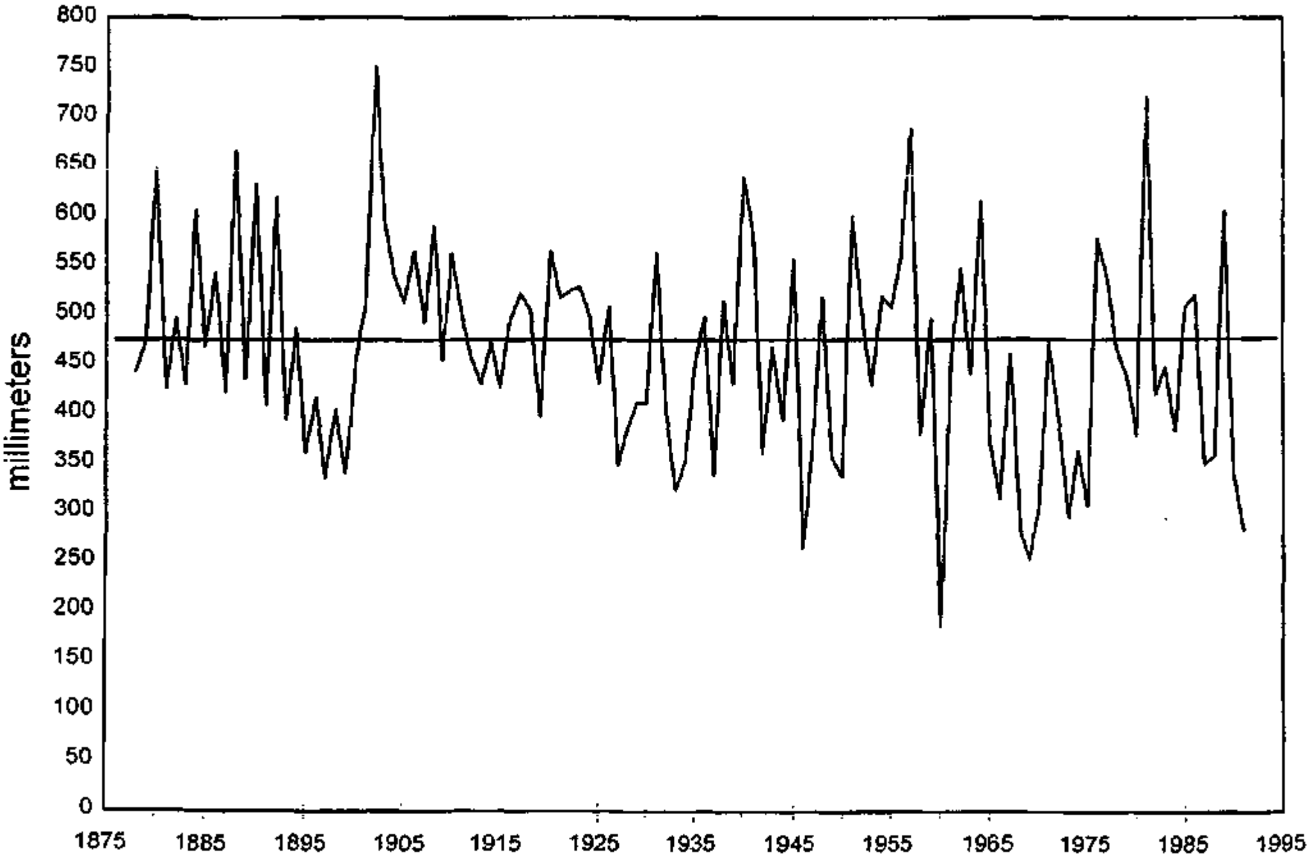


Figure 3.2 Annual Rainfall at Bredasdorp for the years 1878 to 1991
Average is 462.3mm

Data from Weather Bureau
Department of Environmental Affairs

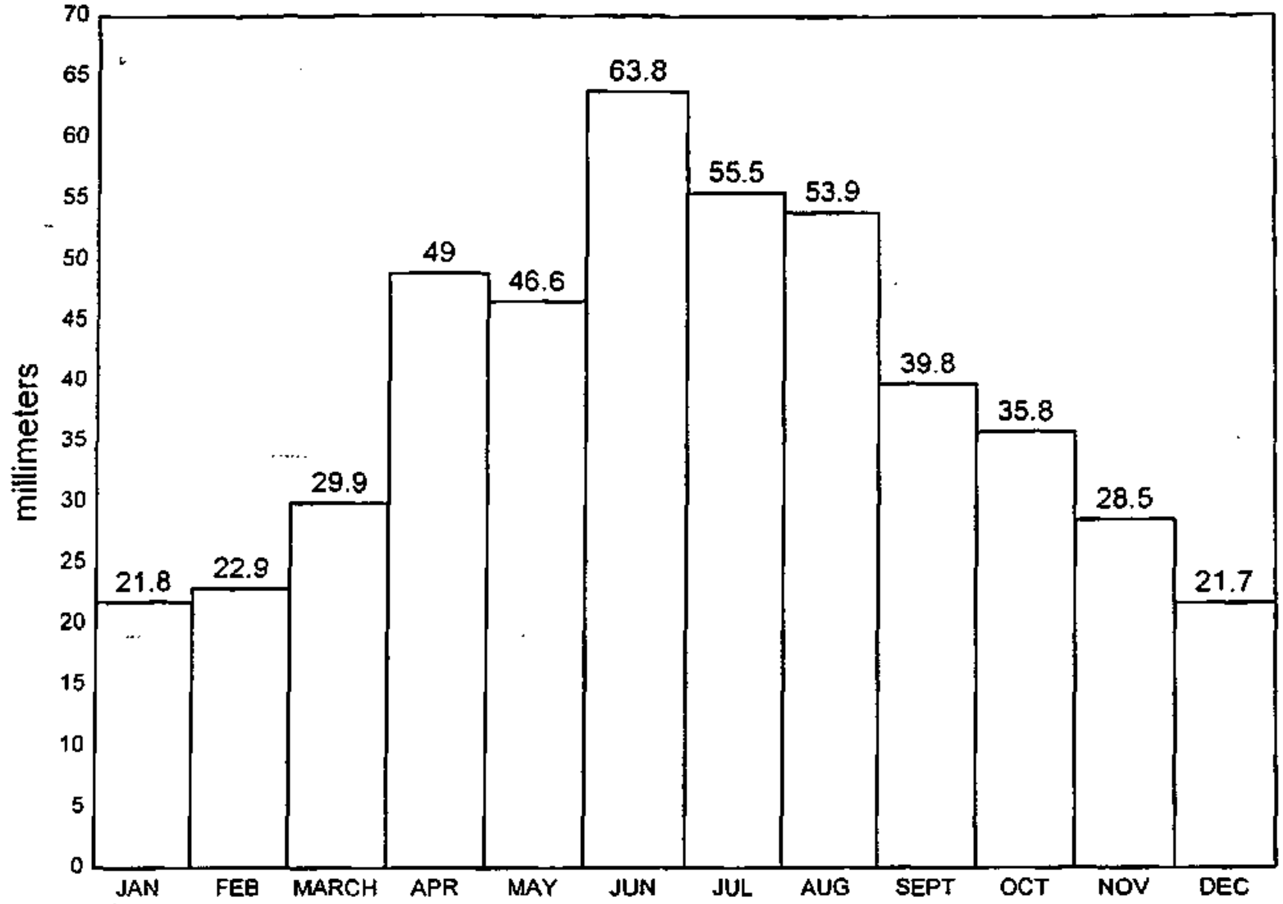


Figure 3.3 Monthly average rainfall for Agulhas Note that the maximum rain is during the winter months nevertheless there is appreciable summer rain

Data from Weather Bureau
Department of Environmental affairs

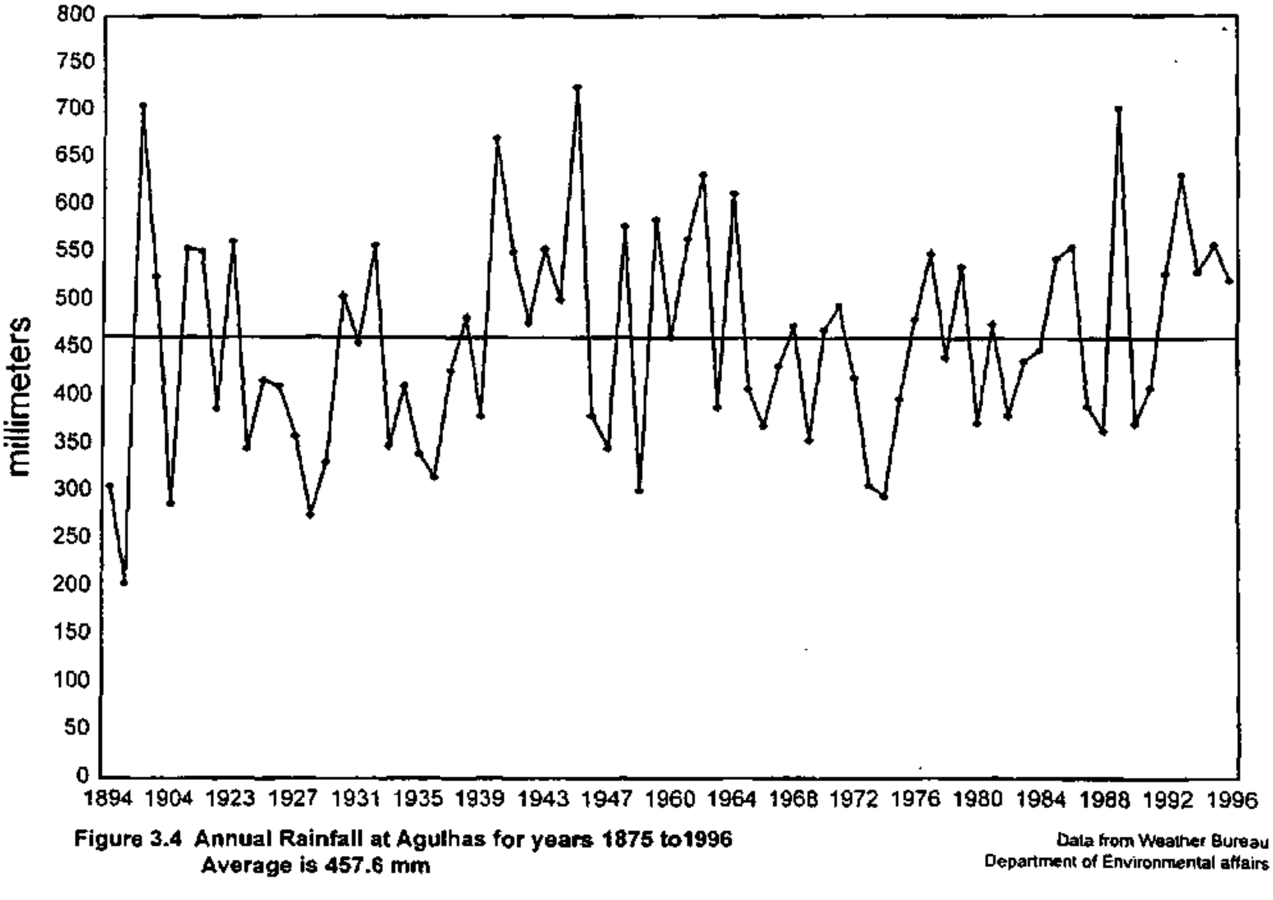


Figure 3.4 Annual Rainfall at Agulhas for years 1875 to1996
Average is 457.6 mm

Data from Weather Bureau
Department of Environmental affairs

The weighted average rain quality was calculated by the following equation:

$$\text{weighted average rain quality} = \frac{\sum_{i=1}^{n} EC_i x_i}{\sum_{i=1}^{n} x_i}$$

where EC_i (mS/m) is the measured rain quality for the i^{th} sample period
X_i is the rainfall (mm) for the i^{th} sampling period as measured at Agulhas

The daily rainfall figures from Agulhas lighthouse were used to determine the total rain for the period that water quality samples were collected. *The data is summarized in Table 3.1 below.*

Table 3.1 Struisbaai. Amount of rainfall, rainfall quality and weighted average quality of rain during period 12/10/93 to 30/08/94.

Period	**Rainfall (mm)**	**SBR1**		**SBR2**	
		EC for period (mS/m)	**Weighted average EC (mS/m)**	**EC for period (mS/m)**	**Weighted average EC (mS/m)**
12/10/93					
	1.0	56		45	
29/10/93					
	4.4	59	12.5	37	10.5
23/11/93					
	53.6	34		24	
16/04/94					
	372.4	9		8.4	
30/08/94					
Total Rain	439.4				

Similarly the weighted average for all the determinants can be calculated and are presented in Table 3.2. There is insufficient data for SBR3 so no calculations are made.

Table 3.2 Struisbaai: Weighted average quality for Struisbaai rainfall as determined for rainfall collectors SBR1 and SBR2 for period 12/10/93 to 30/08/94. EC is in mS/m the rest in mg/L.

	EC	K	Na	Ca	Mg	SO_4	Cl	Alkalinity	Na:Cl
SBR1	12.5	0.7	16.1	3.1	2.0	4.9	31.0	2.0	0.52
SBR2	10.5	0.7	9.8	5.6	1.2	3.4	23.1	6.3	0.42

Examining these data it is seen that SBR1 has higher EC, Na, Mg, SO_4 and Cl whereas SBR2 has higher Ca and alkalinity. This is interpreted to be a reflection of their localities relative to the sea. The south-east wind blows strongly in summer and also in winter after a cold-front has passed by. This wind blows sea-spray (aerosols) and SBR1 being the closest to the sea receives more aerosols than does SBR2 and thus has higher levels of EC, Na, Mg, SO_4 and Cl. The higher Ca and alkalinity for the SBR2 which is inland is explained by this rain collector receiving more dust than SBR1. As the surface soils are calcrete and quartz sand this dust gives the higher Ca and alkalinity. This effect of distance from the sea leading to a relatively higher calcium and alkalinity for the collectors further from the sea has also been observed by Meyer *et al.* (1993) in the Zululand coastal plain.

Nitrate and ammonia are not processed as these are mostly related to insect or bird dropping contamination.

These relatively high salinities for the rainfall will have a marked effect on groundwater quality. For the Struisbaai area there is very little evidence of surface runoff. The calcrete surface has numerous solution cavities. Topographic features are the internal drainage features which can be seen between the ridges of the fossil dunes. In figure 1.3 one of these can be seen 1,5 kilometres south of borehole P3 and another is 500 metres north-northwest of borehole AG1.

Using scenarios of 0% and 20% loss of rainfall due to runoff and evapotranspiration varying between 90% and 70% the quality of recharge water is calculated. Chloride being conservative is used for these calculations. The calculated results are presented in Table 3.3.

Table 3.3 Struisbaai rainfall and recharge water quality simulations

	Runoff %	**Evapotranspiration %**	**Recharge as a % of rainfall**	**Resulting chloride content mg/L of Cl**
SBR1 Weighted average chloride content is 31 mg/L	0	95	5	620
	0	90	10	310
	0	80	20	155
	0	70	30	103
	20	90	8	310
	20	80	16	155
	20	70	24	103
SBR2 Weighted average chloride content is 23.1 mg/L	0	90	10	231
	0	80	20	115
	0	70	30	77
	20	90	8	231
	20	80	16	115
	20	70	24	77

SBR1 was installed at BH10 which has an average chloride content of 532 mg/L. Comparing this value to Table 3.3 it is seen that for the 0% runoff option this value lies between the recharge value of 5% and 10% of rain. Working backwards 532 mg/L implies a recharge of 5.8%. For the 20% runoff option the implied recharge is 4.7% of rainfall.

Similarly for SBR2 the nearest borehole is Bh P_3 with an average chloride content of 141 mg/L the implied recharge at 0% runoff is 16.4% of rainfall and at 20% runoff it is 13.1% of rainfall.

These values of recharge are quite feasible considering the porous nature of the calcrete cover.

Relatively little work has been done on estimating recharge through Bredasdorp Formation calcretes. This is probably due to these aquifers being of local importance to coastal regions in the southern Cape. For the Langebaan limestone aquifer using borehole hydrographs Weaver and Du Toit (1995) determined that groundwater recharge was 8% of annual rainfall.

Salt input to the ground is called cyclic salting (Lloyd and Heathcote, 1985). Cyclic salting has been recognized as a major contributor to the salinity of small islands, coastal aquifers and areas which have low or intermittent recharge (arid zone).

3.3 RECHARGE AND SALINITY

In chapter 3.2 it was shown that the salinity as measured for the rain could quite feasibly be the source of the high salinities recorded for the groundwater. It is however, noted that these are the salinities recorded for all rainfall and include any windblown dust and salts. An argument can be advanced that groundwater recharge occurs only after significant falls of rain and that light rains do not contribute to recharge. Consequently the argument says that only the water quality for the heavy winter rains should be considered. The consequence is that when recharge does take place after heavy rainfall then all salts that have accumulated on surface will dissolve in the rainwater and be flushed and recharged into the groundwater system.

In order to test the proposition that air-borne salts originating from the sea is the primary source of salinity in the groundwater a leaching test of the calcrete was conducted. Two samples of calcrete were collected from a newly developed road approximately 300 metres from the coast and inland from Spookdraai (see figure 1.3). The first sample was from an exposed and weathered rock-face and the second was from a freshly exposed surface, both being collected close to each other in order to have similar exposures to the elements. In hand-specimen the difference between the samples was that the weathered sample was more porous due to calcrete having been weathered. The samples were crushed and split. Fifty grams of crushed sample was mixed and thoroughly stirred with 500 ml of de-ionized water. A water-sample of each was decanted after 24 hours and analysed for cations and anions. The data is presented in Table 3.4 below.

Table 3.4 Analysis of leachable salts from Struisbaai calcrete

Two air dried samples of finely crushed rock was analysed. 50 g of sample was weighed into flasks and deionised water (EC 0.1 mS/m) was added to 500 ml mark.

The slurry was magnetically stirred for 3 hours, (constant EC) and allowed to settle overnight. The supernatant was filtered (0.45 micron) and analysed.

Sample ID:	**Fresh**	**Exposed**
Potassium as K mg/L	2.1	5.4
Sodium as Na mg/L	9	185
Calcium as Ca mg/L	12.5	21
Magnesium as Mg mg/L	1.9	19
Ammonia as N mg/L	0.1	<0.1
Sulphate as SO_4 mg/L	3	24
Chloride as Cl mg/L	6	336
Alkalinity as $CaCO_3$ mg/L	43	25
Nitrate plus Nitrite as N mg/L	0.1	0.3
Ortho phosphate as P mg/L	0.8	<0.1
Conductivity mS/m @ 25 °C	11.6	122
pH (Lab)	8.3	8.8

Analysed by the CSIR Analytical Laboratory, Stellenbosch

Some observations are made on these results. The EC was continuously measured during stirring. For both samples the EC rose to the final EC within ten minutes. This is a reflection of the *solubility* of the various salts, being mainly Na and Cl.

To gain an idea of what minerals could contribute to these results the mineral speciation model MINTEQ was applied to these two analyses.

MINTEQ allows one to model which minerals are likely to precipitate from a given solution, or in this case an analysis of the dissolved ions. Being a modelling package it does not prove that this will occur, but makes a prediction. In addition there is modelling routine which allows one to not allow precipitation, thus enabling one to determine which minerals are supersaturated. The following are the modelling results of applying MINTEQ to the "fresh" and "exposed" analytical results.

For the fresh rock sample, model run standard

- hydroxyapatite ($Ca_5(PO_4)_3OH$) precipitated

when precipitation was not allowed

- hydroxyapatite was supersaturated
- aragonite ($CaCO_3$) and calcite ($CaCO_3$) were just below saturation
- dolomite ($Ca\,MgCO_3$) was well below saturation

For the exposed rock sample model run standard (phosphate taken as equal to 0.1)

- hydroxyapotite and dolomite precipitated

when precipitation was not allowed

- hydroxyapotite and dolomite supersaturated
- calcite just above saturation
- aragonite and magnesite ($MgCO_3$) just below saturation

The conclusion made is that the relatively high presence of magnesium in the exposed rock promotes the formation (potential) of dolomite (and magnesite). This magnesium is from sea-spray. Seawater intrusion promotes dolomitization (Meyer (1991), Fidelibus and Tulipano (1991)). The absence of (potential) dolomite in the fresh sample and the presence of (potential) dolomite in the exposed sample indicates that seawater intrusion has not taken place but that (potential) dolomitization is via sea-spray contact with the calcrete. If the (potential) dolomitization had been caused by seawater intrusion then both samples would have (potential) dolomite.

The ratio of Na to Cl for the exposed sample is 0.551 which is almost exactly that for ocean water. The Indian Ocean off the south coast of Africa is well mixed, has little fresh water influence from major rivers or ice-caps and is not subject to concentration due to limited circulation such as the Arabian Gulf. Table 3.5 gives the concentration of the major ions and ratios of various salts, and Table 3.6 compares these to the ratios for the two rock samples.

Table 3.5 Average seawater concentration of major ions (Goldberg, 1963)

Ion	Concentration mg/L
	Goldberg (1963)
Chloride	19000
Sodium	10500
Sulphate	2700
Magnesium	1350
Calcium	400
Potassium	380
Bicarbonate	142
Bromide	65
Strontium	8
Na^+/Cl^-	0.553
K^+/Cl^-	0.020
Ca^{2+}/Cl^-	0.021
Mg^{2+}/Cl^-	0.071

Table 3.6 Ratios of various ions to chloride for leachate from two rock samples from Struisbaai for the two rainfall collectors and for seawater

	Na/Cl	K/Cl	Ca/Cl	Mg/Cl	SO_4/Cl
Rock sample - fresh	1.5	0.35	2.08	0.317	0.5
Rock sample - exposed	0.552	0.016	0.063	0.057	0.07
Rainfall collector: SBR1	0.52	0.023	0.10	0.065	0.158
Rainfall collector: SBR2	0.42	0.03	0.24	0.052	0.147
Seawater	0.553	0.020	0.021	0.071	0.140

From this table comparing these ratios to the seawater ratios it appears that the rock sample - exposed, SBR1 and SBR2 all have Na, K and Mg approximately in proportion to seawater. Calcium for all three is elevated, which is probably due to dust. SO_4 for the two rain collectors is in proportion, but for the rock sample - exposed is low. The rock sample - fresh ratios have no resemblance to the others.

These results support the argument that windblown sea-spray is a major contributor to groundwater salinity with the three samples, being the two rainfall collectors and the rock sample - exposed, which are exposed to sea-spray having similar ratios of ions as seawater. The rock sample - fresh has no similar ratios. Thus the conclusion is made that the salinity is derived from sea-spray and not from dissolution of the calcrete.

Martin and Harris (1982) working in the Perth area of Western Australia found similar results with the Na and K with rainfall and groundwater having Na, K and Mg to Cl ratios similar to seawater while Ca to Cl was enriched in Ca. Table 3.7 below shows these results.

Table 3.7 Ratios of cation to chloride ion from Perth area, Western Australia (Martin and Harris, 1982)

	Na/Cl	**K/Cl**	**Ca/Cl**	**Mg/Cl**
Rainfall	0.548	0.032	0.075	0.071
Groundwater	0.560	0.050	0.450	0.093
Seawater	0.556	0.020	0.021	0.067

3.4 CONCLUSIONS

Rainfall samples that have been collected and weighted to the average annual rainfall show that rain (plus sea-spray and dry fallout) contributes a high salt load to the area.

Relating the rainfall salinities at each of two rain collectors to local groundwater salinities the implied recharge is 4.7% and 13.1% for the two collectors. These are quite feasible figures.

Leaching of two rock samples shows that the exposed calcrete yields a high salinity and the fresh calcrete low salinity. Mineral speciation modelling of the leachate shows (potential) dolomite is present in the exposed sample and not the fresh sample. Both these results show that sea-spray is the likely origin for the salt and not seawater intrusion or connate water.

Ionic ratios for the two rainfall collectors and the exposed calcrete sample are very similar to those of seawater while the ratios for the fresh rock sample are very different. These results support sea-spray being the origin of salinity.

★★★

CHAPTER 4

GEOLOGICAL CONTROL OF GROUNDWATER SALINITY

4.1 GEOLOGY OF THE STRUISBAAI AREA

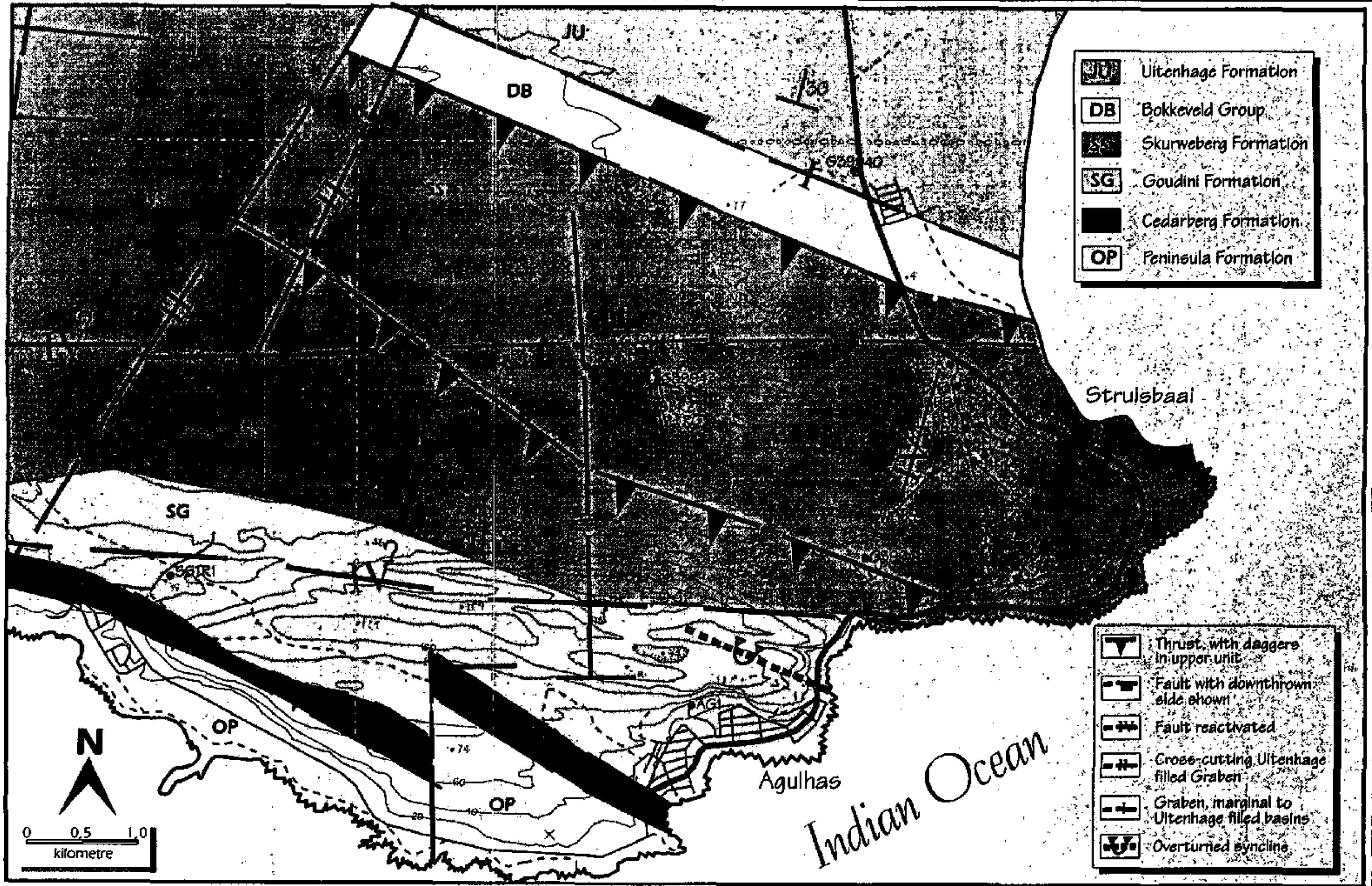
4.1.1 Regional Geology

The first detailed description of the area was by Spies *et al.* (1963) a product of which was the 1:125000 geological map number 235. In the late 1980's the Atomic Energy Corporation on behalf of Eskom conducted an intensive survey of the geology and groundwater from Gansbaai in the west to Waenhuiskrans in the east. This was part of their assessment for the location of a future nuclear power plant. The survey results have been published in map form (Andreoli *et al.*, 1989). This map has been used to compile Figure 4.1 which superimposes contours, borehole positions and the road network over the geology.

The regional geology is best illustrated by the schematic stratigraphic profile developed by Malan and Viljoen (1990) and shown in Figure 4.2. Of the sequences shown in this Figure, at Struisbaai are exposed the Table Mountain Group, the Uitenhage Group and the Bredasdorp Group. Encountered but not exposed in outcrop is the Bokkeveld Group. The stratigraphic column for the regional geology is shown in Table 4.1.

Table 4.1 Struisbaai. Stratigraphic column for regional geology

Period	Group	Formation	Member	Thickness
Quaternary Tertiary		Bredasdorp	Wankoe De Hoopvlei	50 - 290 0.2 - 17
Cretaceous Jurassic	Uitenhage	Enon		
Devonian	Bokkeveld			
Silurian	Table Mountain	Rietvlei Skurweberg Goudini Cedarberg		
Ordovician		Pakhuis Peninsula		



GEOCHEMISTRY & ISOTOPES **WRC K5/481/0/1**

Figure 4-1
Geology of Struisbaal area . Bredasdorp cover removed
(Geology from AEC Report PIN 1133 (B/R) - GEA (July 1989))

Legend

Tracks	Contours (20m interval)
Spot Elevation	Borehole

SBR1 = Rain sampler
WL = Water level recorder
RG = Automatic Raingauge

Groundwater Group
Cape Water Programme
CSIR

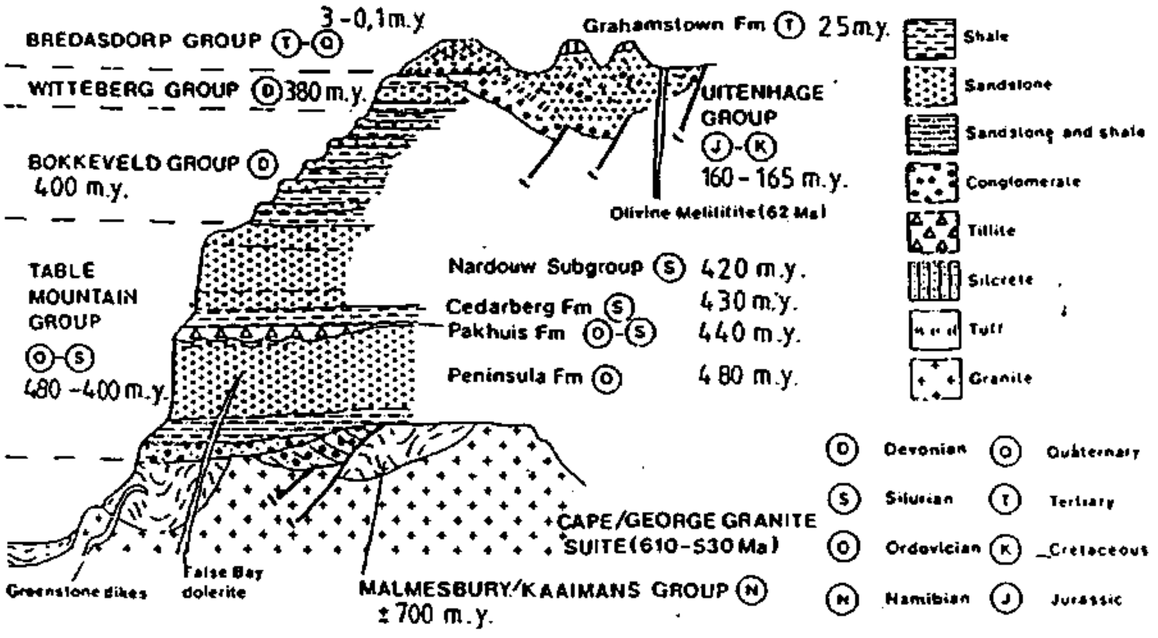
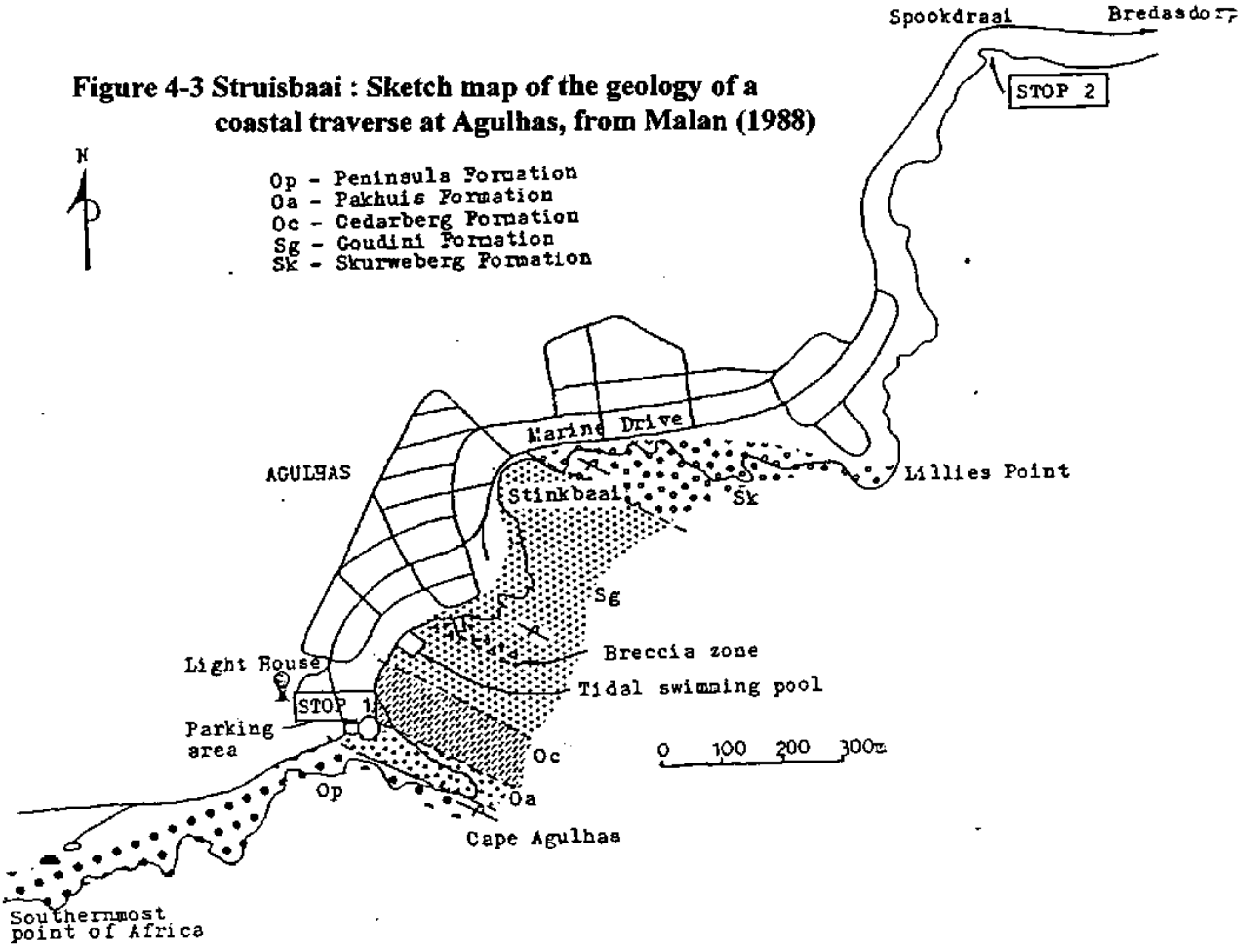


Figure 4-2 Schematic stratigraphic profile in the southern Cape Province Sketch not to scale, from Malan and Viljoen (1990)

Figure 4-3 Struisbaai : Sketch map of the geology of a coastal traverse at Agulhas, from Malan (1988)



4.1.2 Local Geology

The Struisbaai Peninsula is almost completely covered by Bredasdorp Group sediments. Examination of the surface contours of Figure 2.1 shows two parallel ridges running east-west with elevations of up to 156 metres compared to the surrounding countryside to the north which is at 20 metres. These two ridges are calcretised fossil dunes. The east-west direction reflects the prevailing wind direction which is still experienced today, namely west winds in winter bringing the main rain and east winds in summer which also produce rain, but less. Also evident on this figure are some inter-dune slacks. These are hollows from which there is no surface drainage. Field inspection of one of the slacks to the west of borehole G39941 showed solution features which will have a strong influence on recharge.

A traverse along the coast at low tide from Cape Agulhas eastwards to Spookdraai and further east to Struisbaai Point encounters a large part of the stratigraphy of the Table Mountain Group. This is due to the near vertical to overturned attitudes of the stratigraphy. This is shown in more detail in Figure 4.3 which is from the 1988 Agulhas Infanta Excursion Guide (Malan *et al.*, 1988).

The stratigraphic column of the TMG is shown in Table 4.2.

Table 4.2 Stratigraphic column of the Table Mountain Group outcropping in the Struisbaai area (after Levin, 1988 and Malan *et al.*, 1988).

Formation	Lithology
Rietvlei	Does not outcrop.
Skurweberg	White-grey thick-bedded quartzites.
Goudini	White to brown fine grained quartzites with subordinate siltstones and shales, interbedded bioturbated horizons.
Cedarberg	Highly tectonised greenish shales, siltstones and phyllite.
Pakhuis	Dark grey diamictite (tillite) with many small pebbles with overlying massive to cross bedded white quartzites (oskop member).
Peninsula	Medium to coarse grained white quartzite.

The only TMG formation which does not outcrop along the coast is the Rietvlei Formation. The Rietvlei Formation has a distinct magnetic characteristic and consequently has been identified from aeromagnetic surveys. On the AEC geological map (Andreoli *et al.*, 1989) this is shown and appears to the north-east of Figure 4.1. The nearest outcrop of Rietvlei Formation is at the Soetanysberg which is about 20 km westwards along the coast from Agulhas.

Bokkeveld Group rocks are not exposed in outcrop in the Struisbaai area. They have been intersected in boreholes and postulated (Andreoli *et al.*, 1989) to form a narrow strip along the north of the Struisbaai Peninsula as shown in Figure 4.1.

Further to the north (Figure 4.1) is a downthrown graben which has been filled with Enon conglomerates of the Uitenhage Formation. Being relatively soft rocks compared to the TMG quartzite they have been extensively eroded and form a rather flat featureless plain which one crosses when travelling to Struisbaai. There are isolated mounds which are overlying calcretes of the Bredasdorp Formation. Struisbaai Bay owes its presence to the protection provided by the TMG to the soft erodible Enon. About 10 km inland (NNE) of Struisbaai is Jubilee Hill which is an outcrop of Enon Formation exposed in the road cutting and the adjacent quarry. The author visited the site with the 1988 field trip and the notes provided for this trip have the following to say.

> "At this hill in the vicinity of Soetendalsvlei, outcrops of conglomerate interbedded with clay are exposed in a road cutting and adjacent quarry. The deposit itself is capped by surface-cemented gravels on a Tertiary erosion surface but the conglomerates appeared to resemble Enon deposits rather than basal conglomerates of the Table Mountain Group as they had previously been described. Outcrops in the quarry of rock similar to the diamictites of the Pakhuis Formation, TMG, led to further speculation. However, the clasts appeared to be derived from the Skurweberg and Rietvlei Formations of the TMG which outcrop extensively in the immediate vicinity.
>
> A borehole drilled to a depth of about 40 m (log attached) indicated mainly conglomerates with about 5 m of mudstone at 25 m depth and some layers of sandstone and gritstone. From 37.05 m to 37.9 m, the grit and conglomerates contained tuffaceous material. Thin section examination by R G Cawthorn of the Department of Geology of the University of Witwatersrand revealed a few shards of volcanic glass. Fragments of carbonised wood were identified as Gymnosperm by M Zavoda of the Botany Department at the same University.
>
> Air photo interpretation and field mapping were used to extend the occurrence of similar outcrops to a narrow trough of about 3 km in length and 1 km in width to the southeast of Jubilee Hill. This trough appears to be bounded by a fault on its northern side and by a sedimentary contact with rocks of the Table Mountain Group to the south.
>
> A gravimetric survey along the Struisbaai-Bredasdorp road indicates a graben or half-graben type of fault-trough about 2 km wide, to the north of Struisbaai and striking slightly north of west. This trough is likely to be related or connected to that at Jubilee Hill (Malan *et al.*, 1988)."

4.2 GEOMORPHOLOGY

The overall shape of the South African coastline is controlled by geological processes. The outline of the coast was formed by the splitting of Gondwanaland (Du Toit, 1922). The pre-Gondwana rocks are mostly hard and resistant to erosion, especially the quartzites of the TMG and thus readily forms rocky coastlines. By the end of the Cretaceous the present configuration of the coastline was established and the actual position of coastlines was determined by tectonic uplift and flexuring of the subcontinent and eustatic sea level movements caused by changes of the ice masses (Dardis and Grindley, 1988).

The local geomorphology at Struisbaai is characterized by an extensive wave-cut platform of post-cretaceous age mostly covered by a veneer of tertiary sediments. This wave-cut platform is about 20 km wide and has a NE-SW trend which is parallel to the coastline eastwards of Cape Agulhas. The inland border of this wave-cut platform stretches from the Soetanysberg, which is on the coast 14 km west of Struisbaai, and in a NE direction past the village of Bredasdorp towards Potberg. The wave-cut platform is about 1200 km^2 in areal extent and the elevation is between 10 m and 30 m above present sea-level. For the Struisbaai peninsula the elevation has been measured in a number of boreholes and is shown in Figure 4.4. As can be seen this contact has an elevation varying from 8.7 mamsl to 16.5 mamsl.

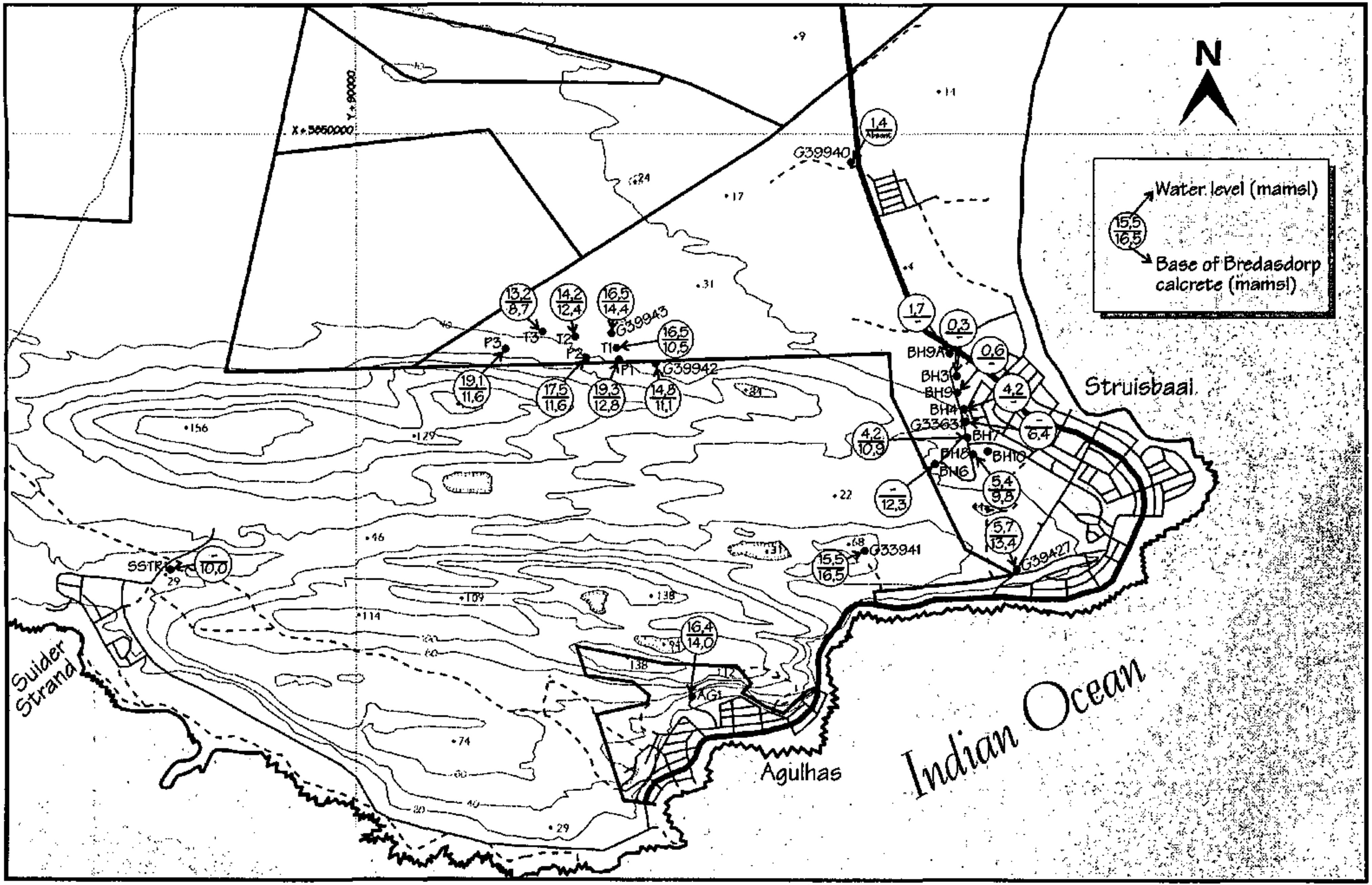
Unconformably overlying this wave-cut platform are the local marine and upper aeolian units of the Bredasdorp Group. The local marine De Hoopvlei Formation varies between 0.2 and 17 m and the aeolian Wankoe Formation is 50 to 290 m thick (Malan, 1988). The De Hoopvlei Formation is a shelly limestone with a local calcirudite and overlying calcarenite. The Wankoe Formation comprised of back shore aeolian sand dunes which lie parallel to the coastline. Examination of Figure 1.3 shows two of these east-west oriented sand dunes. Subsequent to deposition calcretization took place resulting in the present-day strong topographic highs which are resistant to weathering. Nevertheless chemical weathering has occurred and there are a number of surface karst features. Interconnected solution pathways have resulted in caves at the basal contact being common along the coastline. These also result in the numerous springs encountered along the coast, eg at Die Kelders and Stilbaai these springs form the main water-supply for these coastal resorts.

Inland of the Agulhas peninsula the Bredasdorp forms a thin veneer over the underlying geology. This has resulted in very flat topography with vleis, salt-pans and wetlands being common.

4.3 SEA-LEVEL TRANSGRESSIONS AND CONNATE SEAWATER

A sometimes used explanation for groundwater salinities, especially when high salinities are encountered is to ascribe it to rock-bound residual seawater. This is explained either as being from when the rock was deposited as a marine deposit (connate salinity) or from a period of marine transgression when the groundwater was replaced by seawater. The high salinities encountered in shales of the Malmesbury Formation and of the Bokkeveld Formation are usually explained as being derived from connate salinity.

An example of this explanation is from the Breede River Valley. The high and increasing salinities encountered from agricultural return-flow drains are explained as due to farmers developing new fields or ploughing deeper, thus exposing fresh rock-faces to percolating water and thus allowing connate salts to be dissolved (Greef 1991, 1994). Similarly if one collects fresh drill cuttings from a borehole in either of these formations and soak them in water, the salinity of the water increases due to salts being leached from the fresh rock faces exposed on these drill chips.



GEOCHEMISTRY & ISOTOPES **WRC K5/481/0/1**

Figure 4-4

Map showing the relationship of the calcrete/quartzite contact to water levels of August (Both in MAMSL)

Legend

Tracks

•74 Spot Elevation

Farm Boundaries

Contours (20m interval)

•BH8 Borehole

0 0,5 1,0
kilometre

Groundwater Group
Cape Water Programme
CSIR

The calcretes of the Bredasdorp Group have been exposed to seawater both during deposition and during subsequent marine transgressions. An argument for the salinities of the groundwater could be that it is derived from residual seawater. It is not doubted that leaching of the Bredasdorp does occur during rain infiltration as the groundwater has high calcium and alkalinity which is not obtained from the quartzites.

However, over the last 50 000 years the sea-level around the southern African coast has been below its present level, as is shown in Figure 4.5.

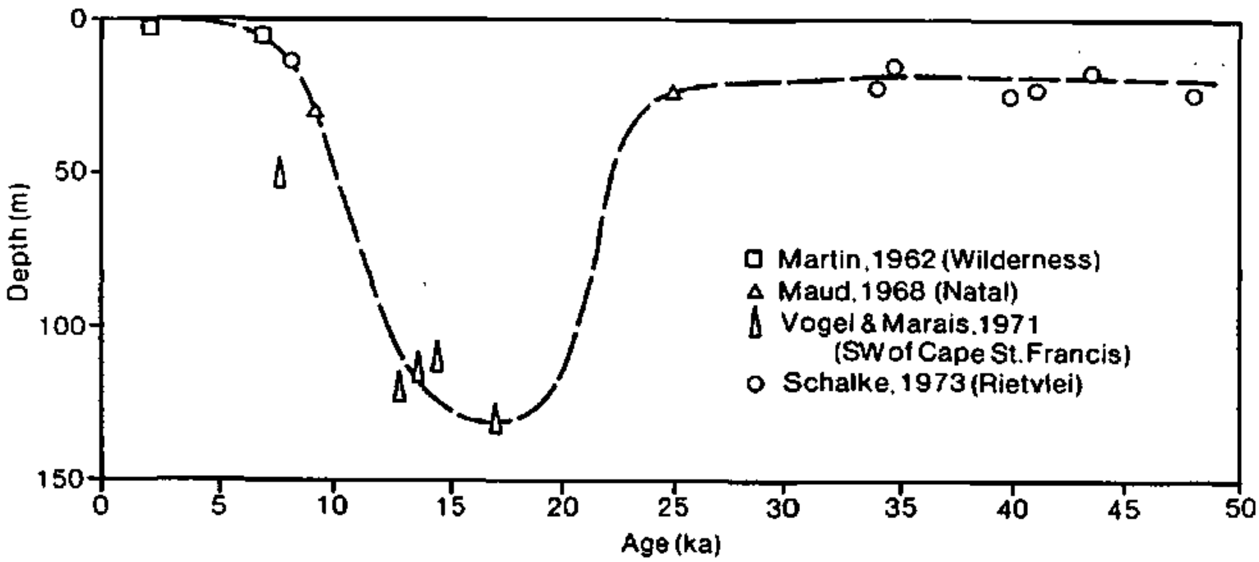


Figure 4-5 Late Quaternary southern African sea-level changes (after Tankard (1976) and Dardis and Grindley (1988))

Figure 4.5 shows that historic sea-levels have always been below current sea-levels. However, there is evidence that for a brief period between 6000 and 5000 B.P. sea-levels were up to 3 metres above present levels (Yates *et al.*, 1986; Miller, 1990; Miller *et al.*, 1993). This sea-level nevertheless is lower than the wave-cut platform which is at + 8.7 to + 16.5 mamsl.

Now if sea-level has been mostly below the present sea-level it has also been below the base of Bredasdorp in the Agulhas Peninsula and the coastal plain. With the relatively high permeability encountered for calcrete it is improbable that after 50 000 years that connate seawater is still encountered in sufficient quantities as to be a cause of the high salinities encountered.

Toens (1991) carried out a hydrocensus of the area up to the Heuningnes River which is 14 km north of Struisbaai and found high salinities of up to 1200 mS/m. This was associated with Bokkeveld Formation shales and these salinities could very well be connate salinity.

4.4 CONCLUSIONS REGARDING CONNATE SEAWATER

In the Agulhas peninsula there is a wave-cut platform at an elevation of 8.7 to 16.5 mamsl. The basal rocks are quartzites of the TMG and unconformably overlying this wave-cut platform are calcretes of the Bredasdorp Formation.

For the last 50 000 years sea-levels were mostly below the current sea-level. For a brief period 6000 to 5000 B.P. sea-level was + 3 mamsl. This is below the wave-cut platform which is + 8.7 m to + 16.5 mamsl. As the calcretes have some permeability it is highly unlikely that there is sufficient residual connate seawater which could give rise to the salinities encountered in the Struisbaai water-supply.

The conclusion is thus that connate seawater is not the source of salinity in Struisbaai water-supply.

* * *

CHAPTER 5

HYDROGEOLOGY OF THE STRUISBAAI AREA

5.1 OVERVIEW

In the Struisbaai Peninsula there are two geological formations which each have an important role to play in controlling the hydrogeology. The TMG quartzites which have been wave-cut to form a flat topped unit and the overlying calcretes of the Bredasdorp are the role players.

Minor other aquifers lie to the north of the NW-SE trending thrust fault, these are the Bokkeveld shales and north of the NW-SE trending graben fault are the Uitenhage Formation sediments.

5.2 QUARTZITES OF THE TMG

Geological mapping shows three quartzite formations, Skurweberg, Goudini and Peninsula (Figure 4.1). In terms of groundwater hydraulics these can be lumped together as one aquifer. They are all quartzites which effectively have no primary porosity as lithification has remobilized quartz which has filled the voids between the original sand grains. Secondary porosity associated with weathering and micro-fracturing forms the storage which is exploited by boreholes which intersect the larger and more open fractures. The quartzites are very competent thus during deformation the fractures that form tend to stay open and to stay open to great depths. Elsewhere in the Cape Province are found numbers of hot springs all of which are associated with TMG quartzites. This confirms that these fractures remain open at great depth. Examination of the geology map (Figure 4.1) shows that a number of faults have been recorded. These are a variety of types and are of different ages. In the bottom right corner of Figure 4.1 are listed the various structural features. It is seen on this map that both the old and the new wellfield have faults recorded in the vicinity.

Drilling and test-pumping records for the old wellfield boreholes do not exist. The only available data is from Meyer's (1986a and 1986b) reports on Struisbaai and Agulhas. The data for Struisbaai is shown in Table 5.1 below.

Detailed borehole logs as well as test-pumping data are available for the three production boreholes P1, P2 and P3 from the new wellfield. Also available are drill records but no test pumping for the boreholes G39940 to G39943. These are presented in Appendix 1 (drilling logs) and Appendix 2 (test-pumping data). Down hole geophysics is presented in Appendix 4.

From these data the elevation of the calcrete/quartzite contact can be determined as well as the depth of the main water strikes below this contact. This is numerized in Table 5.2. The calcrete/quartzite contact and water-level data is also depicted in Figure 4.4.

Table 5.1 Struisbaai. Borehole details for the old wellfield (from Meyer, 1986a)

Borehole No.	Depth (m)	Tested delivery (L/s)	Water-level (mbd)	Water-strike (m)	EC (mS/m)	Water-levels (1994) (mbd)	Remarks
3	?	6.3	?	?	?	4.5	Abandoned. Collapsed.
4	85	11.3	9.10	?	?	-	Pump not working.
5	90	8.6	?	?	?	10.3	Not in use, equipment blocking borehole.
6	117	7.5	9.14	35-85	153	4.76	Pumping @ 5 L/s. Production borehole.
7	153	13.9	10.67	137-139	148	9.0	Pumping @ 7.6 L/s. Production borehole.
8	130	13.3	12.19	56-107	145	10.6	Pumping @ 7.6 L/s. Production borehole.
9	123	8.8	8.00	?	167	-	Pumping @ 8.8 L/s. Production borehole.
9A	*	*	*	*	*	2.3	Abandoned due to poor quality water. Position approximated.
10	88	8.8	?	?	?	-	Pumping @ 8.8 L/s. Production borehole.

*No details. Poor quality water. Possibly drilled into Bokkeveld shales.

Table 5.2 Struisbaai. Table showing the calcrete/quartzite contact elevation, water-strike position and water-levels.

Borehole No.	**Calcrete/quartzite contact elevation (mamsl)**	**Main water-strike (mamsl)**	**Water-level (mamsl)**
AG1	14.0	13 to 14	16.4
BH6	12.3	-20 to -70	11.3
BH7	10.9	-120 to -124	4.2
BH8	9.8	-38 to -90	5.4
BH9	-	-	0.6
G39927	13.4	-28 to -36**	5.7
G39941	16.5	-4*	15.5
G39942	11.1	-25*	14.8
G39943	14.4	-16*	16.5
P1	12.8	-13 to -46	19.3
P2	11.6	-30 to -60	17.5
P3	11.6	-55 to -71	19.1
T1	10.5	-	16.5
T2	12.4	-	14.2
T3	8.7	-	13.2
** From down hole log * First water-strike			

Examination of Table 5.2 shows that the calcrete/quartzite contact varies from 8.7 to 16.5 mamsl and excluding the lowest and highest there are 12 records of contacts which are between 9.8 and 14.4 mamsl. The water-level in the old wellfield area is mostly a few metres below this contact and for AG1 and the new wellfield it is a few metres above this level. This shows how uniform was the wave-cut platform.

Most notable, however, is that the water-strikes in the quartzites are all well below this contact and thus is also well below sea-level. Two cross-sections have been drawn, Figure 5.1 being north-south and Figure 5.2 east-west. These two figures show these water-strikes and the "zone of water-strike" which has been assigned a relatively high permeability factor. This could be a bit misleading in that the impression is given that there is only this single water-bearing zone. However, if a very deep borehole were to be drilled there will quite likely be more water intersections at greater depths.

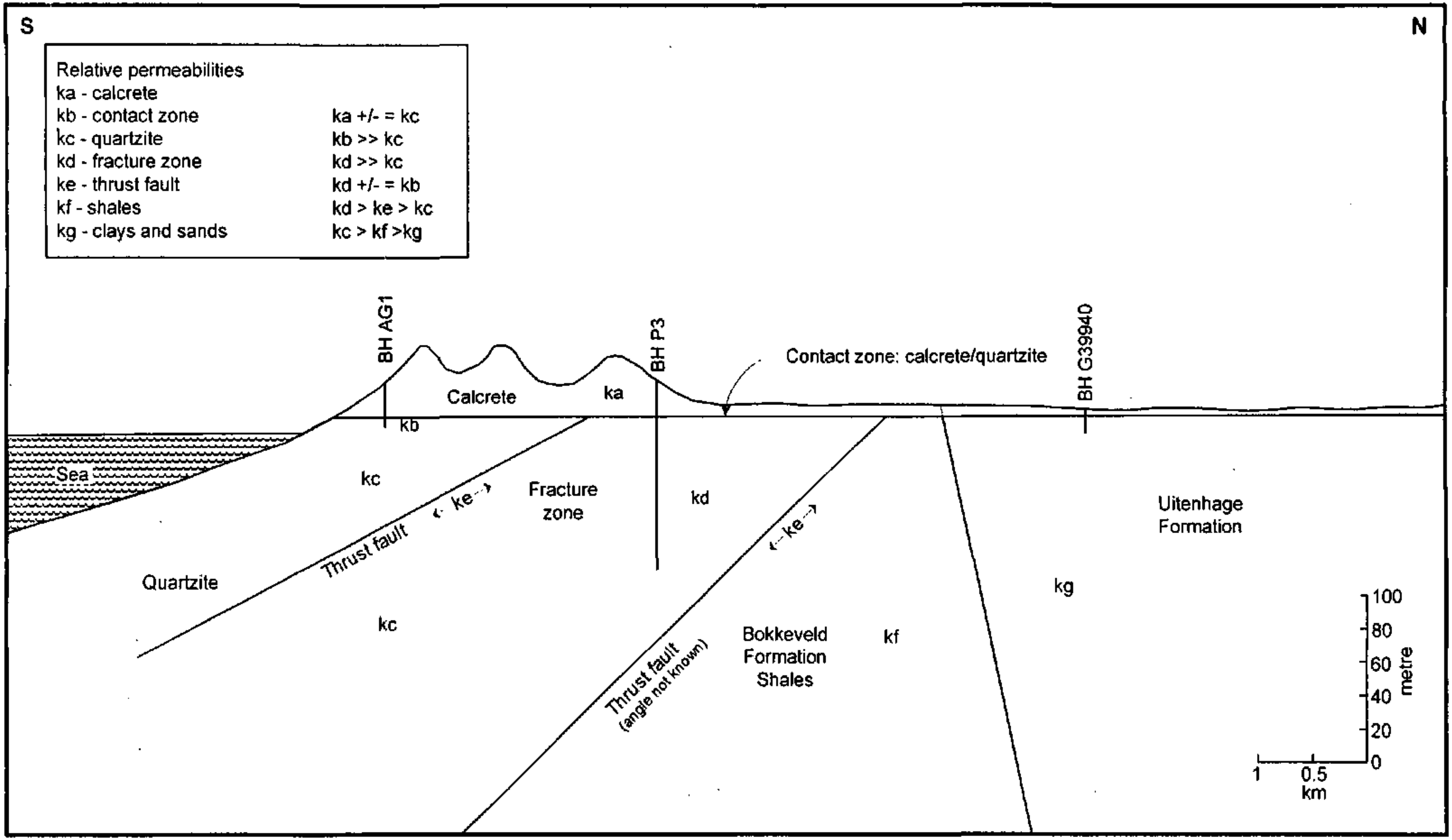


Figure 5-1: Struisbaai N-S geological sketch section (not to scale with vertical exaggeration of about 12 times)

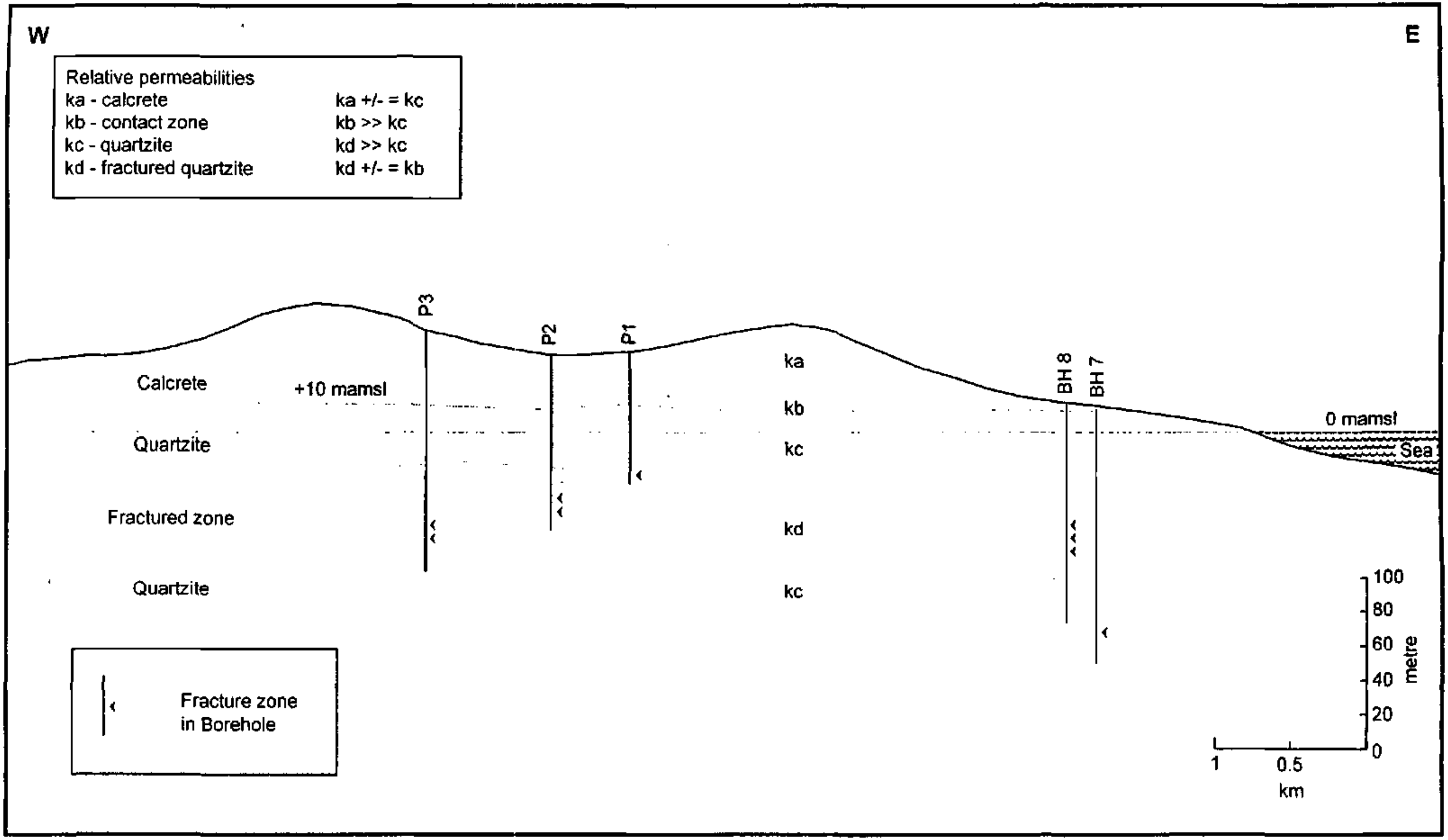


Figure 5-2: Struisbaai E-W section (roughly to scale)

Examining the data for the old "wellfield" it is seen that the water-levels are about 4 to 5 m above sea-level, with water-strikes up to 124 m below sea-level. Using the Ghyben-Herzberg relationship of 1:40 this would indicate that the saline interface is 160 to 200 m below surface. With the high hydraulic conductivities associated with fracture flow it is quite feasible that this interface could be drawn into the boreholes zone of influence. Up-coning would be a mechanism which would pose considerable danger of inducing salinity.

5.2.1 Test-pumping of boreholes in TMG quartzites

There are three boreholes for which proper test-pumping has taken place. The test pumping exercises for each borehole has been:

- multiple rate test comprising four to five steps of one hour each
- recovery test for multiple rate test
- constant discharge test of 72 hours
- recovery test of 70 minutes for P1, 200 minutes for P2 and for P3

The various test pumping curves are presented in Appendix 2. Also shown on these curves are the hand drawn straight lines which have been used to calculate transmissivity according to the Jacob Straight Line Method (Kruseman and De Ridder, 1991, Hazel, 1975).

From the McLea (1990, 1991) reports no data has been given for drawdowns measured in the observation boreholes. The only information given is the following:

"A drawdown of 2.2 m occurred in borehole P1 after 72 hours of pumping in P2, a distance of 280 m away" (McLea, 1990) and

"Monitoring of the existing borehole No. P2 was carried out during the 72 hour constant delivery test. The existing borehole No. P2 was monitored for the duration of the 72 hour test and showed only very slight fluctuations of less than 0.03 m over the period and returned to the static water level, at the end of the recovery period" (McLea, 1991). The distance of P3 to P2 is 710 metres. Thus no other analytical method can be used to determine transmissivity other than using Jacob Straight Line. The test pumping data and results are summarized in Table 5.3.

5.2.2 Analysis of test-pumping data

The test-pumping curves show two stages of reaction of the aquifer to pumping. The first stage (early curve) is the reaction of the fracture to pumping and the second stage (late curve) is that of the micro fractures and weathered quartzite. This is the double porosity model for fractured rock. The curve has a similar shape to that of a primary aquifer with leakage, except that for a fractured rock environment the second stage can continue indefinitely. Transmissivity has been calculated for both stages and presented in Table 5.3. It must be appreciated that although the transmissivity of the fracture is lower than that of the matrix the hydraulic conductivity of the fracture will be much higher. The hydraulic conductivity is not calculated as the thickness of the fracture is not known. For modelling purposes and long-term prediction of aquifer behaviour the late curve (second stage) transmissivity is used.

Storativity is calculated using formula 3.10 on page 66 of Kruseman and De Ridder (1991).

$$S=\frac{2.25kDt}{r^2}$$

where kD = transmissivity = 100 m^2/d
t = time = 3 days
r = radius P1 to P2 = 280 m

$$=\frac{2.25\times100\times3}{280\times280}$$

$$=8.6\times10^{-3}$$

This value is in the range that is generally observed and accepted for fractured rock aquifers.

Table 5.3 Struisbaai. Test-pumping data for new wellfield boreholes P1, P2 and P3 (from McLea, 1990; 1991)

Borehole No	**P1**	**P2**	**P1 (OBS)**	**P3**
Elevation of water strike (mamsl)	-13 to -38	-29 to -59	P2 (Pumping)	-55 to -67
Test rate m^3/hr	25.2	46.0	46.0	34.8
Drawdown at end of constant rate CD (m)	11.7	21.3	2.2	24.7
Residual drawdown after 3.3 hour recovery (m)	0.7	1.2	?	0.2
Elevation of drawdown at end of CD test (mamsl)	+7.6	-3.9	15.2	-5.6
EARLY CURVE T from Jacob Str. Line Pumping Recovery	25 35	29 30	No data	17 13
LATE CURVE T from Jacob Str. Line Pumping	205	145	No data	182
Storativity	-	-	8.6 x 10^{-3}	-
Transmissivity and storativity calculated by Weaver (the author) from the McLea test-pump data.				

5.3 CALCRETES OF THE BREDASDORP GROUP

The calcretes have an important role in influencing recharge. On surface are observed many solution features. Internal drainage features can be seen between the ridges of the fossil dunes.

The second important feature of the calcretes is found at the basal contact with the underlying quartzites. At this contact is often found a cavernous solution cavity. This feature possibly has a strong control on the hydrogeology in that the hydraulic conductivity is very high and this acts as a drainage feature providing an upper limit to the water-table. High-yielding springs at this basal contact are a feature of the South Cape coast, eg. at Stilbaai and the Kelders.

Borehole AG1 is exploiting groundwater from this contact zone. This borehole intersected the cavity at 21 m below surface and drilling was stopped at 22 metres. The water-level is at 18.6 m which means that there is 2.6 metres of available drawdown. A pumping rate of 31.5 L/sec for 48 hours was sustained which indicates the very high hydraulic conductivity of this contact zone. Unfortunately no drawdown data is available and thus transmissivities cannot be calculated.

5.4 SHALES OF THE BOKKEVELD GROUP

No outcrop is exposed and no information is available for the strip of shales to the north of the quartzites. Further north from the Enon infilled graben, Toens (1991) in a hydrocensus identified boreholes drilled into the Bokkeveld shales. He did not note any hydraulic information, merely ascribing the high measured salinity to being derived from the shales.

5.5 ENON GROUP

No hydraulic information is known for this formation.

★★★

CHAPTER 6

HYDROGEOCHEMISTRY AND ISOTOPES

6.1 OVERVIEW

As mentioned in Chapter 1.3 the original investigation was aimed at determining variations of groundwater chemical and isotopic content with time and relating these variations to groundwater reservoir capacity. No variations of any significance were observed and after one year monitoring was discontinued. The data are presented in Appendix 3.

Considering two of the production boreholes, AG1 which supplies Agulhas and P3 supplying Struisbaai, if one examines the data then this reasoning for stopping the monitoring is illustrated. AG1 has C^{14} of 45% which is taken to be old water, while P3 has C^{14} of 83% making this water old but younger than AG1. Table 6.1 below shows selected determinants and the observed consistent results over a period of about two years.

Table 6.1 Struisbaai. Selected determinants from two production boreholes illustrating the consistent results.

Date of sampling		4/3/93	27/10/93	15/4/94	28/8/94	6/12/94
AG1 Agulhas						
Chloride	mg/L	347	359	356	364	367
Silica	mg/L	4.4	3.8	3.8	3.9	3.9
Alkalinity	mg/L	215	228	216	217	212
C^{14}	PMC	45.5	46.3	45.1	45.3	44.7
$\delta^{18}O$	$^0/_{00}$	-4.8	-4.7	-4.7	-	-5.0
P3 Struisbaai						
Chloride	mg/L	139	142	138	140	147
Silica	mg/L	4.8	4.1	4.3	4.4	4.2
Alkalinity	mg/L	208	220	209	238	208
C^{14}	PMC	84.1	83.2	82.6	84.1	82.3
$\delta^{18}O$	$^0/_{00}$	-4.9	-4.8	-4.0	-	-5.1

6.2 DISCUSSION OF HYDROCHEMICAL DATA

As the results show little variation with time an average of the results has been calculated and is presented in the data sheets of Appendix 3 in the final column of data for each borehole. This data has been used to prepare the tri-linear plot or Piper diagram of Figure 6.1.

Piper Diagram

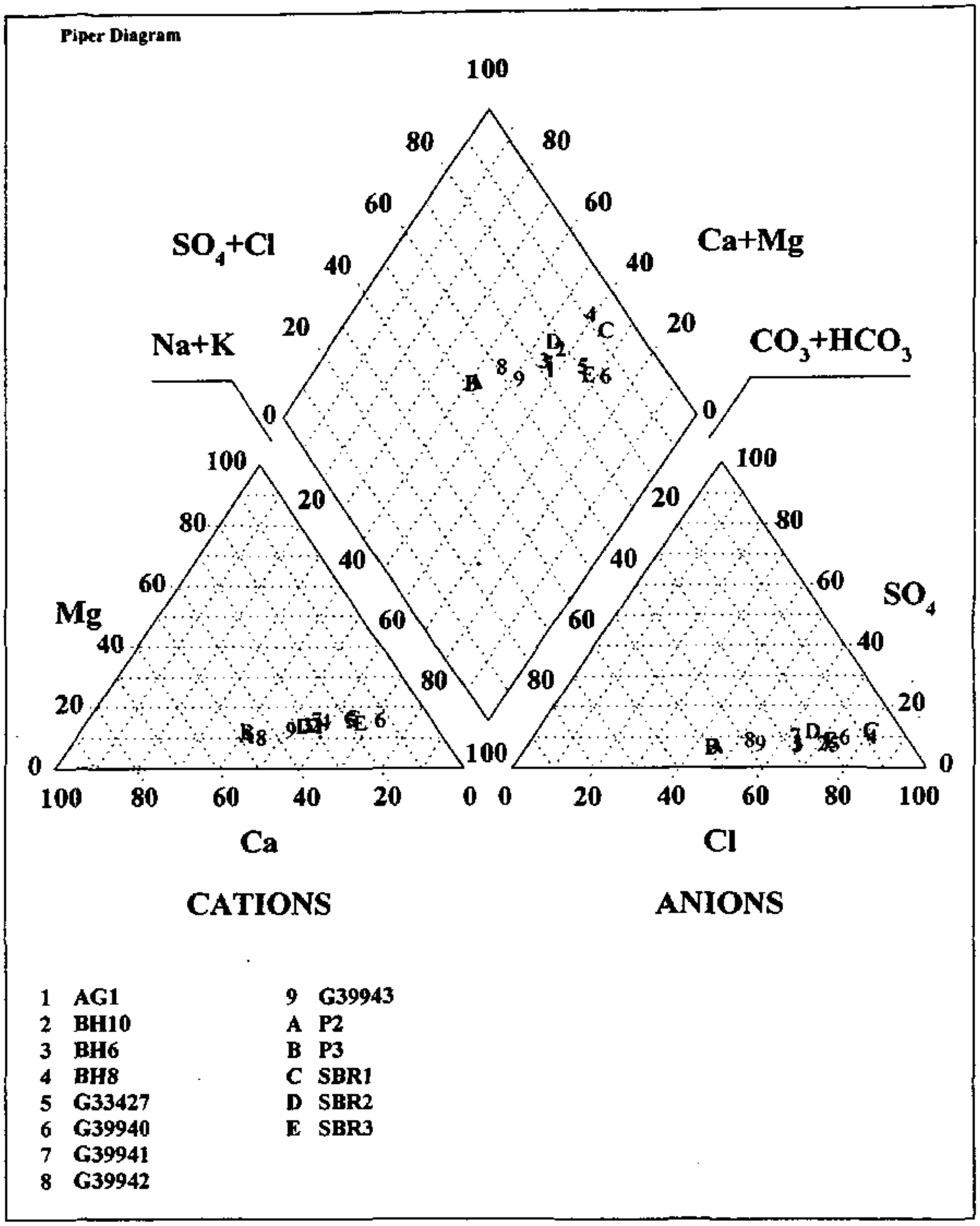


Figure 6-1 Struisbaai : Piper diagram of groundwater from sampled boreholes and rainwater from rain-collectors

For the Piper diagram the left corner represents newly recharged water which is relatively high in calcium magnesium and alkalinity, and low in sodium, and chloride. The right hand corner is regarded as stagnant water or old water from the discharge zone of an aquifer. Also the right hand corner represents sea water (Johnson, 1975; Mazor, 1991; Lloyd and Heathcoate, 1985).

Mazor (1991) further shows that the straight line joining these two end points represents mixing of waters from these two end points. This is shown in Figure 6.2.

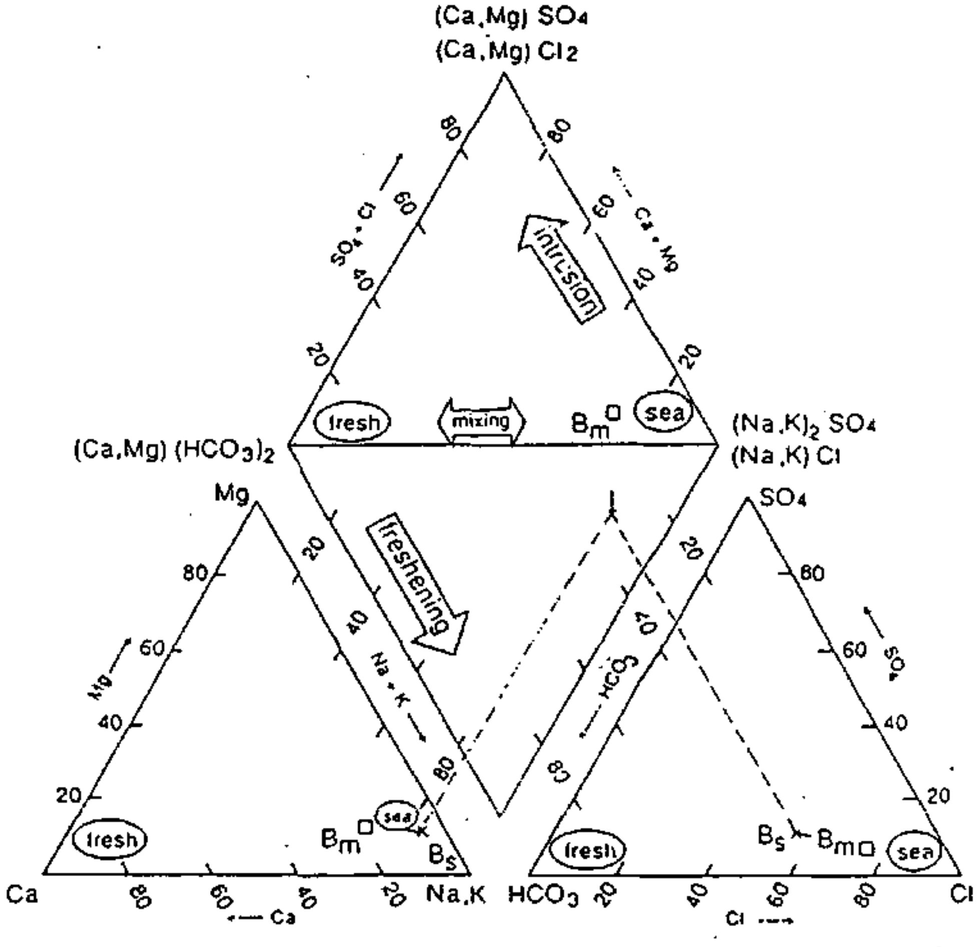


Figure 6-2 Piper diagram showing average compositions of fresh water and seawater (from Mazor 1991)

Also shown in Figure 6.2 are the two directions in which chemistry will plot for an aquifer which is either in the process of flushing out, saline water "freshening", or is being subject to saline intrusion. Comparing Figure 6.1 to Figure 6.2 it is seen that all these boreholes plot in the mixing zone except perhaps for borehole BH8. Note also that SBR1 the rain sampler with the more salty (Na and Cl) water also plots along this line. This would support the saline rainwater theory. The connate water theory for the origin of salinity would plot on the freshening area of the piper plot, while seawater intrusion would plot on the intrusion part of the diagram. BH8 could be considered to be in the intrusion area of this graph. This is discussed further in Chapter 6.5.2.

A number of graphical plots of one chemical determinant versus another have been prepared and presented as Figures 6.3 to 6.9. Also plotted on these Figures is the seawater mixing line which has been derived from Table 3.5.

Figure 6.3 is chloride versus sodium. Notable on this figure is the very close correlation of the boreholes with the seawater mixing line. This indicates that the salinity of these boreholes is derived from either seawater intrusion or sea-spray and not from connate salts. Also plotted is the crystalline sodium chloride ratio. This would represent solution of crystallised sea salt. It is noted that G39940 plots between these two mixing lines. This could mean that the salinity encountered in G39940 is a mixture of seawater/sea spray and residual crystalline salt from previous seawater transgressions.

Figure 6.4 is chloride versus potassium. There is a reasonable correlation with the seawater mixing line supporting seawater intrusion or salt spray.

Figure 6.5, chloride versus calcium, shows that all samples are enriched in calcium compared to the seawater mixing line. This represents calcium dissolved from the limestone during rainwater recharge.

Figure 6.6 shows chloride versus magnesium. This shows a very good correlation with the seawater mixing line showing that the magnesium is derived from either seawater intrusion or salt-spray. During salt water intrusion dolomitization processes which characteristically accompany saline intrusion (Fidelibus and Tulipano, 1991; Mazor, 1991) tends to reduce the magnesium concentration in the mixed water. This is, however, a slow process.

It is noted that G39940 and BH8 do plot slightly below the seawater mixing line indicating that there could be some dolomitization effect. All the waters are regarded as salt spray mixing or young salt water intrusion.

Figure 6.7 shows chloride versus sulphate. There is a good correlation to the seawater mixing line.

Figure 6.8 shows chloride to strontium. All analyses show enrichment of strontium. This strontium is derived from dissolution by percolating rainwater of the calcretes which were derived from seashells. The strontium levels are thus enhanced similar to calcium.

Figure 6.9 shows chloride versus iodine. Iodine levels are enriched versus the seawater mixing line. It is thought that this iodine, similar to strontium, is derived by percolation of rainwater. No literature could be obtained mentioning this phenomenon.

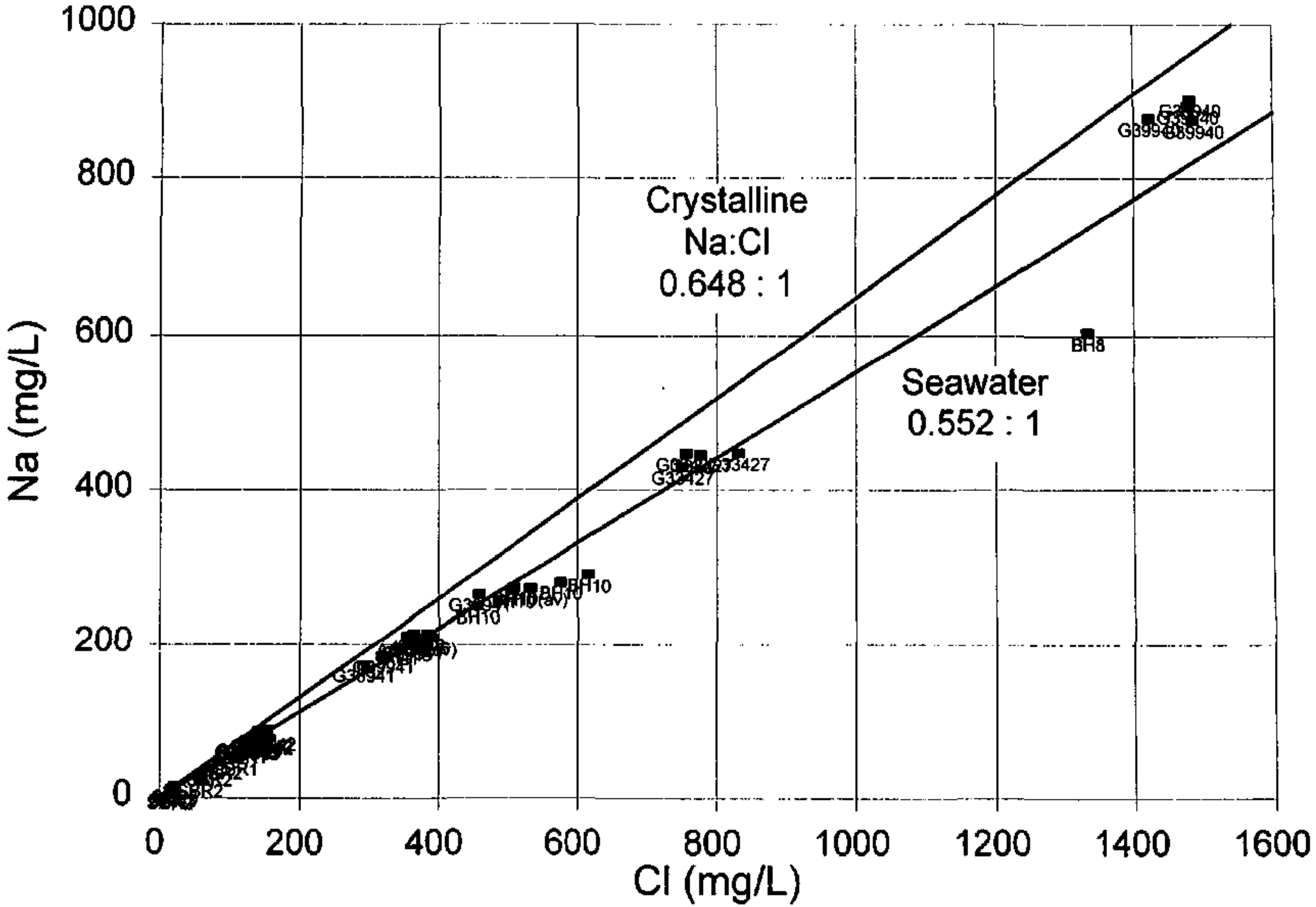


Figure 6.3: Struisbaai. Chloride versus Sodium

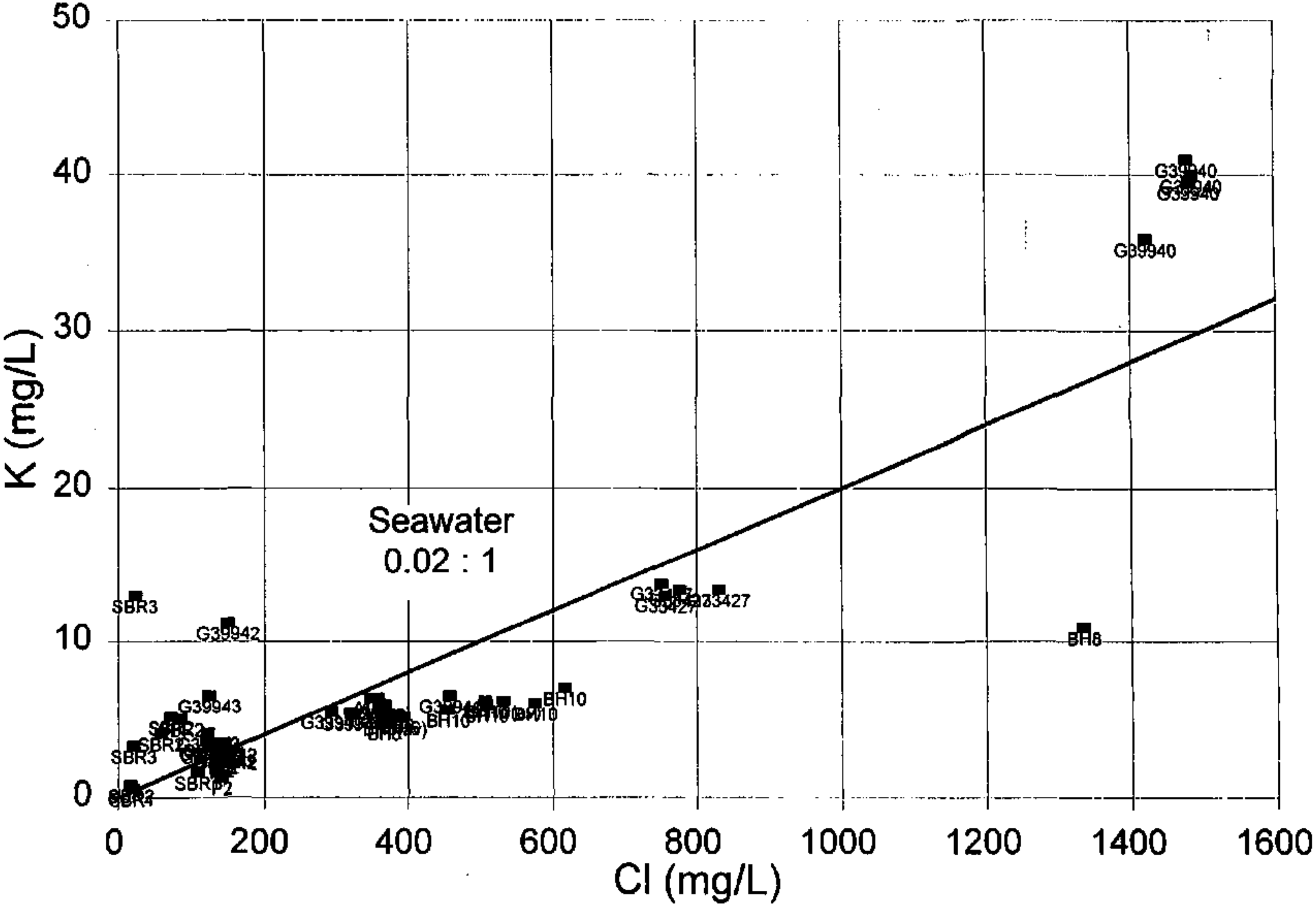


Figure 6.4: Struisbaai. Chloride versus Potassium

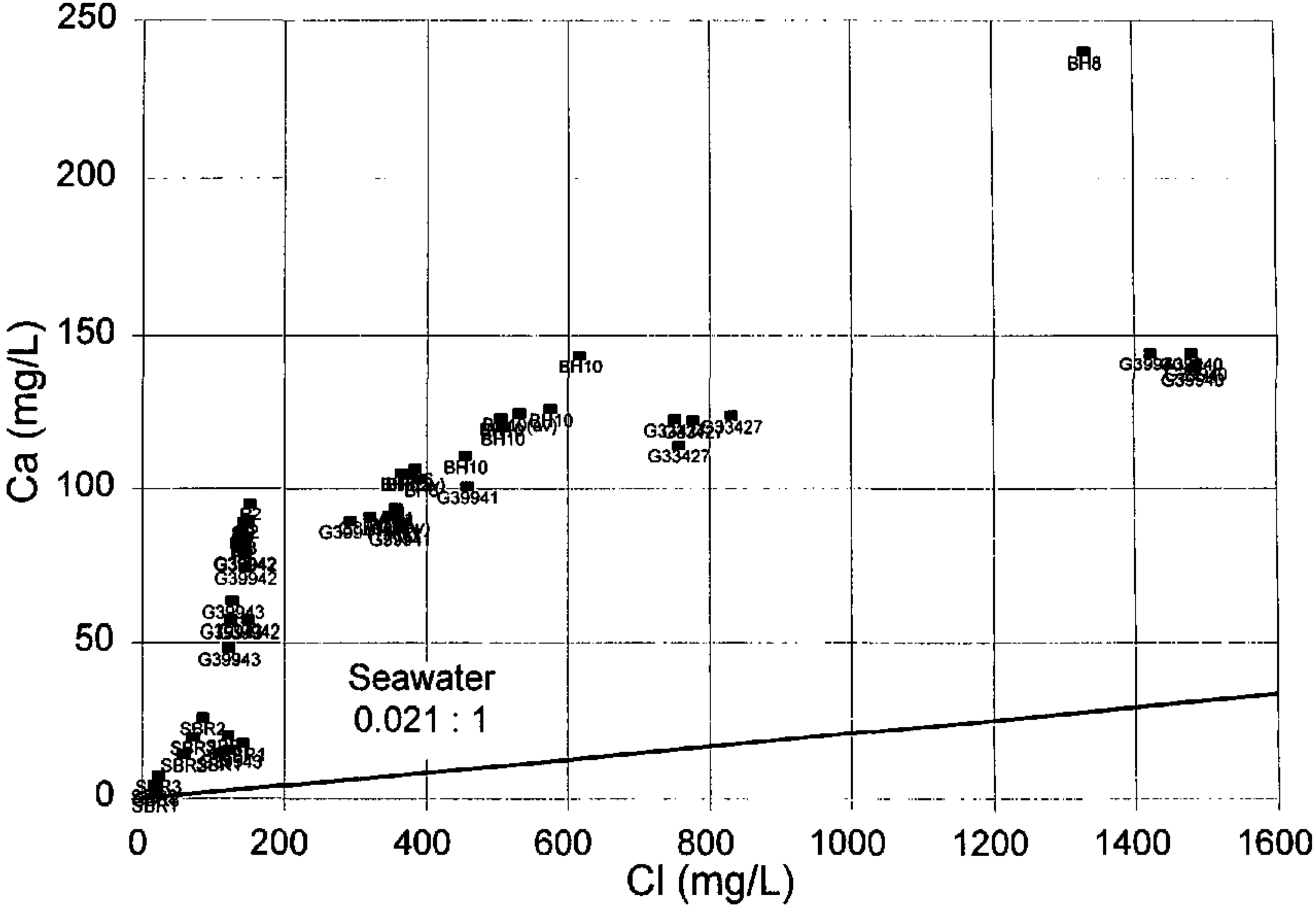


Figure 6.5: Struisbaai. Chloride versus Calcium

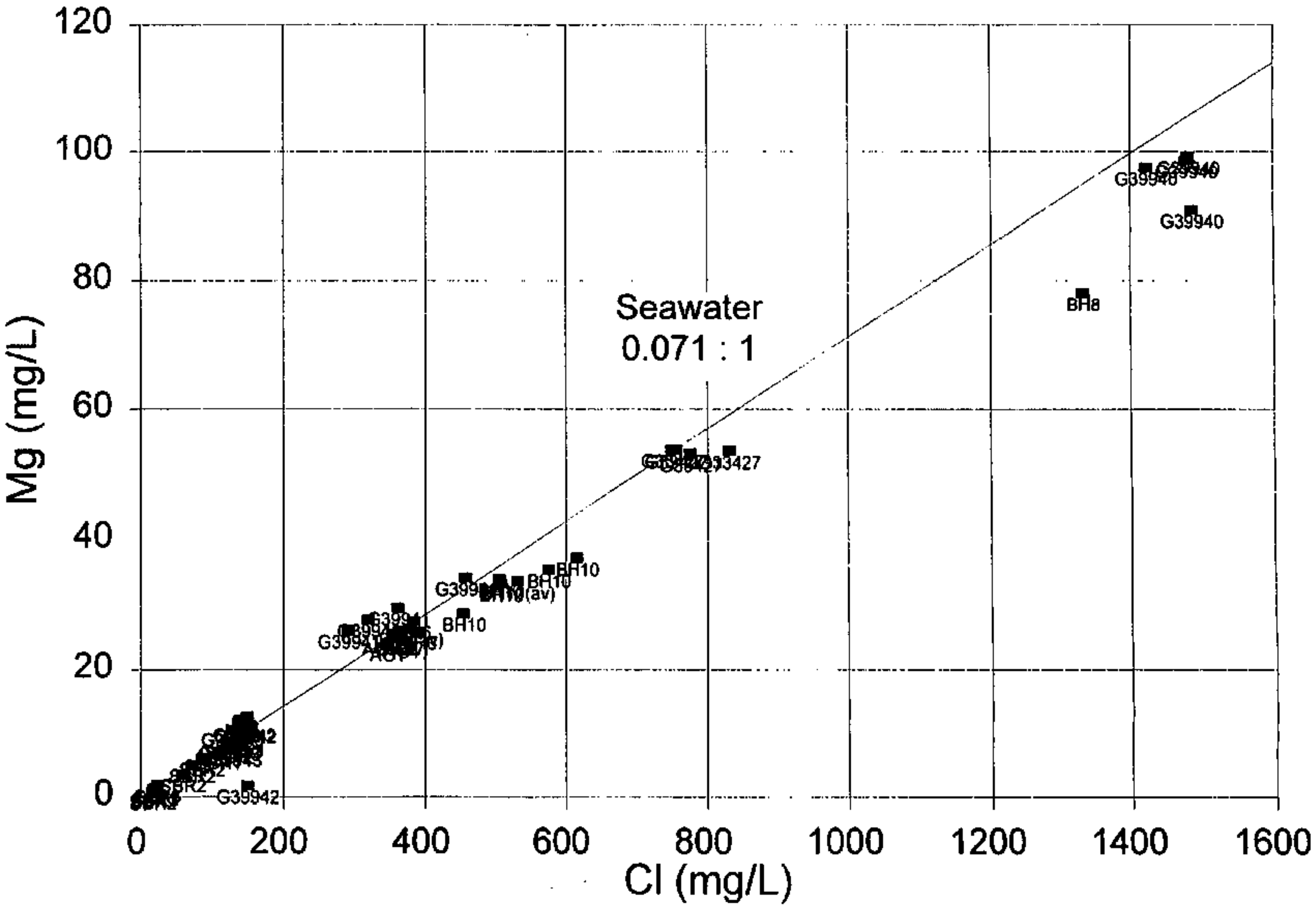


Figure 6.6: Struisbaai. Chloride versus Magnesium

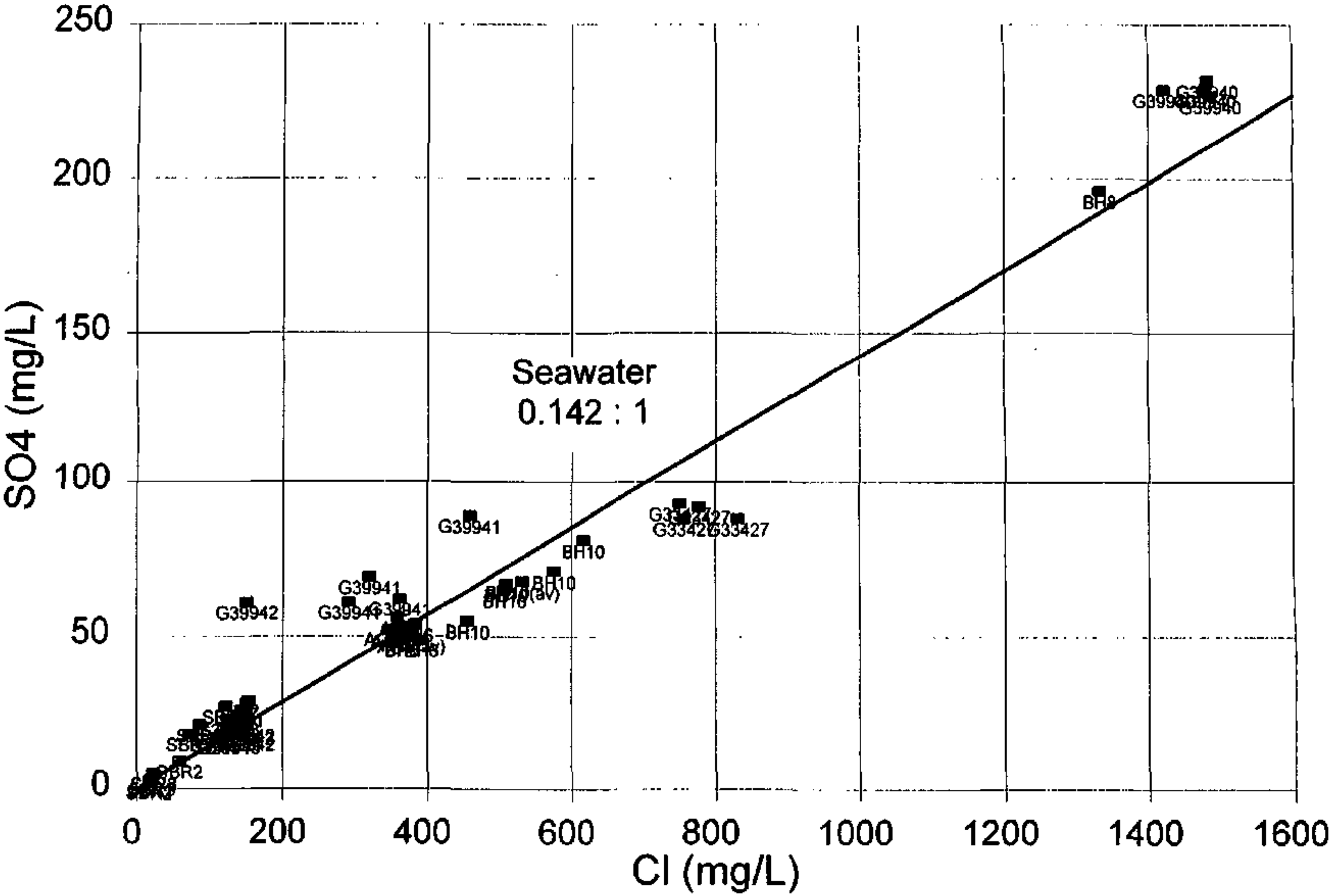


Figure 6.7: Struisbaai. Chloride versus Sulphate

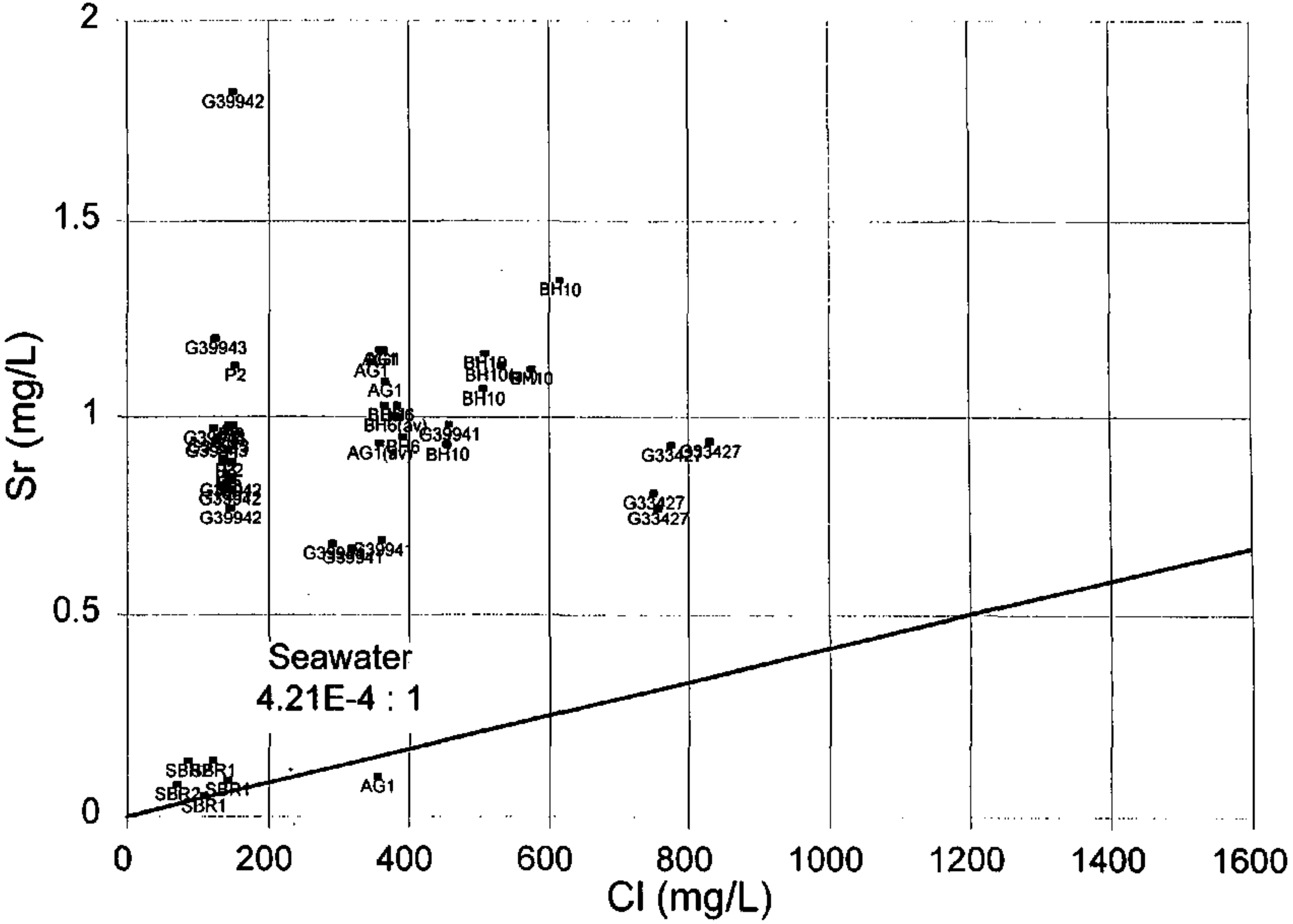


Figure 6.8: Struisbaai. Chloride versus Strontium

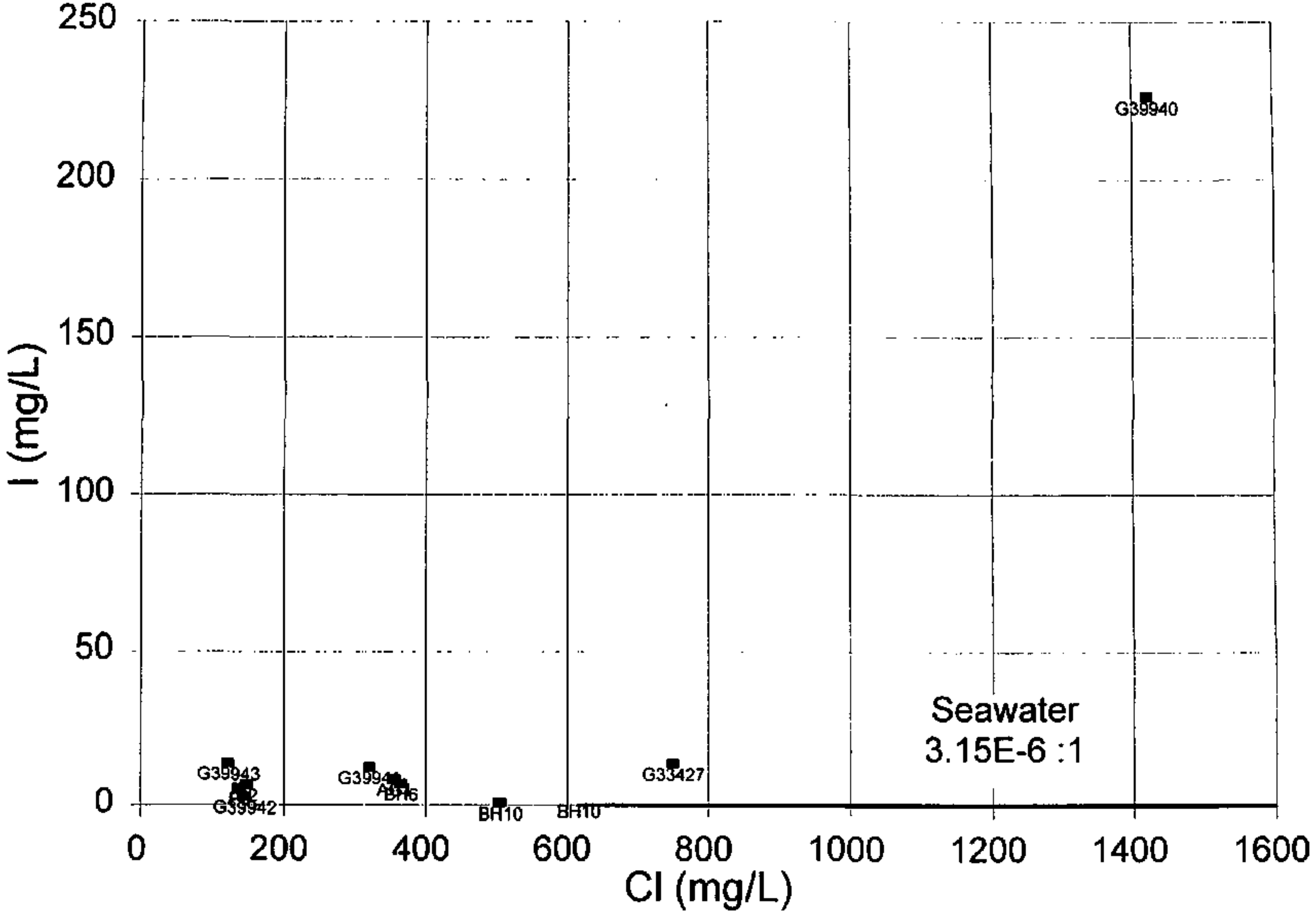


Figure 6.9: Struisbaai. Chloride versus Iodine

6.2.1 Conclusions from Chemistry Overview

- The Piper diagram shows that all boreholes fall on a mixing line between the left and right corners of the triangle. BH8 appears to be on the saline intrusion mixing line extending towards the top corner.

- Calcium and strontium are enriched by solution of calcretes during recharge.

- Sodium, chloride, potassium, magnesium and sulphate all fall on the seawater/sea spray mixing line thus indicating that there is no other source for these ions. This precludes the shales of the Bokkeveld being a source of salinity. Calcrete being composed of quartz, sand and calcium carbonate can only contribute calcium and strontium. Quartzites of the TMG being inert will not contribute any ions.

6.3 USES OF ENVIRONMENTAL ISOTOPE HYDROLOGY IN GEOHYDROLOGY

The naturally occurring stable isotopes, hydrogen (H), deuterium (D), oxygen-16 (^{16}O), oxygen-18 (^{18}O), carbon-12 (^{12}C) and carbon-13 (^{13}C) and the radioactive forms, tritium (T) and radiocarbon (^{14}C), have become useful tools in groundwater studies. The main hydrogeological use of environmental isotopes can be summarised as follows:

- to provide a signature to a particular water type;
- to identify the occurrence of mixing two or more water types;
- to provide residence time information about groundwater;
- to provide information concerning travel times and groundwater velocities;
- to provide information on water-rock interaction (Lloyd and Heathcote, 1985).

As it is not useful to present the absolute concentration of a single isotope, stable isotopic abundances are reported as a ratio to some abundant isotope of the same element or as positive or negative deviations of these isotope rations (R) away from a standard. The relative difference is designated by δ (normally expressed in parts per thousand, permil %).

$$\delta_x = \frac{R_x - R_{std}}{R_{std}} x1000$$

R is the particular isotopic ratio (for example $^{18}O/^{16}O$ or $^{13}C/^{12}C$) for the sample and standard. The standard used for carbon is PDB (Pee Dee Belemnite) and for oxygen and hydrogen SMOW (Standard Mean Ocean Water).

The isotope ratios of natural compounds may change as a consequence of the history and processes to which such compounds have been submitted in the environment. The mass differences between isotopes of the same element produces small differences in their chemical and physical behaviour which in turn establish slightly different isotopic compositions (isotope fractionations), among co-existing chemical compounds or phases (Unesco, 1973).

6.4 CARBON ISOTOPES

6.4.1 Introduction

Three isotopes of carbon occur naturally: stable ^{12}C and ^{13}C and radioactive ^{14}C.

The behaviour of ^{13}C in groundwater is studied in the context of the carbonate system. This system is complex in the subsurface and the most important application of $\delta^{13}C$ data is in process identification (Domenico and Schwartz, 1990).

The ^{13}C content of groundwater is controlled by dissolution, precipitation and fractionation processes. Initially the ^{13}C chemistry is controlled by the $\delta^{13}C(CO_2)_{gas}$ in the atmosphere, which falls in a range from -7 to -10%.... with respect to the carbonate PDB standard (Domenico and Schwartz, 1990). Changes in $\delta^{13}C$ occur when carbon is added to, or removed from, the water during its transit through the aquifer. Possible sources of carbon are:

- Dissolution of calcite, aragonite, or dolomite from limestone, which introduces relatively heavy carbon.
- Oxidation of organic matter, which introduces relatively light carbon.
- Transport of CO_2 gas from a soil atmosphere, which also introduces relatively light carbon.

Carbon may be lost from the water by precipitation of a carbonate mineral or by loss of CO_2 gas. In general ^{13}C is used to identify sources of carbon and is particularly valuable for distinguishing between carbon derived from organic matter (light) and carbon derived from carbonate minerals (heavy) (Drever, 1988).

Radiocarbon (^{14}C) is produced in the atmosphere by interaction of cosmic rays with nitrogen and was introduced in large amounts by nuclear weapons testing. ^{14}C has a half-life of 5730 years, making it a useful tool for dating waters as old as 50 000 years. The ^{14}C generated in the atmosphere is carried down to the earth's surface by precipitation, and becomes incorporated into the biomass or transported into water bodies such as lakes, the ocean and groundwater (Drever, 1988).

Measurements of ^{14}C are reported in terms of per cent modern carbon (pmc) where:

$$A = \frac{(^{14}C/^{12}C)_{SAMPLE}}{(^{14}C/^{12}C)_{MODERN}} x\, 100 pmc$$

There are some complications in the behaviour of ^{14}C during recharge, so the "absolute" age of a groundwater cannot be determined reliably. However, if the ^{14}C concentration is measured at several points along a flow line within an aquifer, the differences in age between the points and hence the flow velocity can be determined (Vogel, 1967). One complication is that dissolution of organic matter or carbonate minerals within the aquifer may add "old" or "dead" (no detectable ^{14}C) carbon to the water, giving an erroneously old age. The contribution of carbon from these sources can sometimes be estimated from the $^{13}C/^{12}C$ measurements and chemical arguments, so corrections can be made (Talma *et al.*, 1984). Another complication is mixing. A low ^{14}C concentration may mean that we are looking at relatively "old" water, or it may mean that we are looking at a mixture of relatively "young" water and "dead" water. ^{14}C measurements can be interpreted as ages only where mixing is insignificant (Drever, 1988).

6.4.2 Discussion of Carbon Isotope Results

These processes and methods of quantitative treatment of these processes in order to develop a full interpretation of the isotopic composition of dissolved carbon is extensively discussed in Mook (1983) and Lloyd and Heathcote (1985). Using these descriptions, the carbon isotope results from Struisbaai are discussed. As the analytical data was found to be constant with time the average of the sets of analyses for each borehole is used and is shown in Table 6.2 below, arranged in descending order of ^{14}C content.

Table 6.2 Struisbaai. Carbon and oxygen isotope data. The values shown are average valued for the various sampling runs and arranged in descending Carbon-14 content within wellfield groupings.

Borehole No	Carbon-13 (‰ PDB)	Total Inorganic Carbon (TIC) mM/L	Carbon-14 (PMC)	Oxygen-18 $\delta^{18}O$ (‰ SMOW)	Model Age (years)
G39940	-11.4	8.8	86.1	-4.2	recent
G39942	-11.2	3.6	90.4	-4.8	recent
G39943	-11.4	2.8	89.3	-4.8	recent
P3	-11.2	4.3	83.3	-4.9	50 - 400
P2	-11.2	4.5	80.8	-5.0	50 - 400
BH10	-12.7	4.9	84.7	-4.8	50 - 400
BH6	-12.3	4.8	81.9	-4.9	50 - 400
BH8	-12.5	4.5	81.0	-4.6	50 - 400
G39427	-12.3	6.0	68.0	-4.8	1800
G39941	-11.4	4.3	65.2	-4.9	2200
AG1	-10.6	4.4	45.4	-4.8	3800
Modern Seawater	+2.0	2.2	120	+0.3	

Depending on the various processes that take place young recharge water can have a ^{14}C content varying between 114 pmc and as low as 65 pmc. At Agter Witzenberg (Weaver *et al.*, 1997) there are no soil carbonates and the TIC (total inorganic carbon) comprises virtually entirely of CO_2 derived from the decay of plant material. Vogel (1970) found recent waters with ^{14}C content of 85 ± 5 pmc and explained this by isotopic exchange between inorganic cabon and gaseous CO_2 in the unsaturated zone. Lloyd and Heathcote (1985) present data from the Chalk aquifer in England where recent recharge water samples have a ^{14}C of 65 pmc.

The four boreholes in the new wellfield are G39942 and G39943 which have been drilled to the first water intersection at about 33 m and stopped and P_3 and P_2 which have been drilled much deeper to intersect higher yielding fractures. The two shallow boreholes show ^{14}C of 90.4 pmc and 89.3 pmc which shows good agreement with Vogels (1970) observation. The production boreholes which have the main water yielding intersections at about 100 m both have slightly lower ^{14}C at 83.3 pmc and 80.8 pmc which indicates slightly older water.

As the water strikes in the shallow boreholes and the deep boreholes are all in the quartzites there can be no isotope exchange reactions which could explain these differences. The difference is a hydrogeologic difference - the deeper water is the older water.

The old wellfield data from BH6, BH8 and BH10 show similar ^{14}C content as the new wellfield production boreholes P_2 and P_3.

If one argues that the discharge zone for the regional groundwater flow is along the coast, then G39427, G39941 and AG1 can be regarded as sampling discharge water which would be the oldest water.

The ^{14}C values for these boreholes confirm this proposition by having the lowest ^{14}C values. Taking these ^{14}C values borehole AG1 apparently has the oldest water of all the boreholes. This, however, may be a result of solution - precipitation exchange processes. This occurs when the aquifer water which contains ^{14}C is in contact with the calcrete which has zero ^{14}C. In other words the C of the aquifer water moves into the calcrete which is exchanged for C from the calcrete which has no ^{14}C thus reducing the ^{14}C content of the groundwater and increasing the ^{13}C content. This borehole is the only production borehole where the aquifer water is in direct contact with the calcretes. The production zone is the solution cavity at the quartzite - calcrete contact. All other boreholes have the high yielding fractures in the quartzites which being pure quartz are not subject to aquifer carbonate solution-exchange processes. Supporting this theory that the ^{14}C has been lowered by solution-exchange processes is that the ^{13}C for AG1 is also lower than for any other borehole. Nevertheless the amount of exchange that has occurred is low, with ^{13}C only decreasing from -12.5 to -10.6 $^0/_{00}$. The ^{14}C thus indicates this water is old.

6.4.3. Conclusions from carbon isotopes

The carbon isotopes show variations according to sampling position in the regional aquifer.

➠ At the same site deeper water has lower ^{14}C than shallower water thus confirming that deeper water is older water.

- Water from discharge zone sample sites have lower ^{14}C than boreholes up-gradient confirming that regional groundwater flow is from the interior towards the sea.
- Where aquifer water is in contact with calcretes then solution-precipitation processes occur increasing the heavier carbon-13 and reducing the ^{14}C content of the groundwater giving an apparently older age to the water.

6.5 STABLE ISOTOPES OF OXYGEN AND HYDROGEN IN THE HYDROLOGICAL CYCLE

6.5.1 Introduction

The most important physical process causing variation of isotopic composition in natural waters is vapour-liquid fractionation during evaporation and condensation. The vapour pressure of water containing the light isotopes (^{1}H and ^{16}O) is greater than that of water containing the heavier isotopes (D and ^{18}O). When liquid water and water vapour are in equilibrium, the vapour is isotopically lighter with respect to both D/H and $^{18}O/^{16}O$ than the liquid, and hence water vapour in the atmosphere is isotopically lighter than water in the ocean (Drever, 1988).

Water vapour which evaporates from the ocean is depleted by 10 - 15 $^{0}/_{00}$ in ^{18}O and by 80 - 120 $^{0}/_{00}$ in D with respect to SMOW (Standard Mean Ocean Water) (Unesco, 1973; Drever, 1988).

When water vapour condenses to form rain, fractionation takes place in the reverse direction, with the liquid being isotopically heavier than the vapour. The fractionation during evaporation is thus largely reversed during condensation and the first rain to fall from water vapour over the ocean would have an isotopic composition of about -3 $^{0}/_{00}$ (Drever, 1988). If this rain again forms a vapour, ^{18}O will be selectively removed from the vapour phase and the $\delta^{18}O$ of the vapour will become progressively more negative as the rain continues to fall. By this process of *Rayleigh fractionation*, rainfall becomes progressively lighter in both δD and $\delta^{18}O$ as it occurs further from the ocean source. The δD and $\delta^{18}O$ values in precipitation generally plot close to a straight line (the *meteoric water line*) with equation:

$$\delta D = 8 . \delta^{18}O + 10$$

The slope (8) is a general determined by the physical properties of the isotopes. The intercept (10), also called the d-excess, is a general one applicable to the world's composite set of samples (Dansgaard, 1964). Locally d-excess values ranging from 0 to +25 have been observed (IAEA, 1922; Gat and Carmi, 1970).

Water with an isotopic composition falling on the meteoric water line is assumed to have originated from the atmosphere and to be unaffected by other isotopic processes. Evaporation from open water and exchange with rock minerals are two of the more commonly observed processes causing deviations from the meteoric water line (Domenico and Schwartz, 1990).

As temperature has a dominant effect on isotopic fractionation, variations in isotopic concentrations in precipitation can relate to climate and altitude (Lloyd and Heathcote, 1985). This dependency on temperature produces seasonal isotope variations (winter precipitation is depleted in heavy isotopes with respect to summer precipitation); latitude variations (high latitude precipitation is depleted with respect to low latitude precipitation) altitude effects (the heavy isotope content of precipitation decreases with increasing altitude) and amount effects (larger rainstorms tend to have lower heavy isotope content). In regional hydrological studies, the altitude effect can be used to differentiate groundwaters derived from recharge areas at different elevations. In general there is about a 0.3 $^0/_{00}$ decrease in $\delta^{18}O$ and 2.5 $^0/_{00}$ decrease in δD per 100 metres increase in elevation (Unesco, 1973; Midgley and Scott, 1944).

Isotopes of oxygen and hydrogen are, in a certain sense, ideal geochemical tracers of underground water because their concentrations are not subject to changes by interaction with the aquifer material (Unesco, 1973). Once underground and removed from zones of evaporation, the isotope ratios are conservative and only affected by mixing. When precipitation infiltrates to feed groundwater, mixing in the unsaturated zone smoothes the isotopic variations, so water in the saturated zone has a composition corresponding to the mean isotopic composition of infiltration in the area. This may differ slightly from the mean isotopic composition of precipitation due to the fact that not all precipitation during the year infiltrates in the same proportion (Unesco, 1973).

Analyses of δD and $\delta^{18}O$ can be used to identify the probable source of an underground water. If the isotopic composition of an underground water plots close to the meteoric water line in a position similar to that of present-day precipitation in the same region, the water is almost certainly meteoric. Although the isotopic composition of precipitation at a particular location is approximately constant, it varies from season to season and from one rainstorm to another. The variations can be used to identify the season at which most of the recharge takes place (Drever, 1988).

Groundwater recharged by seepage from surface waters such as rivers or lakes should reflect the isotopic signature of the surface water body eg. a river may collect water which originates at higher altitudes and is depleted in heavy isotopes while seepage from lake waters which have been evaporated will be enriched in heavy isotopes. Isotopic imaging of surface water/groundwater interactions is a useful application of δD and $\delta^{18}O$ data. Groundwater isotope data across the Sacremento Valley, California has been used to establish groundwater mining of ancient groundwater and to identify regions of limited recharge by surface water and areas of rapid recharge by irrigation water (Criss and Davisson, 1996). Such information can now be used to design an aquifer management scheme for the region.

In some areas palaeowaters may be present with different isotope ratios, often lower than those of modern age (Heaton *et al.*, 1986). These were recharged under different climatic conditions from those prevailing now, and are generally of great age.

6.5.2 Discussion of results

6.5.2.1 Overall results

The results are tabled in the last column of Table 6.2. Figure 6.10 shows chloride versus $\delta^{18}O$. This figure shows that $\delta^{18}O$ is independent of chloride. Examining the average results, except for G39940, the variation is minimal, ranging from -4.6 $^0/_{00}$ to -5.0 $^0/_{00}$. Examining the individual analyses for each sampling run it is seen that the range is from -4.6 $^0/_{00}$ to -5.1 $^0/_{00}$ which if one considers that the analytical error is ± 0.2 $^0/_{00}$ indicates a uniform and localized direct recharge. The calculated average of all the analyses excepting those for G39940 and the incorrect analysis for P3 is -4.86 $^0/_{00}$ for a total of 32 analyses.

6.5.2.2 *Borehole G39940*

Borehole G39940, however, shows a significant increase of $\delta^{18}O$. This increase can be one of two factors, mixing with seawater or evaporation effects. This borehole has a higher salinity than any other sample which supports either of these two scenarios.

Accepting that the average rainfall salinity, as discussed in chapter 3, is 62 mg/L of chloride and that there is 10% recharge then the recharge water will have 620 mg/L of chloride. Seawater has 19000 mg/L of chloride. This borehole has an average of 1467 mg/L of chloride.

This mixing percentage is calculated as follows:

X% x 620 mg/L + (100 - X)% x 19000 = 100% x 1467
thus X = 95.4%

Thus the mixing ratio of recharge water to seawater would be 95.4% to 4.6%. Ocean water has a $\delta^{18}O$ of zero, so mixing seawater with the local recharge water which has a $\delta^{18}O$ of -4.86 in the ratio of 95.6 : 4.6 gives an end product of -4.65 $^0/_{00}$ which is above that of the measured value of -4.2 $^0/_{00}$. Thus mixing with seawater is not seen as a mechanism.

Looking at Figure 1.3 it is seen that the area inland of borehole G39940 is very flat. The 1 : 50 000 topographic map shows a number of wetlands confirming that pools of standing water is common. Thus recharge via open pan is to be expected in this area and the $\delta^{18}O$ enriched groundwater sample from G39940 confirms this.

6.5.2.3 *Borehole BH8*

BH8 has an anomalously high chloride content of 1333 mg/L, considering it is situated between BH6 with 380 mg/L chloride and BH10 with 532 mg/L chloride, and that BH10 is closer to the sea than BH8 (Figure 1.3). The $\delta^{18}O$ for BH8 may be the clue. BH8 has a $\delta^{18}O$ of -4.6 $^0/_{00}$ which at first glance does not seem out of line with the other samples. However, following the seawater intrusion mixing model for chloride the mixing ratio would be 96.1% to 3.9%. This would result in an $\delta^{18}O$ of -4.67. It is thus concluded that it is quite possible that BH8 has been subjected to seawater intrusion. This would have to be discrete fracture related because the adjacent boreholes are apparently not affected. Referring back to the Piper diagram discussion for Figure 6.1 and 6.2 it is seen that BH8 is the only borehole which plots on the seawater intrusion line of Mazor (1991) further supporting the theory that this borehole has been subjected to seawater intrusion.

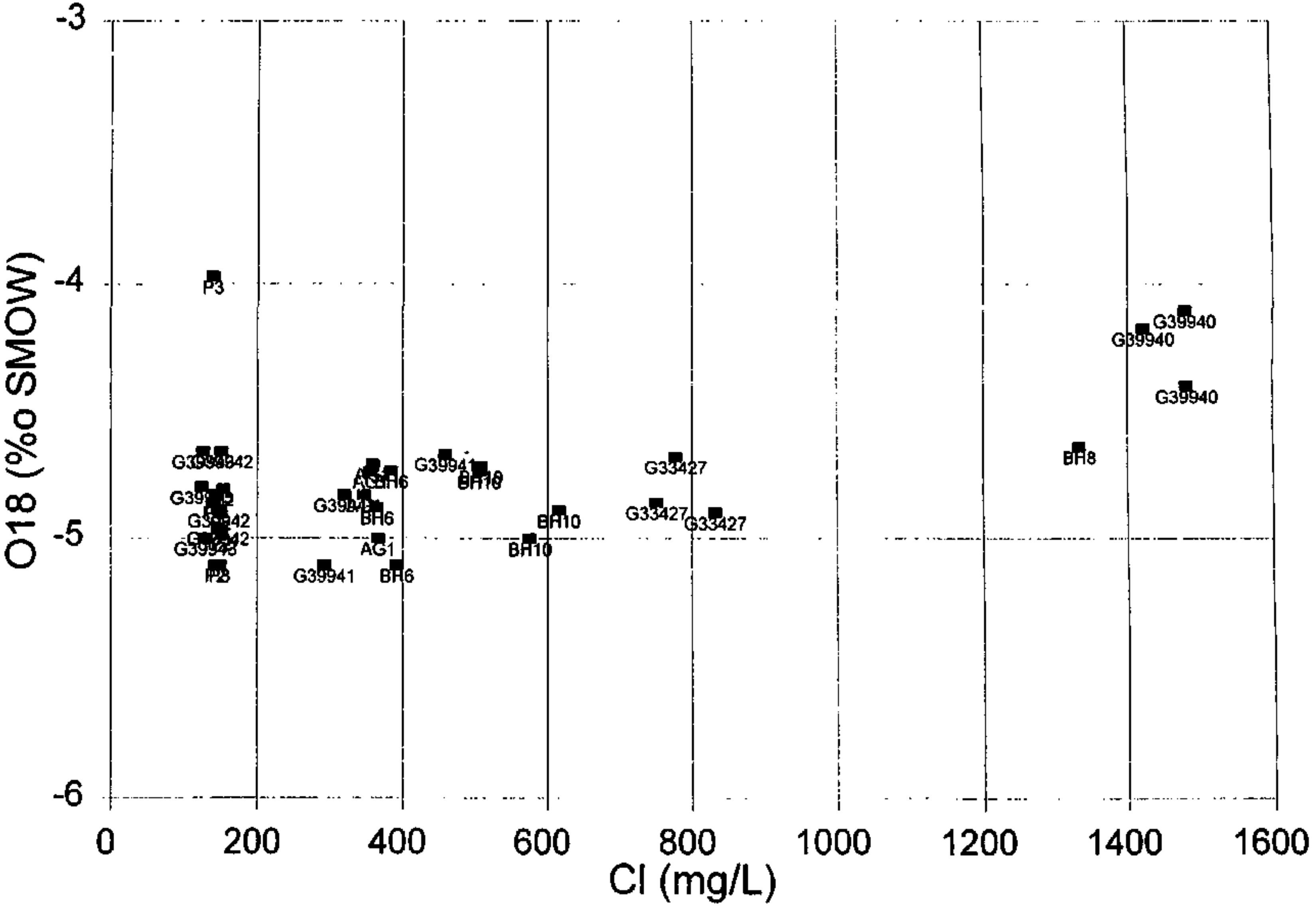


Figure 6.10: Struisbaai. Chloride versus Oxygen-18

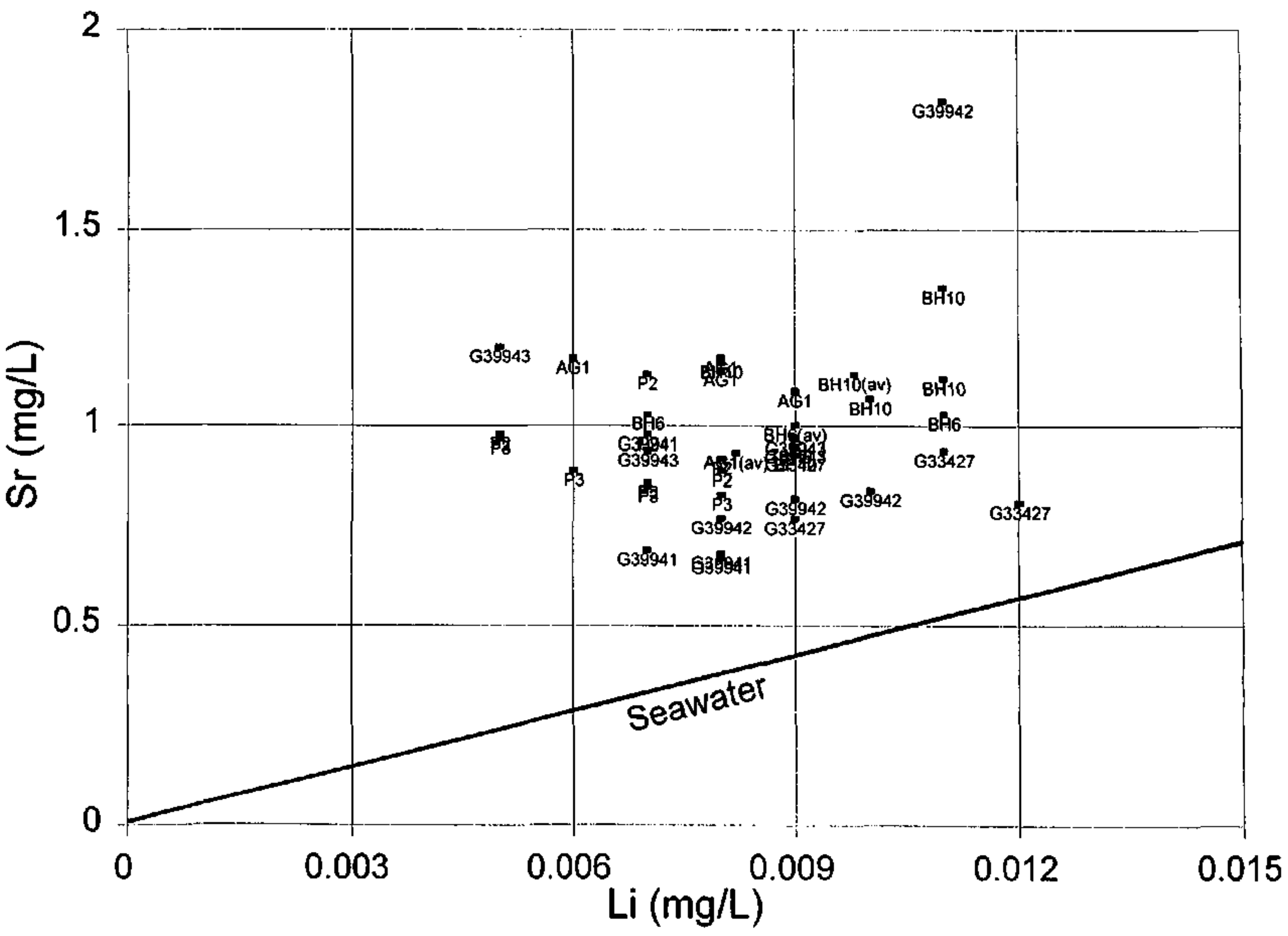


Figure 6.11: Struisbaai. Strontium versus Lithium

6.5.3 Conclusions

- The boreholes related to the main aquifer show a uniform $\delta^{18}O$ of -4.86 $^{0}/_{00}$ with a variation less than the analytical error of ± 0.2 $^{0}/_{00}$. This indicates uniform and localized direct recharge.

- Borehole G39940 shows a significantly different $\delta^{18}O$ of -4.2 $^{0}/_{00}$. This enrichment is due to recharge from open pan.

- Borehole BH8 shows a slight enrichment at $\delta^{18}O$ of -4.6 $^{0}/_{00}$. This borehole also has anomalously high salinity which is 2½ to 3½ times that of surrounding boreholes. Both these can be explained by mixing with 3.0% of seawater. The plotting position of BH8 on the piper diagram (Figure 6.1) supports the theory that this borehole has been subjected to seawater intrusion. This will have taken place along discrete high permeability fractures.

6.6 STRONTIUM ISOTOPES AND LITHIUM : STRONTIUM RATIOS

6.6.1 Introduction

The source of salinity for Struisbaai as discussed in Chapter 1.3 is one of the following:

- sea-spray
- connate water
- seawater intrusion

Considering strontium and its isotopes, any of these will and can contribute strontium according to the seawater mixing line. However, when one adds the aquifer material then dissolution of this rock will change isotopic ratios and move the sample plotting point away from the mixing line. The sampling data for the various boreholes are presented in Table 6.3 below. The boreholes are presented in the same order as in Table 6.2. Both lithium and strontium are useful ions to consider because they both have high solubility in water and similar to chloride are conservative. Hence these are good tracers to consider when investigating groundwater problems.

Figures 6.11 and 6.12 plot total strontium versus lithium and calcium and Figure 6.18 which is chloride versus strontium it is seen that all the samples except the rain samples plot above the mixing line. The strontium levels are independent of chloride. It was shown earlier, Figure 6.3 chloride versus sodium, that all samples plot on the seawater mixing line, thus for Figure 6.8 there is excess strontium indicating an additional source of strontium, probably from the aquifer material, probably calcrete.

Examining the ^{87}Sr / ^{86}Sr ratios it is seen that there is no difference between the groundwater values, seawater and shells, both modern and fossil. The Sr ratios can thus not be used to identify the source of salinity for any of these. However, the Sr ratios do exclude solution of either the Bokkeveld shales or TMG quartzites as being the source of salinity.

Table 6.3 Struisbaai. Strontium and lithium concentration and strontium isotope ratios. The values shown are average values for the various sampling runs. Lithium is included.

Borehole No	**Strontium concentration (mg/L)**	**^{87}Sr / ^{86}Sr ratio**	**Lithium concentration (mg/L)**	**Li/Sr**
G39940	2.62	.709298	.023	0.009
G39942	0.81	.709302	0.009	0.011
G39943	1.02	.709402	0.008	
P3	0.88	.709204	0.007	
P2	0.98	.709215	0.007	
BH10	1.12	.709241	0.010	0.009
BH6	1.00	.709234	0.009	
BH8	2.35	.709260	0.016	
G39427	0.86	.709286	0.010	0.012
G39941	0.68	.709224	0.008	0.012
AG1	1.14	.709185	0.008	0.007
Seawater	8.0	.7092	0.17	0.021
Sea shells [1] (modern)	-	.709197	-	
Fossil [1] quaternary	-	.70920	-	
Fossil [1] tertiary	-	no data available	-	
TMG [2] Quartzite	<0.05	.712900	<0.005	
Bokkeveld [2] shale (Agter Witzenberg)	0.2	.718	0.03	0.15
Bokkeveld [3] shale (Breede)	0.17	.717674	0.026	0.15

[1] Data from Eglington (1997)
[2] Data from Agter Witzenberg (Weaver *et al.*, 1997)
[3] Data from Kirchner (1995)
No data is available for cretaceous rocks.
Average for all boreholes is 0.709259.

Figure 6.11 shows total strontium versus lithium. Excepting for the two anomalous boreholes BH8 and G39940, there is a general scatter around lithium 0.008 mg/L and strontium 0.9 mg/L. This indicates a uniform source the most likely origin being solution of aquifer rock. Common to all of this grouping is calcrete and quartzite. During the investigation at Agter Witzenberg, Weaver *et al.* (1997) analysed for lithium and strontium in groundwater from quartzites of the Table Mountain Group and in groundwater from shales of the Bokkeveld Group. The results are shown in Table 6.3. The strontium and lithium for the quartzites for the total of 16 samples was always below detection limit. There is no reason to assume that the Struisbaai quartzites are any different from those of Agter Witzenberg, thus the quartzites cannot be the source of either lithium or strontium. There is a possibility that the strip of Bokkeveld shales to the north could provide/be the source of strontium and lithium. For Struisbaai the Li : Sr ratio is 0.009 while for Agter Witzenberg it is 0.153, a 17x difference. Thus the Bokkeveld shale is ruled out as a source rock. By the process of elimination the source of the strontium and lithium is from solution of the calcretes. This also shows that the source of salinity is unlikely to be from the Bokkeveld shales as postulated by Meyer (1986a).

Figure 6.12 shows strontium versus calcium. Also plotted on this graph is the seawater mixing line and the sea shell (modern) solution line. All the samples plot between these two lines. From the Sr vs Cl graph it has been shown that the Sr cannot be derived from seawater/sea-spray alone. It is thus concluded that the strontium and lithium is derived from solution of calcretes possibly with some additional input from seawater/sea-spray. Figure 6.5 which is chloride versus calcium shows enrichment of calcium from solution of calcretes. The sample from G39942 and G39943 plotting above the seawater mixing line plot anomalously due to drilling fluid effect (chapter 3.6.4).

Examining the ^{87}Sr / ^{86}Sr isotope data it is seen that TMG quartzites and Bokkeveld shales give significantly different values while whole rock analyses for sea shells, both modern and tertiary, show very good agreement to the groundwater samples.

The consistent ^{87}Sr / ^{86}Sr ratio for groundwater from the Bokkeveld shales for Agter Witzenberg and Breede River indicates that one could expect a similar value from this area which is not found in any of the Struisbaai boreholes.

Examining the variation of the $^{87}Sr/^{86}Sr$ ratio for all the boreholes it is seen that the values are very consistent. The $^{87}Sr/^{86}Sr$ ratios unfortunately does not allow one to distinguish between seawater and calcrete as the origin. Sea shells both modern and fossil grow in the sea and thus the $^{87}Sr/^{86}Sr$ ratio is identical to that of seawater. The calcium carbonate for the calcretes of the Bredasdorp is derived from solution/dissolution of calcareous material within the formation and thus has the same signature as the sea shells have and thus of seawater. Thus there would be no difference of $^{87}Sr/^{86}Sr$ ratios of groundwater whose salinity is derived 100% from seawater/sea-spray, from 100% solution of calcretes or from a 50 : 50 mix of the two.

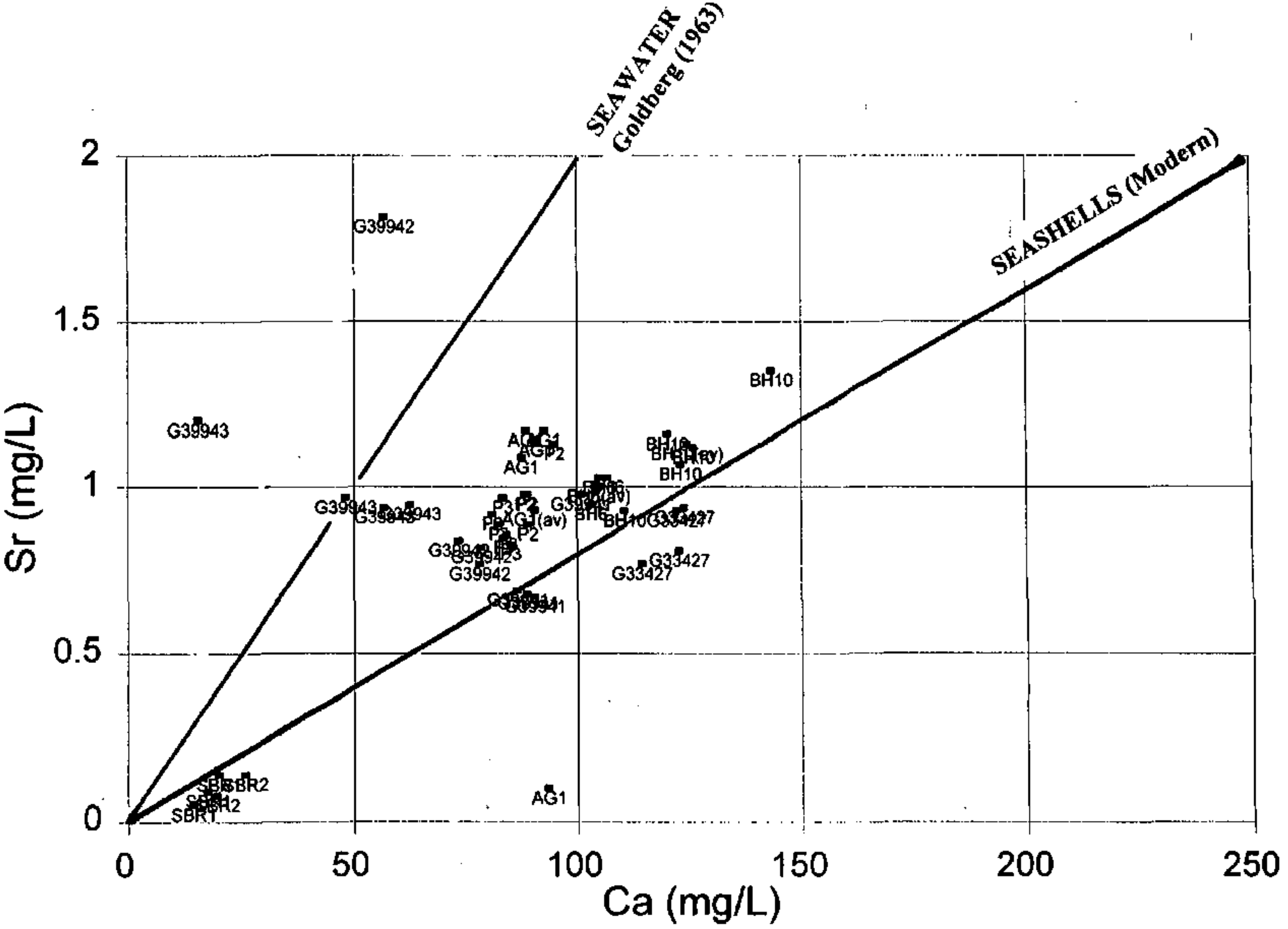


Figure 6.12: Struisbaai. Strontium versus Calcium

6.6.2 Conclusions from strontium data

Except for borehole G39940 and BH8 strontium and lithium group quite closely around strontium values of 0.9 mg/L and lithium of 0.008 mg/L. The ^{87}Sr/^{86}Sr ratio show very similar values with the average being .709259.

Conclusions are that:

- the strontium and lithium detected in groundwater is derived from solution of calcretes
- *^{87}Sr/^{86}Sr ratios as well as strontium and lithium content show that there is no contribution* from solution of either Bokkeveld shales or from TMG quartzites
- ^{87}Sr/^{86}Sr ratios for the groundwater is virtually identical to sea shells both modern and tertiary which in turn is virtually identical to seawater. The groundwater ^{87}Sr/^{86}Sr is thus derived via solution of calcrete formed from fossil sea shells which grew in the sea.

* * *

CHAPTER 7

MODELLING THE POTENTIAL FOR SEA-WATER INTRUSION AT STRUISBAAI

7.1 SEAWATER INTRUSION

Around the turn of the century the two scientists Ghyben (1888) and Herzberg (1901) working independently along the coastline of the North Sea first described the relationship between fresh water and salt water in the underground environment. They found that salt water occurs not at sea-level but at a depth of about 40 times the height at which the water-table is above mean sea-level. They analysed this relationship and attributed it to the relative densities of the two waters. Seawater has a density of 1.025 g/cm^3 and freshwater has a density of 1.000 g/cm^3. Under simple hydrostatic conditions this yields the 1:40 relationship which is generally referred to as the Ghyben-Herzberg relation.

Under real conditions there is some variation to this relation. Where freshwater flow towards the sea occurs then the interface between the fresh and salt water is displaced seawards. At the coastline the water-table is usually assumed to be at mean sea-level. If there is abundant wave action or significant tidal variation then the water-table will tend to be above mean sea-level. The net effect of these phenomena is to shift the interface both deeper than the 1:40 relation would predict and also extends the freshwater discharge zone seawards so that undersea freshwater springs can be encountered.

Seawater intrusion occurs when pumping of boreholes which are situated close to the interface cause the interface to either migrate inland or to cause upconing of the underlying interface. Typically seawater intrusion occurs when boreholes are sited too close to the coastline or when boreholes are closely concentrated and local overpumping occurs.

Todd (1980) describes five methods for controlling seawater intrusion:

(1) Modification of pumping pattern: Changing the location of pumping wells, typically by dispersing them in inland areas.
(2) Artificial recharge: Which raises groundwater levels.
(3) Injection barrier: Similar to artificial recharge except the freshwater is recharged by injection boreholes.
(4) Extraction barrier: Which is a line of coastal boreholes which captures the saline water, preventing it from moving further inland.
(5) Subsurface barrier: Construction of an impermeable subsurface barrier parallel to the coast and through the vertical extent of the aquifer.

The method most commonly and effectively used is the first one. By calculating the drawdowns created by a pumping wellfield and developing contours of the resulting cone of depression one can measure the effect on the natural watertable contours. By ensuring that the watertable or piezometric surface is always a few metres above sea-level then seawater intrusion can be prevented.

7.2 APPLICABILITY OF MODELLING TO THE STRUISBAAI SITUATION

The new wellfield at Struisbaai is more than 3000 m from the coastline. This distance affords good protection against seawater intrusion. The water-levels in these boreholes at the time of test-pumping were between 17 m and 19 m above mean sea-level. Applying the Ghyben-Herzberg principle this means the interface is 680 m to 760 m below the watertable at this point. This is well below the water-strikes and also below the base of the boreholes which is 78 m, 100 m and 133 m for the three production boreholes. When these boreholes are in production the dynamic water-levels will be +7 m, -4 m and 0 m above sea-level respectively. Although the water-levels for P2 and P3 are below and at sea-level, which is potentially harmful, the water-levels between the boreholes and the sea will be well above sea-level, thus maintaining a barrier to seawater intrusion.

However, the question arises as to what will happen in the future when water demand increases, and more boreholes are drilled.

To test scenarios such as this where the behaviour of aquifers in time and space is investigated, it is necessary to employ a mathematical model.

In recent years, numerous groundwater models have been used to simulate the behaviour of groundwater systems. The models are flexible and powerful, but the construction of a site model, can be time consuming because of the large amounts of data required, especially for three dimensional models. Models accurately reflecting actuality require large amounts of accurate input data. Unfortunately it is seldom that large amounts of data are available. Consequently when using available data (less than desired) as is the case for Struisbaai the model results must be viewed as an indication of what is probable rather than a faultless reflection of reality.

For Struisbaai the aquifer was assumed to be homogeneous in the vertical direction. Hence, a two dimensional flow model was used during the investigation. The aim of the model was to examine the effect of pumping at various discharge rates on the regional water-levels and hence to deduce, using the Ghyben-Herzberg principle the potential for seawater intrusion of the new wellfield

7.3 MODEL SOFTWARE AND INPUT DATA

7.3.1 Model software

MODFLOW was the software used during the investigation (McDonald and Harbough, 1988). It is an internationally accepted modelling package, which calculates the solution of the groundwater flow equation using the finite difference approach. The software package MODIME (Zhang *et al.*, 1996), was used as a pre and post processor for MODFLOW. MODIME allows the user to graphically specify model parameters. It then automatically generates input files in the right format for MODFLOW, PATH3D and MT3D. The user can also zoom into a subregion of the model for the execution of high resolution equations.

7.3.2 Discretization

MODFLOW is a finite difference code that makes use of quadrilateral/block network. A regular mesh size was chosen. The mesh consisted of 93 x 98 cells in the x and y directions with the dimensions 120 x 75 m. Figure 7.1 is a schematic representation of the mesh.

In the simulations, the fault to the north of the aquifer was taken as a no flow boundary (refer to Figure 4.1).

7.3.3 Model Input Parameters

The aquifer thickness was taken to be 500 m. The thickness of the Peninsula Formation is ~ 1500 m in this area, but because of the numerous reverse overthrust faults and other faults this was reduced to 500 m. Initial water level data was obtained from the boreholes present in the area. These values were then extrapolated over the whole network.

Two parameters are used to describe the physical properties of an aquifer, namely hydraulic conductivity and aquifer storage. The first of these two quantifies the rate at which water moves through the aquifer and the latter quantifies the aquifer's ability to store water. The hydraulic conductivity was taken as 3 m/d and the storage coefficient as 0.009. These values were obtained from pumping tests performed on boreholes P1, P2 and P3. The average annual recharge was taken as 15 % of the rainfall. The average rainfall is 469.2 mm/annum (refer to Figure 3.3).

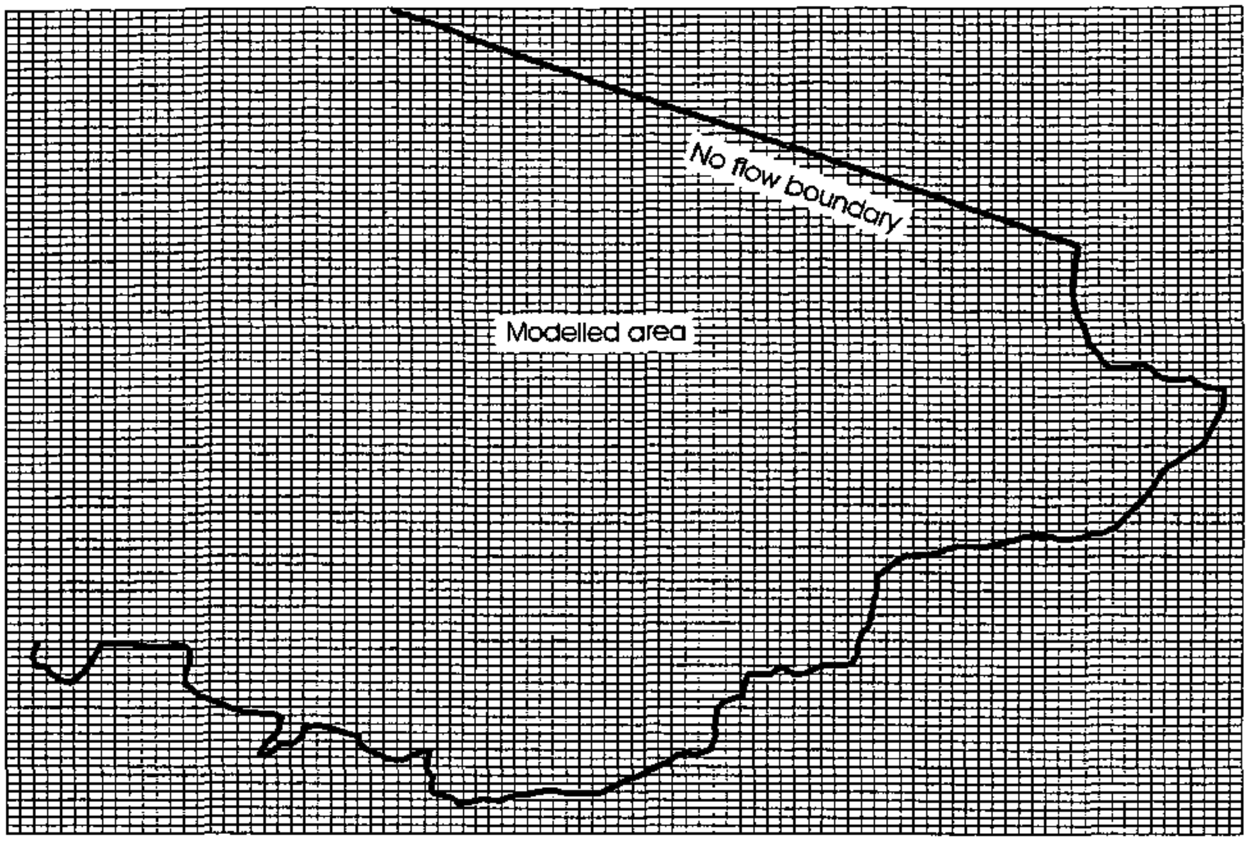


Figure 7.1 : Modelling network for the Struisbaai aquifer

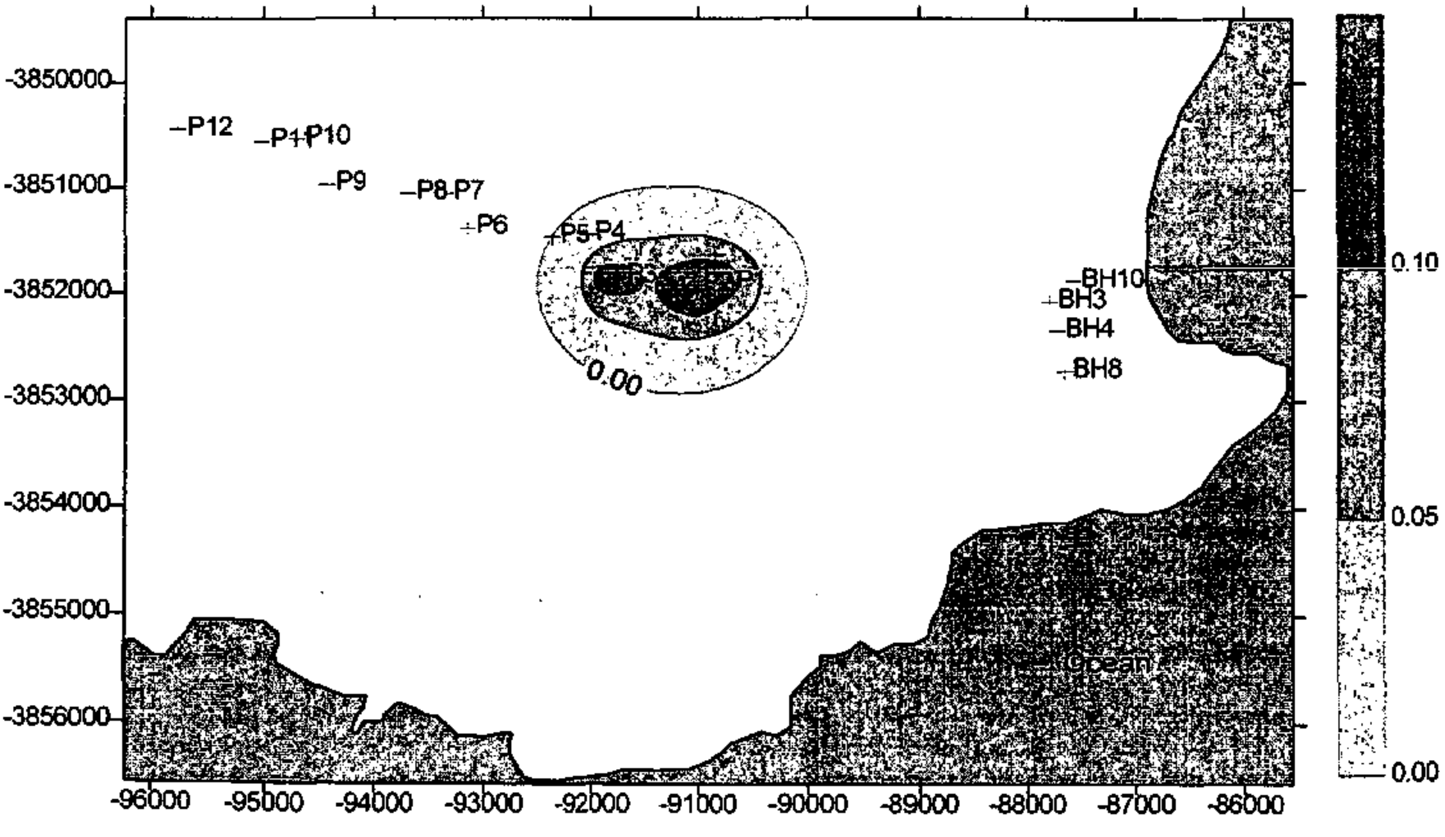


Figure 7.2 : Modelled decrease in waterlevels after 5 years of pumping at current pumping rates of 1350 m3/d for the existing boreholes P1, P2 and P3

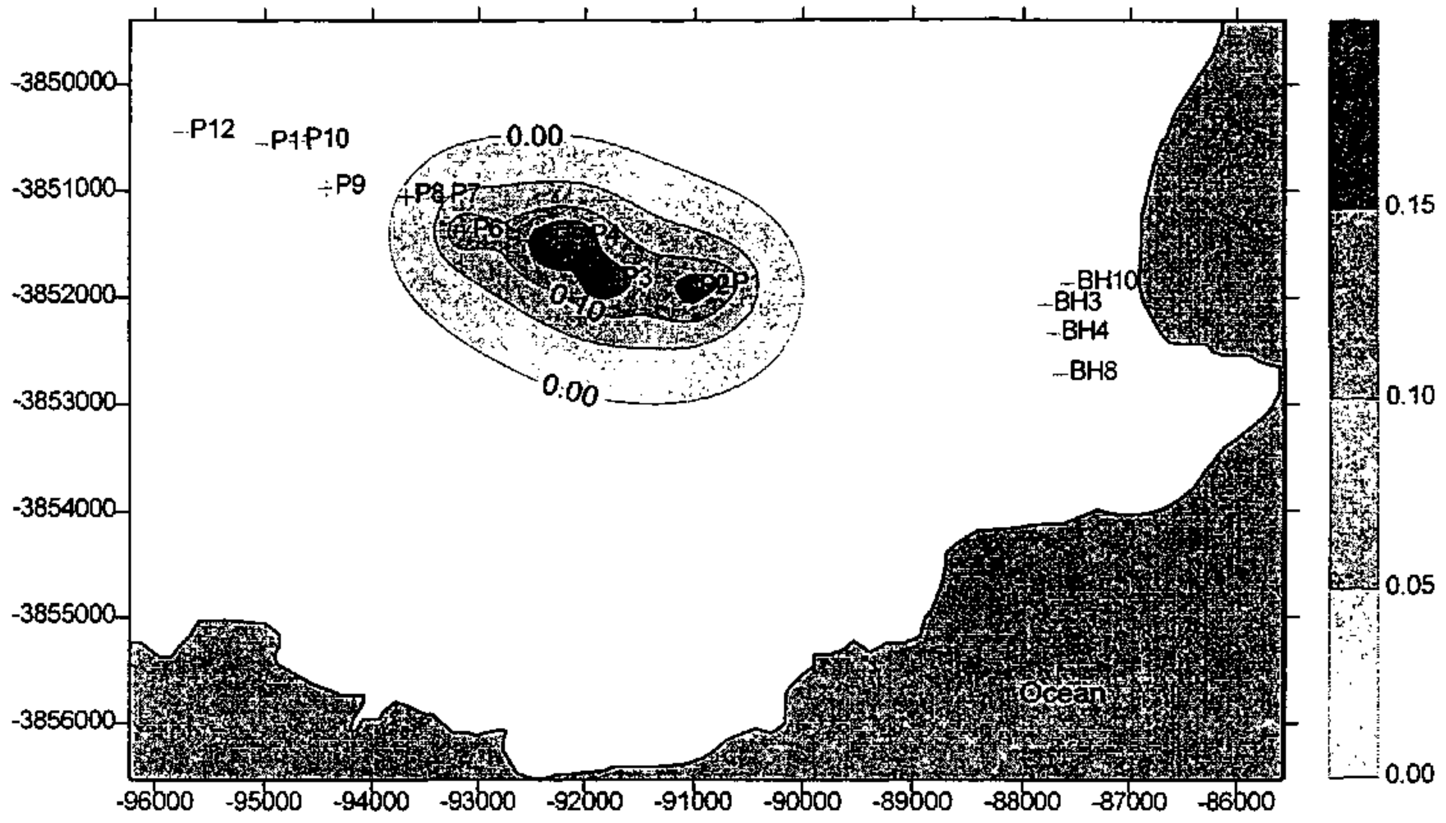


Figure 7.3 : Modelled decrease in waterlevels after 5 years of pumping at twice the current pumping rate (ie at 2700 m3/d)

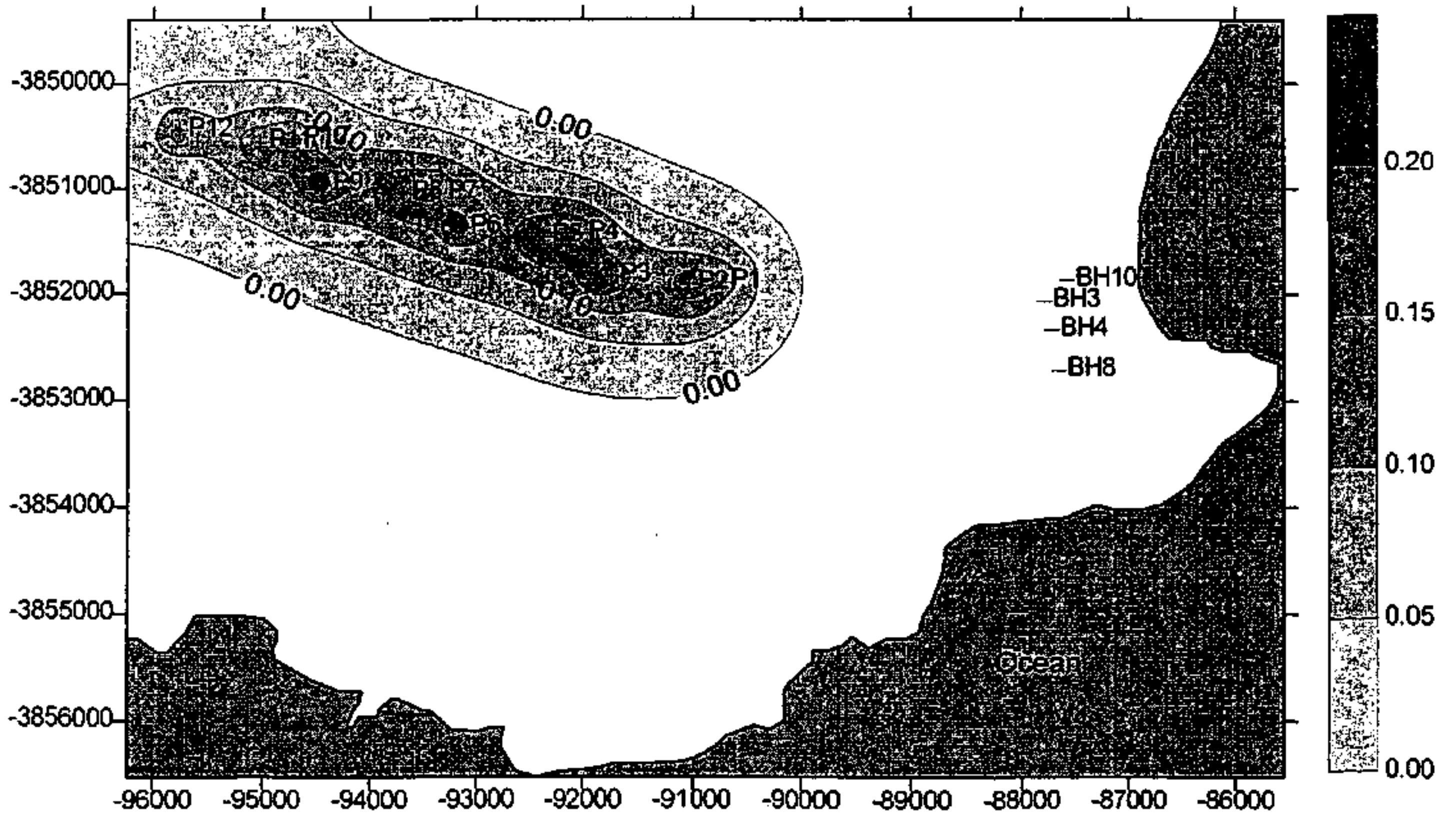


Figure 7.4 : Modelled decrease in waterlevels after 5 years of pumping at four times the current pumping rates (ie at 5400 m3/d)

7.4 SCENARIO'S TESTED

Once all data has been entered a steady state model was run. A transient flow model was then run for a period of 5 years, allowing the model to once again reach steady state conditions. Three scenarios were tested.

Scenario 1:

P1 and P2 were pumped at 500 m^3/d and P3 at 350 m^3/d for the whole simulation period. These are the current production rates of discharge. The difference between the initial water levels and those simulated after 5 years is shown in Figure 7.2.

Scenario 2:

A doubling of the current rate of discharge to 2700 m^3/day is simulated by adding an extra three boreholes pumping at the same rates as P1, P2 and P3. The difference between the initial water-levels and those simulated after 5 years of pumping is shown in Figure 7.3.

Scenario 3:

A four-fold increase of the current rate of discharge to 5400 m^3/day is simulated by adding an extra 9 boreholes pumping at the same rates as P1, P2 and P3. The difference between initial and those simulated after 5 years of pumping is shown in Figure 7.4.

7.5 DISCUSSIONS

Figure 7.2, 7.3 and 7.4 all show that water-levels between the pumping wellfield and the sea remain positive, i.e. above sea-level. This positive water-level barrier will reduce, if not prevent, the potential for landward migration of the interface. This is Todd's (1980) first recommended method.

With the limited data available it appears that moving the wellfield inland has reduced the probability of seawater intrusion affecting the quality of groundwater being pumped.

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CHAPTER 8

CONCLUSIONS

The water-supply for Struisbaai has a historical reputation for high salinity. Previous groundwater investigators have ascribed this salinity mainly to seawater intrusion but including other factors. None of these investigators gave any conclusive evidence for their theories.

This investigation identified three possible sources of salinity.

- Salinity derived from sea-spray causing high salinity recharge
- Geological factors which yield high salinity groundwater
- Hydrogeological factors which result in seawater intrusion

8.1 SALINITY DERIVED FROM SEA-SPRAY CAUSING HIGH SALINITY RECHARGE

Three rain collectors were installed and samples collected at intervals. Relating the rainfall recorded to the quality of the rain samples collected showed that the rain has an EC of 12.5 mS/m for the collector closer to the sea and 10.5 mS/m for the collector further from the sea. This is the first indicator of the groundwater salinity being derived from sea-spray.

Relating the chloride content of rain from these collectors to the chloride content of groundwater from the closest boreholes indicates a recharge of between 4.7 % and 5.8 % for the collector closer to the sea and between 13.1 % and 16.4 % for the collector further from the sea. These values are quite feasible further supporting the premise that the groundwater salinity is derived from sea-spray.

Two samples of calcrete were collected from a newly developed road-cutting which is approximately 300 metres from the sea. The samples were fine crushed and leached with deionised water. The leachate from the weathered rock produced an EC of 122 mS/m whereas the leachate from the freshly exposed rock produced an EC of 11.6 mS/m. This showed the sea-spray does contribute significantly to the inland salinity. Most if not all of this sea-spray will wash down into the aquifer. Examination of various ionic ratios show that the leachate from the exposed rock has similar ratios to that of seawater, whereas the ratios from the fresh rock-sample are dissimilar. For example, the ratio Na/Cl for seawater is 0.553, for the exposed sample is 0.552, for the fresh sample is 1.5, and for the rain collector close to the sea is 0.52 and for the rain collector further away is 0.42. These results and similar results for other ionic ratios strongly support the premise that the salinity is derived from sea-spray and not from dissolution of the calcrete.

Five sampling runs of existing and newly drilled boreholes were carried. The first sampling run was of existing boreholes and the next four were of a total of 10 boreholes. Plotting the results on a Piper plot shows that all the results lie on the mixing zone except for the result from one borehole

BH8 which is in the seawater intrusion portion of the diagram. The addition of sea-spray is the same as mixing.

A number of graphical plots of one chemical determinant shows that chloride, sodium, potassium, magnesium and sulphate all correlate closely to the seawater mixing line indicating they are derived from seawater. Conversely strontium, calcium and iodine appear to be derived from dissolution of calcrete.

$\delta^{18}O$ versus chloride showed that all but two of the boreholes plotted on the seawater mixing line. BH8 showed slightly higher $\delta^{18}O$ than the rest and this could be due to seawater intrusion. Borehole G39940 shows significant enrichment and this is due to recharge from open pans where evaporation has occurred.

Graphical plots of strontium versus calcium, strontium versus lithium and also $^{87}Sr/^{86}Sr$ ratios show that strontium and lithium are derived from dissolution of the calcrete and that there is no contribution from solution of either the Bokkeveld shales or of the TMG quartzites.

8.2 GEOLOGICAL FACTORS WHICH YIELD HIGH SALINITY GROUNDWATER

Connate seawater originating either from previous sea-level transgressions or from deposition of the formation is often invoked as the source of salinity. The last transgression which could have affected the area is over 50 000 years B.P. The calcretes have high permeability so it is improbable that salinity is still encountered in sufficient quantities as to be the cause of the high salinities encountered.

As described above the $^{87}Sr/^{86}Sr$ ratios show that the excess strontium found in the groundwater is derived from calcrete dissolution and not from the Bokkeveld shales. Thus the Bokkeveld shales, which elsewhere do give high salinities to groundwater, in the case of Struisbaai are not a contributing factor.

8.3 HYDROGEOLOGICAL FACTORS WHICH RESULT IN SEAWATER INTRUSION

Except for the Agulhas borehole, AG1, all the boreholes have their water-strike well below sea-level. The water-levels vary from a few metres above sea-level for the old wellfield to nearly 20 m above sea-level for the new wellfield. For the old wellfield the water-strikes have been recorded at 124 m below sea-level. According to the Ghyben-Herzberg principle the interface is 160 m to 200 m below surface, thus when these boreholes were pumping it is quite conceivable that upconing of the interface would result in seawater intrusion and thus high salinities.

As mentioned earlier in section 8.1, for BH8 which is in the old wellfield, evidence from both the Piper plot and the $\delta^{18}O$ data indicates it was subjected to seawater intrusion.

The new wellfield has been moved 3 kilometres inland and the risk of seawater intrusion has been reduced.

8.4 CONCLUSION

The overall conclusion that is made is:

- that salinity in the old wellfield was quite probably due to a degree of seawater intrusion;
- that the salinity observed in the new wellfield and the Agulhas borehole is due to sea-spray.

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APPENDIX 1

DRILL AND GEOLOGICAL LOGS FROM ALL AVAILABLE BOREHOLES AT STRUISBAAI

- ➡ Survey co-ordinates for 15 boreholes
- ➡ Summary of geology intersected
- ➡ Detailed descriptive geological logs G39940, G39941, G39942, G39943
- ➡ Detailed construction data for G39940 - G39943
- ➡ Schematic borehole logs for G39940 - G39943
- ➡ Drill logs borehole P1, P2, P3, T1, T2 and T3 (McClea, 1991)

	ID-NO	EW-COORD	NS-COORD	COL-ELEV
1	P3	91745.500	3851831.500	46.92
2	P2	91035.000	3851905.000	40.41
3	G39942	90818.898	3851697.500	25.17
4	G39943	90425.703	3851951.500	26.13
5	BH9	87793.898	3852201.250	8.62
6	BH3	87798.898	3852063.500	4.84
7	BH4	87729.602	3852336.250	15.3
8	BH7	87705.898	3852574.000	14.91
9	G39940	88615.500	3850225.500	7.39
10	G39941	88598.398	3853529.500	64.52
11	G33427	87286.500	3853704.000	28.94
12	BH6	87960.430	3852784.750	?
13	BH10	87584.055	3852716.250	?
14	BH9A	87809.719	3851866.250	?
15	BH8	87656.898	3852713.750	18.01
16	P1	90753.35	3851886.96	32.41
17	T1	90773.14	3857823.93	28.77
18	T2	91173.17	3851719.67	24.30
19	T3	91422.97	3857676.60	26.12

SUMMARY OF GEOLOGY AND GEOLOGICAL FORMATIONS INTERSECTED BY VARIOUS BOREHOLES IN STRUISBAAI

Borehole No	Depths	Geological Formation	Rock Type
G39940	0-12	Uitenhage Formation	Shelly sand and calcrete
G39941	0-47 47-70	Bredasdorp Formation Skurweberg Formation	Calcrete Quartzite and phyllite
G30042	0-12	Bredasdorp Formation Skurweberg Formation	Calcrete Quartzite and phyllite
G30043	0-15 15-42	Bredasdorp Formation Skurweberg Formation	Calcrete Quartzite and phyllite
P1	0-19 19-78	Bredasdorp Formation Skurweberg Formation	Calcrete Quartzite and phyllite
P2	0-28.5 28.5-100	Bredasdorp Formation Skurweberg Formation	Calcrete Quartzite and phyllite
P3	0-35 35-133	Bredasdorp Formation Skurweberg Formation	Calcrete Quartzite and phyllite
T1	0-17.9 17.9-18.3	Bredasdorp Formation Skurweberg Formation	Calcrete Quartzite
T2	0-11.5 11.5-12.5	Bredasdorp Formation Skurweberg Formation	Calcrete Quartzite
T3	0-17 17-18.3	Bredasdorp Formation Skurweberg Formation	Calcrete Quartzite
AG1	0-21 21-22	Bredasdorp Formation Goudini Formation	Calcrete Quartzite
BH3	Not known		
BH4	Not known, depth 85 m		
BH6	0-3.7 3.7-11.7	Bredasdorp Formation Skurweberg Formation	Calcrete Quartzite
BH7	0-4 4-153	Bredasdorp Formation Skurweberg Formation	Calcrete Quartzite
BH8	0-8.2 8.2-130	Bredasdorp Formation Skurweberg Formation	Calcrete Quartzite
BH9	Not known, depth 123 m		
BH9A	Not known, reported to be in Bokkeveld shale		
BH10	Not known, depth 88 m		

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DRILLING LOG OF BOREHOLE G39940 AT STRUISBAAI

DRILLED DATE	20/08/93
DRILLING COMPANY	J.J. Myburgh and bros.
DRILLER	J. van Zyl
DRILLING METHOD	Mud Rotary with Tri cone bit

GEOLOGICAL FIELD LOG

0 - 1m	No Sample
1 - 2m	Fine to Medium Light brown angular Quartzose sand
2m	Hard layer
2m - 8m	Fine to Medium Quartzose sand with coarse shell fragments and small calcrete pebbles
8m	Softer layer
8m - 9m	Fine shelly layer
9m - 10m	Light yellow very coarse shelly layer
10m - 12m	Very coarse shelly layer with fine 3mm - 5mm angular Quartzose pebbles
Well losses	
12m	Very hard layer

Drilling stopped.

LOGGED BY A. J. HÖN

DRILLING LOG OF BOREHOLE G39941 AT STRUISBAAI

DRILLED DATE	2/9/93
DRILLING COMPANY	J.J. Myburgh and bros.
DRILLER	J. van Zyl
DRILLING METHOD	Mud Rotary with Tri cone bit and Air percussion

GEOLOGICAL FIELD LOG

Hard cemented calcrete layer on surface

0 - 3m	Fine to coarse angular and sub angular poorly sorted Quartzose sand in Calcrete matrix
4 - 8m	Fine to coarse angular and subangular poorly sorted Quartzose sand in Calcrete matrix with coarse shelly fragments Hard cemented calcrete layer up to 13m
9 - 13m	Fine to coarse angular and subangular poorly sorted Quartzose sand in calcrete matrix with coarse shelly fragments
14 - 18m	Creamy calcrete with fine brown pebbles of cemented calcrete
18.8m	Water strike
19m	Creamy calcrete with fine brown pebbles of cemented calcrete
20 - 25m	Creamy calcrete with fine to coarse quartzose sand
26m	Water strike
27.2m	Very hard layer of cemented calcrete
28 - 30m	Creamy calcrete with fine to coarse quartzose sand
30m	Hard cemented calcrete layer
31.8m	Hard cemented calcrete layer
32 - 33m	Creamy calcrete with fine to coarse quarzose sand
33.5m	Extremely hard layer of brown cemented calcrete
34 - 38m	Creamy calcrete with fine to coarse quartzose sand with angular brown cemented calcrete pebbles
38.6m	Hard layer of brown cemented calcrete
39.2m	Hard layer of brown cemented calcrete
40 - 45m	Creamy calcrete with fine to coarse quartzose sand with angular brown cemented calcrete pebbles
45.2m	Hard layer of brown cemented calcrete
46 - 48m	Creamy calcrete with fine to coarse quartzose sand with angular brown cemented calcrete pebbles
48m	Extremely hard layer. T.M.S. Quartzite contact

BOREHOLE CASED OFF WITH STEEL. AIR PERCUSSION FURTHER

49 - 53m	Very fine to coarse angular grey and cream quartzite pebbles
53.2m	Water strike estimated 0.1 L/s
54 - 62m	Very fine to coarse angular grey and cream quartzite pebbles

63m	Very fine to coarse angular grey and cream quartzite pebbles with phyllitic particles
63m	Water strike estimated 0.2 L/s
64 - 68m	Very fine to coarse angular grey and cream quartzite pebbles
68.5m	Water strike measured 0.3 L/s
69 - 70m	Very fine to coarse angular grey and cream quarzite pebbles

STOPPED

LOGGED BY A.J. HöN

DRILLING LOG OF BOREHOLE G39942 AT STRUISBAAI

DRILLED DATE	8/9/93
DRILLING COMPANY	J.J. Myburgh and bros.
DRILLER	J. van Zyl
DRILLING METHOD	Mud Rotary with Tri cone bit and Air percussion

GEOLOGICAL FIELD LOG

0 - 2m	No Sample
2.5m	Hard layer. Cemented calcrete
2 - 7m	Creamy calcrete with fine to coarse well rolled quartzose sand
7.5m	Very hard layer Brown cemented calcrete
7.8m	Well losses till 10m
7 - 10m	Fine pebbles of brown cemented calcrete 10.8m Hard layer. T.M.S. contact
11m	Fine pebbles of brown cemented calcrete and fine pebbles of white quartsite
12m	Extremely hard layer.

BOREHOLE CASED OFF WITH STEEL. AIR PERCUSSION FURTHER

13 - 14m	Very fine to coarse angular grey and cream quartzite pebbles
14.2m	Water strike Not measured
15 - 18m	Very fine to coarse angular grey and cream quartzite pebbles
18.2m	Water strike estimated 0.1 L/s
19 - 32m	Very fine to coarse angular grey and cream quartzite pebbles
32m	Blow yield estimated 0.3 L/s
33 - 40m	Very fine to coarse angular grey and cream quartzite pebbles
40m	Blow yield Measured 0.59 L/s
41 - 46m	Very fine to coarse angular grey and cream quartzite pebbles
46.3m	Water strike not measured
47 - 49m	Very fine to coarse angular grey and cream quartzite pebbles with ferrous intrusions
49m	Soft phyllitic layer
49 - 51m	Very fine to coarse angular grey and cream quartzite pebbles with phyllitic pebbles Water strike Blow yield measured 0.814 L/s

STOPPED

LOGGED BY A.J. Hön

DRILLING LOG OF BOREHOLE G39943 AT STRUISBAAI

DRILLED DATE	16/9/93
DRILLING COMPANY	J.J. Myburgh and bros.
DRILLER	J. van Zyl
DRILLING METHOD	Mud Rotary with Tri cone bit and Air percussion

GEOLOGICAL FIELD LOG

0 - 2m	Dark brown fine well rolled and sorted quartzose sand
3 - 8m	Light brown fine well rolled and sorted quartzose sand with coarse shell fragments
8.5m	Very hard layer. Brown cemented calcrete
8 - 10m	Fine pebbles of brown cemented calcrete in cream coloured calcrete
10.1m	50% well losses to 13m
11m - 14m	Fine pebbles of brown cemented calcrete in cream coloured calcrete
15m	Extremely hard layer. T.M.S. contact
15m	Fine pebbles of brown cemented calcrete and fine pebbles of white quartzite

BOREHOLE CASED OFF WITH STEEL. AIR PERCUSSION FURTHER

15 - 23m	Very fine to coarse angular grey and cream quartzite pebbles
23.2m	Water strike not measured
23 - 25m	Very fine to coarse angular grey and cream quartzite pebbles
25.2m - 25.5m	Soft weathered zone
25 - 27m	Very fine to coarse angular grey and cream quartzite pebbles
27.2m	Water strike not measured
27 - 33m	Very fine to coarse angular grey and cream quartzite pebbles. Weathered zone
33m	Blow yield measured 0.53 L/s
33 - 42m	Very fine to coarse angular grey and cream quartzite pebbles. Very weathered
42m	Hole collapsing Blow yield measured 1 L/s

STOPPED

LOGGED BY A J HÖN

BOREHOLE CONSTRUCTION AT STRUISBAAI

Borehole no.

G39940

Drilled to 12m using 300mm Tri Cone bit
3m Screen at base with end cap

Screen supplied

3m Slotted P.V.C.
186mm outside diameter
166mm inside diameter
5 vertical rows of 0.8mm slotsize
5mm horizontal spacing
110 mm not slotted at top
170 mm not slotted at bottom

Casing supplied

P.V.C. solid casing
180mm O.D.
166mm I.D.

Construction

320 Litres of 7/16 Consol gravel pack
Level up to 7m below surface
10mm grit pack to surface
1m square concrete block with lockable steel cap on surface

Borehole no.

G39941

Drilled to 48m using Tri Cone bit
300mm Steel casing down to 48m
Drilled to 71m using 212.5mm Air percussion
3m Screen at base with end cap

Screen supplied

3m of Slotted P.V.C. Screen
186mm Outside diameter
166mm Inside diameter
5 vertical rows of 2mm Slotsize
75 to 80mm O.D. Slot length
50mm I.D. Slot length
10mm horizontal spacing
170mm not slotted at top
110mm not slotted at bottom

Casing supplied

High impact P.V.C.
186mm Outside diameter
166mm Inside diameter
Casing fitted with wedges at 4m and 8m from base

Construction

200 Litres of 10mm Grit pack
Level up to 50m below surface
20 Litres of 7/16 Consol gravel pack level up to 49.5m below surface
1.5 bags of cement for plug below steel casing
1m Square concrete block with lockable steel cap on surface

Borehole no.

G39942

Drilled to 12m using 300mm Tri cone bit
300mm Steel casing to 12m
Drilled to 51m using 212.5mm air percussion
3m of Screen at base.

Screen supplied

3m of 2mm slot High impact P.V.C.
Same dimensions as G39941

Casing supplied

High impact P.V.C.
Same dimensions as previous boreholes

Construction

210 Litres of 10mm grit pack
Level up to 20m below surface
90 Litres of 7/16 Consol gravel pack
Level up to 14.2m below surface
4 bags of cement for plug
1m square concrete block with lockable steel cap on surface

Borehole no.

G39943

Drilled to 15m using 300mm Tri cone bit
300mm Steel casing to 15m
Drilled to 42m using 212.5mm air percussion
6m Screen at base with end cap

Screen supplied

3m of 0.8mm slotted P.V.C.
Same dimensions as G39940

Casing supplied

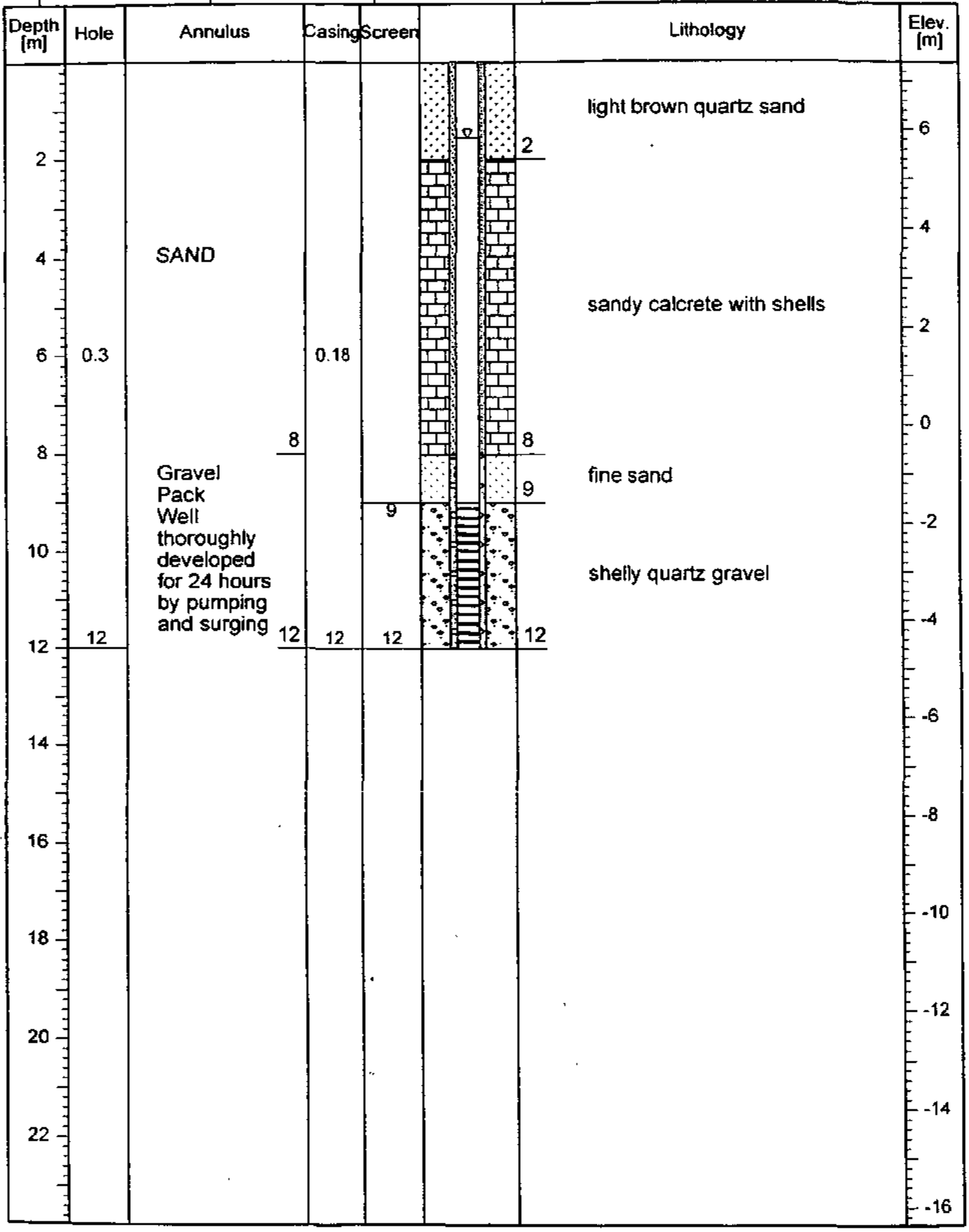
High impact P.V.C.
Same dimensions as previous boreholes

Construction

270 Litres of 7/16 Consol gravel pack
Level up to 21m below surface
30 Litres of 10mm grit pack
Level up to 20m below surface
4 bags of cement for plug
1m square concrete block with lockable steel cap on surface

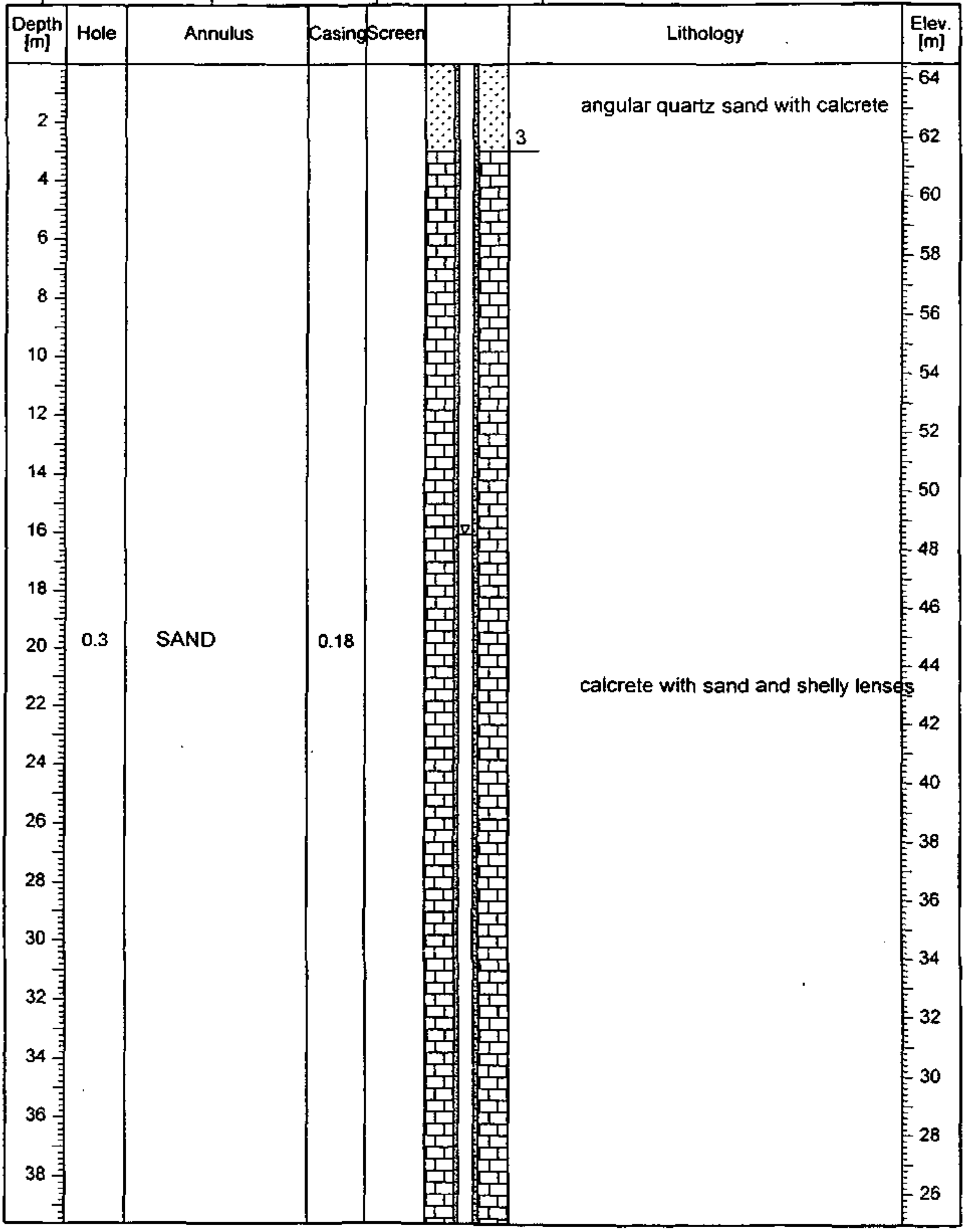
Struisbaai

Well Ident G39940			
Drilling Date 20 August 1993	SWL 5.83	Use Exploration	
Vert.Scale 120.0	Hor.Scale 50.0	Drilling Method Mud rotary with Tri cone bit	
X 50226	Y 88616	ZM	



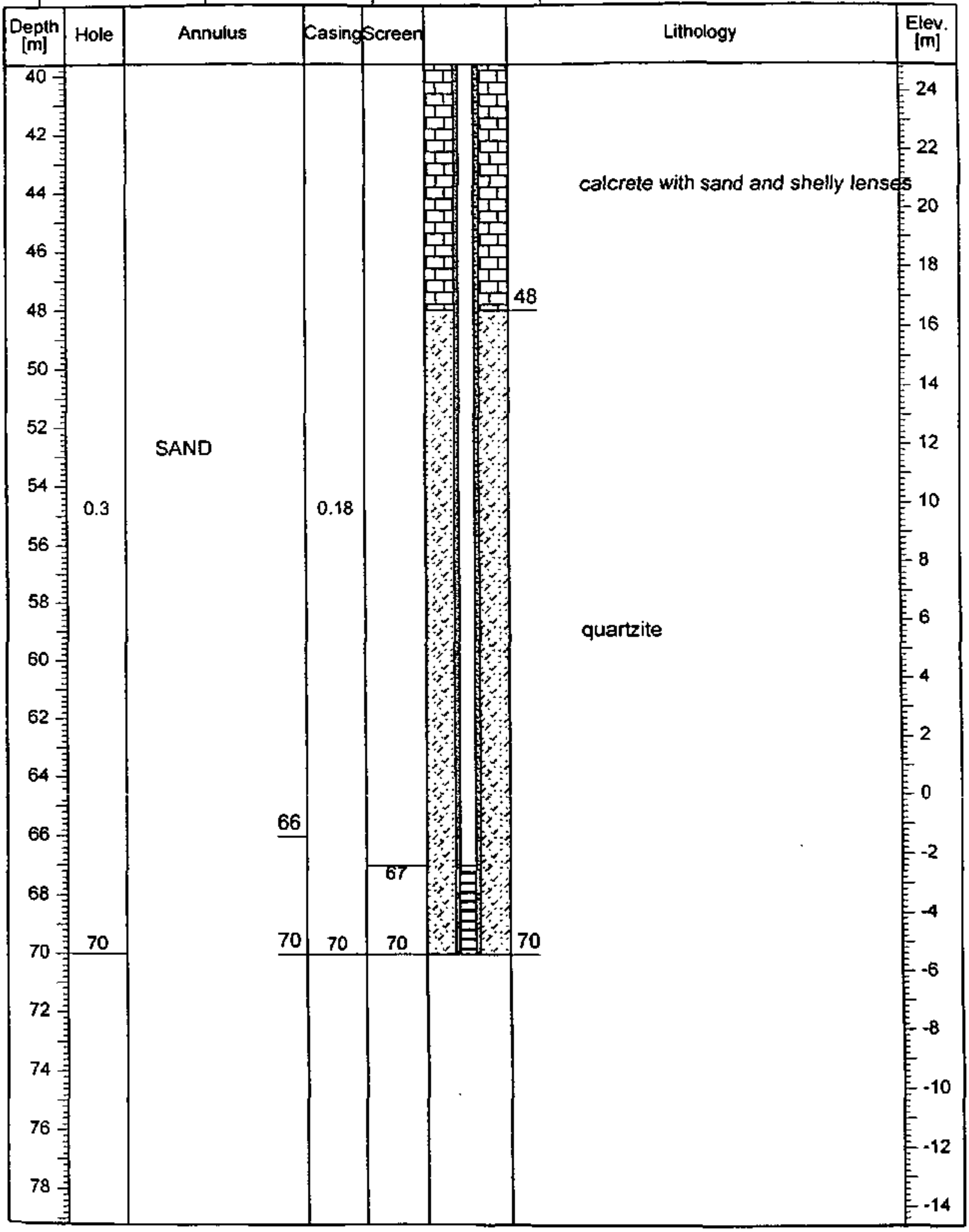
Struisbaai

Well Ident G39941			
Drilling Date 2 September 199	SWL 48.50	Use Exploration	
Vert.Scale 200.0	Hor.Scale 75.0	Drilling Method Mud rotary and air percussion	
X 53529	Y 88598	Z 64.52	



Struisbaai

Well Ident G39941			
Drilling Date 2 September 199	SWL 48.50	Use Exploration	
Vert.Scale 200.0	Hor.Scale 75.0	Drilling Method Mud rotary and air percussion	
X 53529	Y 88598	Z 64.52	



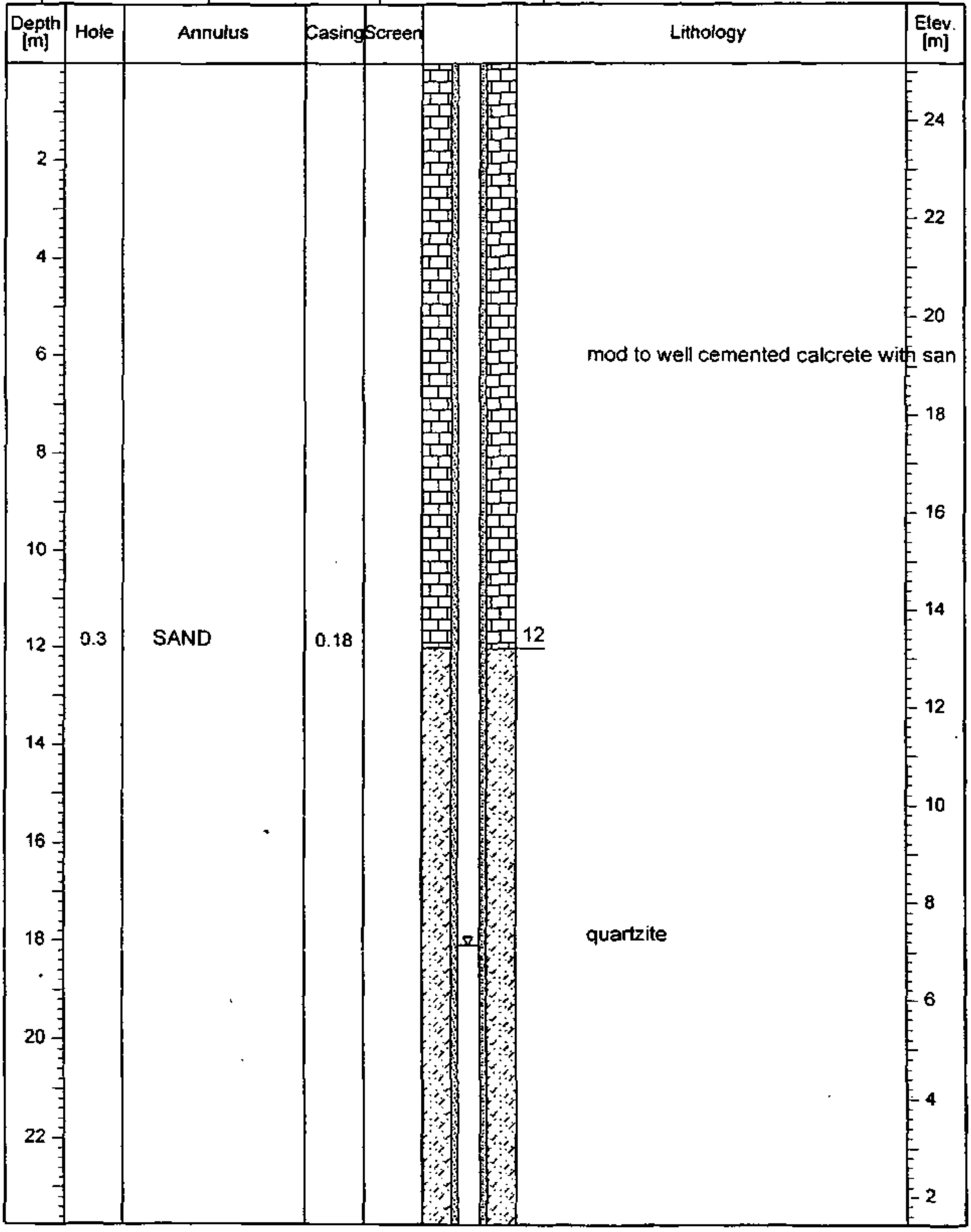
Struisbaai

Well Ident	G39942

Drilling Date	SWL	Use
8 September 199	7.10	Exploration

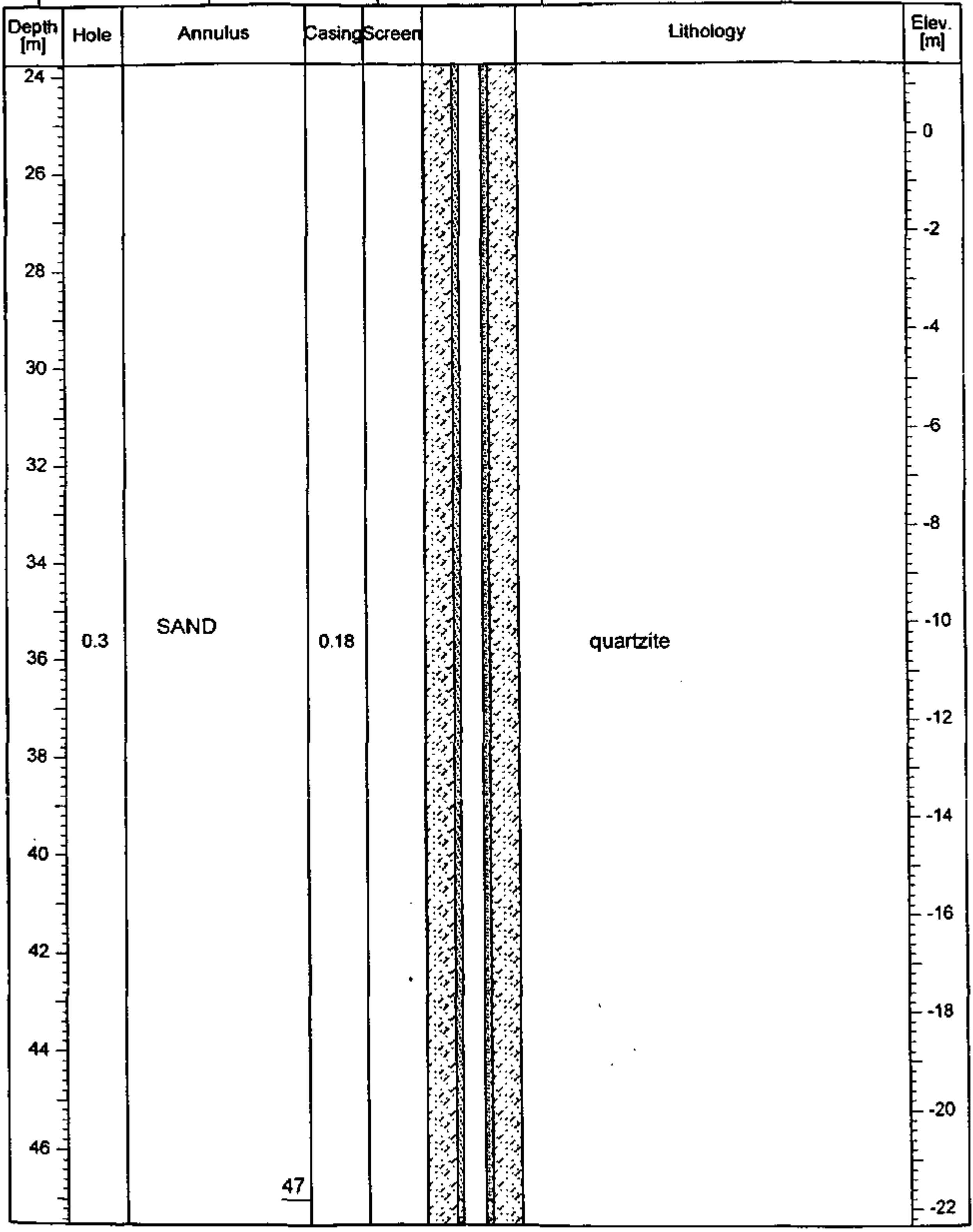
Vert.Scale	Hor.Scale	Drilling Method
120.0	50.0	Mud rotary and air percussion

X	Y	Z
51698	90819	25.17



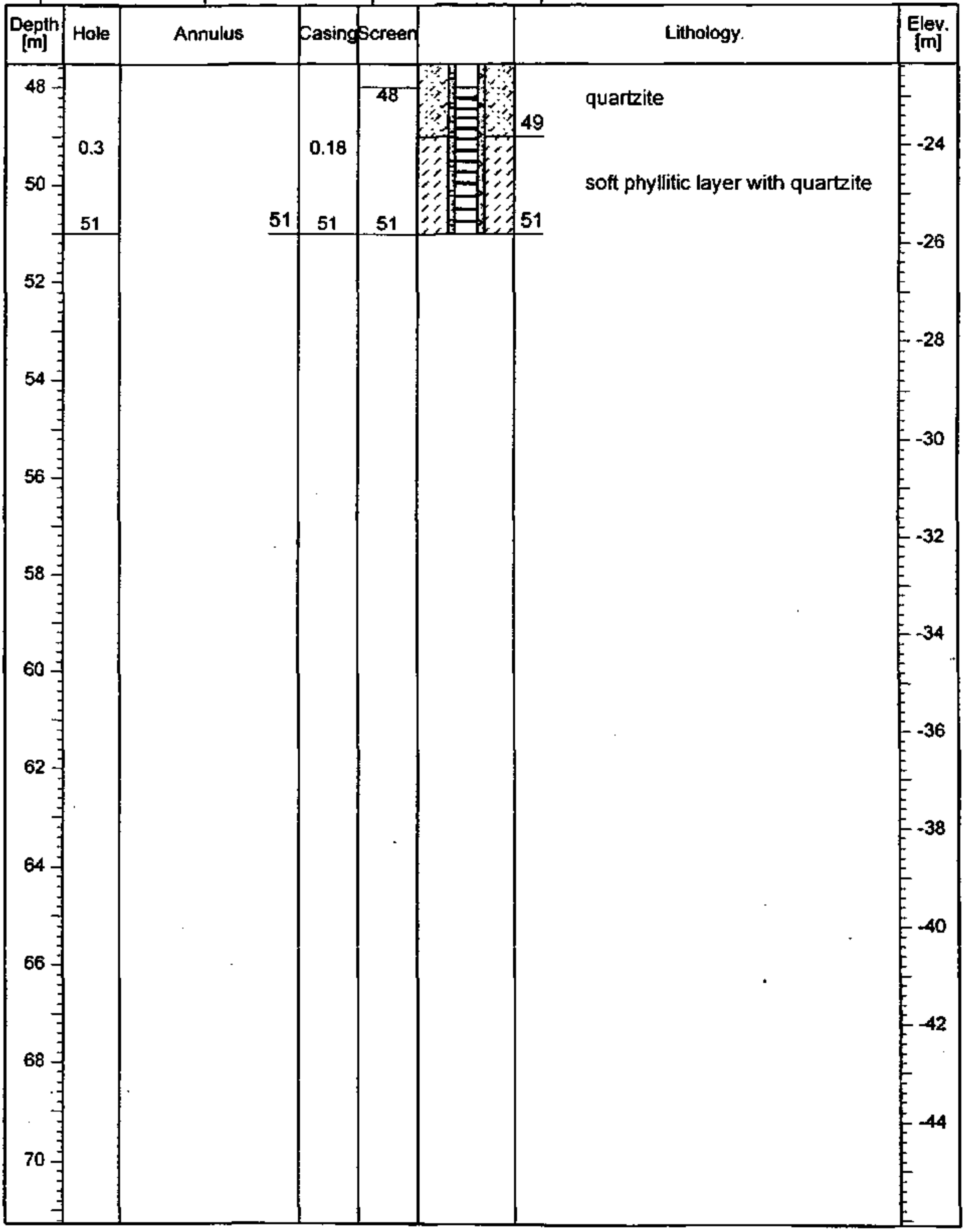
Struisbaai

Well Ident G39942			
Drilling Date 8 September 199	SWL 7.10	Use Exploration	
Vert.Scale 120.0	Hor.Scale 50.0	Drilling Method Mud rotary and air percussion	
X 51698	Y 90819	Z 25.17	



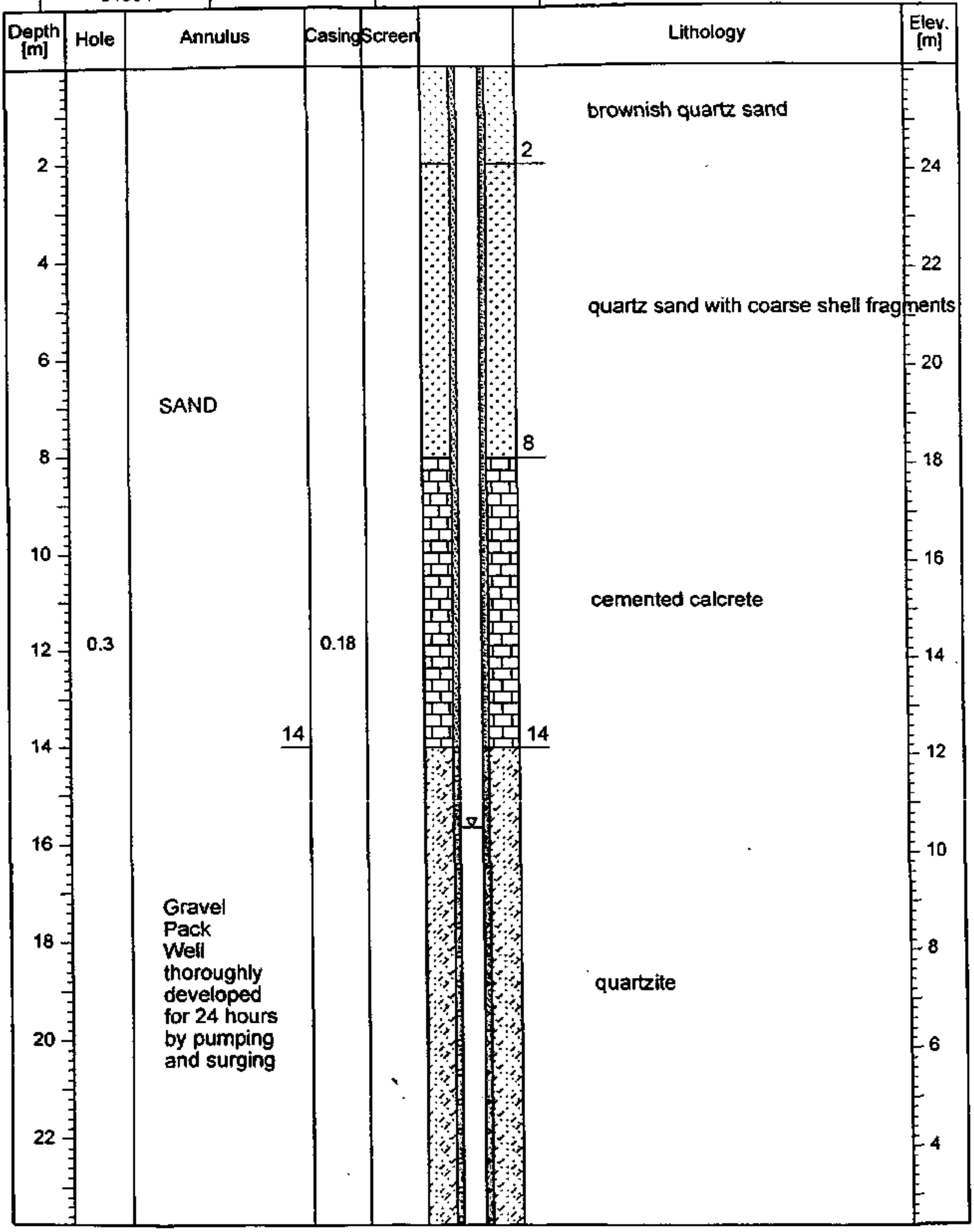
Struisbaai

Well Ident G39942			
Drilling Date 8 September 199	SWL 7.10	Use Exploration	
Vert.Scale 120.0	Hor.Scale 50.0	Drilling Method Mud rotary and air percussion	
X 51698	Y 90819	Z 25.17	



Struisbaai

Well Ident G39943		
Drilling Date 16 September 19	SWL 10.50	Use Exploration
Vert.Scale 120.0	Hor.Scale 50.0	Drilling Method Mud rotary and air percussion
X 51951	Y 90426	Z 26.13



Struisbaai

Well Ident G39943			
Drilling Date 16 September 19	SWL 10.50	Use Exploration	
Vert.Scale 120.0	Hor.Scale 50.0	Drilling Method Mud rotary and air percussion	
X 51951	Y 90426	Z 26.13	

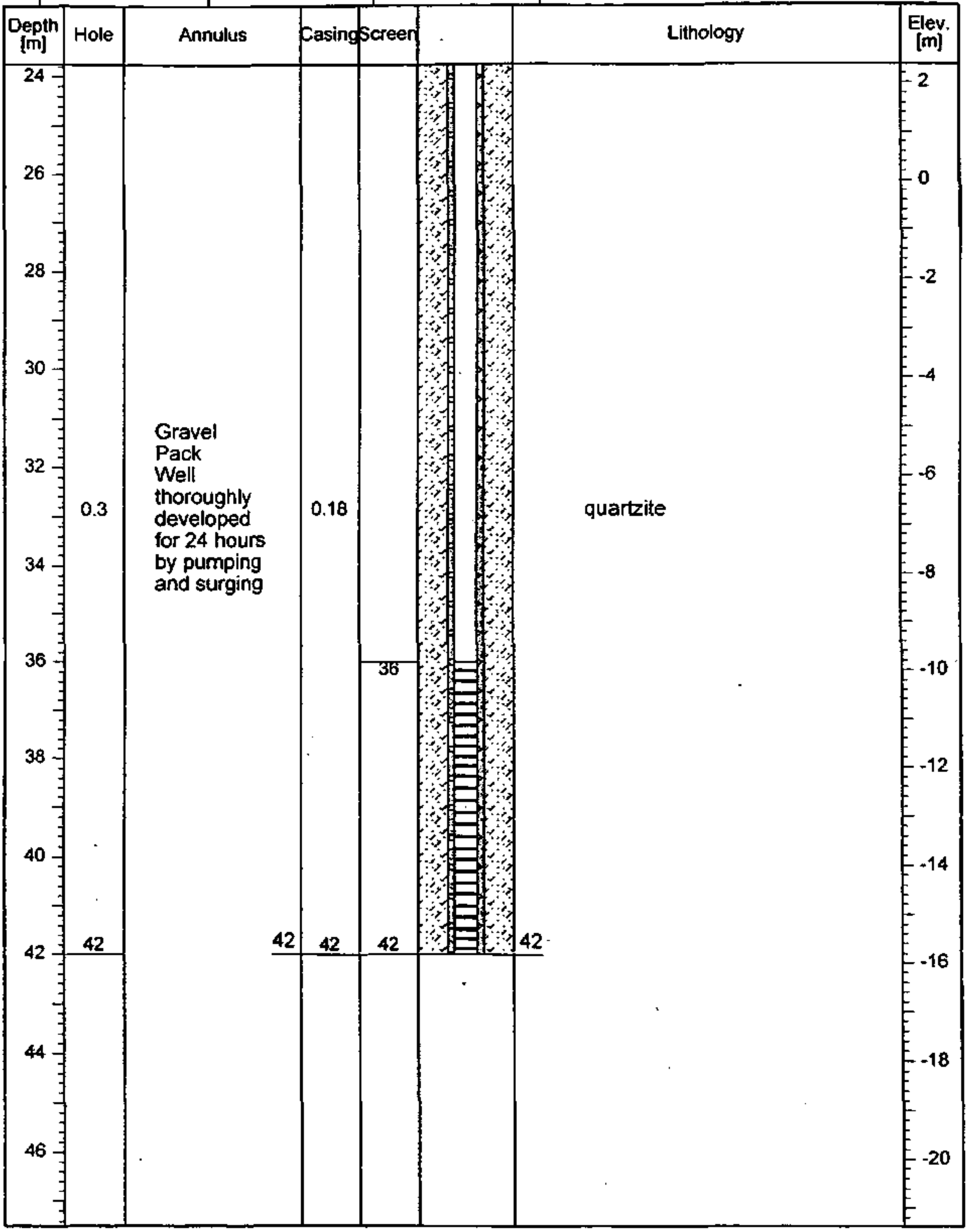


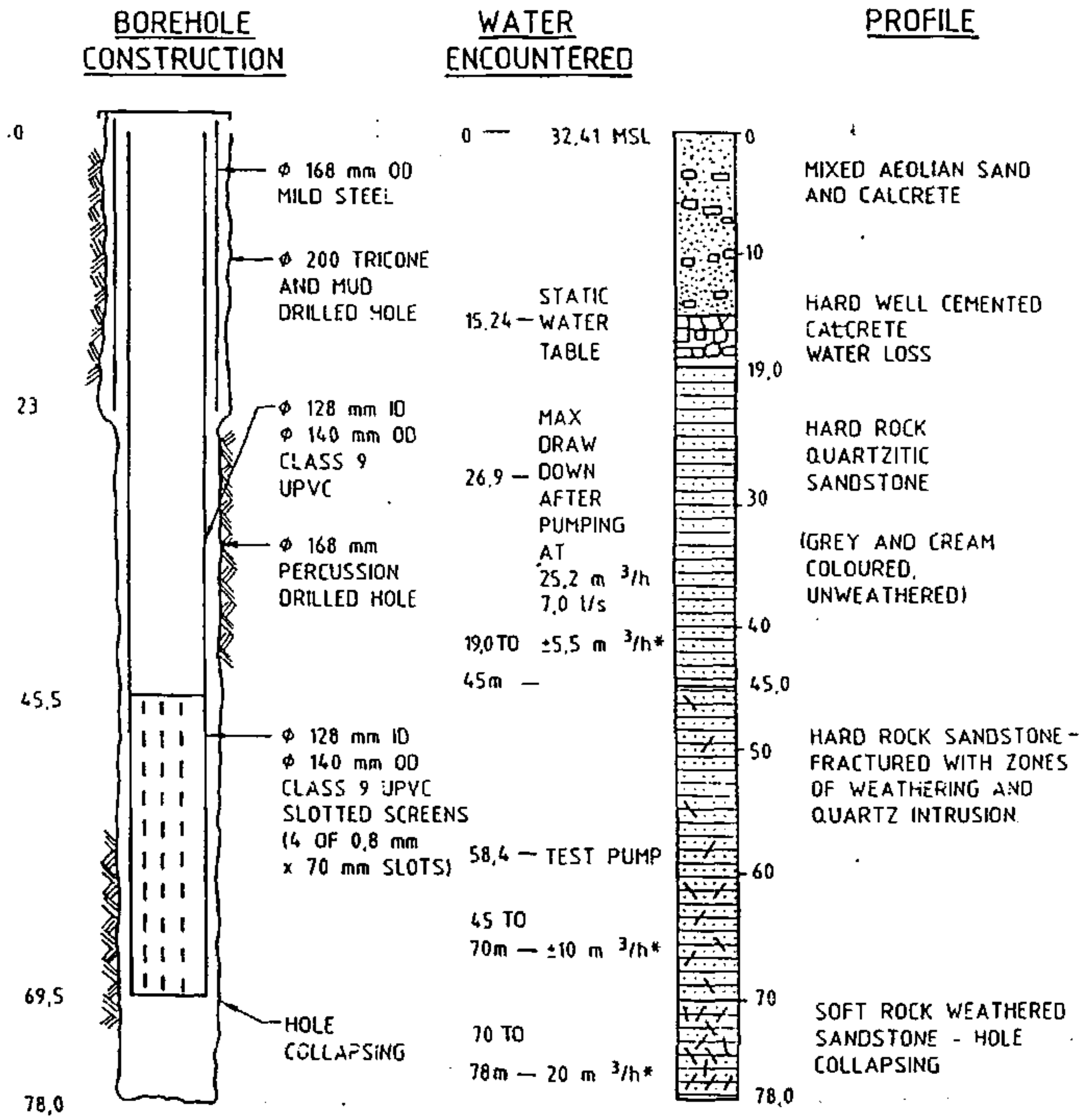
TABLE 1

STRUISBAAI - ERF 920

SUMMARY OF PRODUCTION BOREHOLE DATA

BOREHOLE	P1		P2	
LOCATION Y:	90 735,35		91 034,82	
LOCATION X:	51 886,96		51 904,96	
ELEVATION	32,41		40,52	
	DEPTH Below Surface (m)	ELEVATION (MSL)	DEPTH Below Surface (m)	ELEVATION (MSL)
Bredasdorp Formation:	19,00	13,41	28,50	12,20
Borehole base:	78,00	-45,59	100,00	-59,48
Water inflow:	45 to 70,00	-13 to -38,00	70 to 100,00	-29 to -59
Static water level:	13,10	19,30	23,07	17,52
Test pump location:	58,40	-25,99	66,86	-26,34
Constant delivery:				
Test yield: (m^3/hr)	25,20m^3/hr		46m^3/hr	
Max drawdown after 72 hours:	24,82	7,59	44,46	-3,94
Hole diameter (OD)	168mm		200mm	
Casing diameter (OD)	140mm		-	
(ID)	128mm		-	
Type	UPVC class 9		-	
Screens	UPVC class 9 0,8mm slots		-	
Conductivity (mS/m)	97,8		98,4	
TDS (mg/1)	636		639	

P1



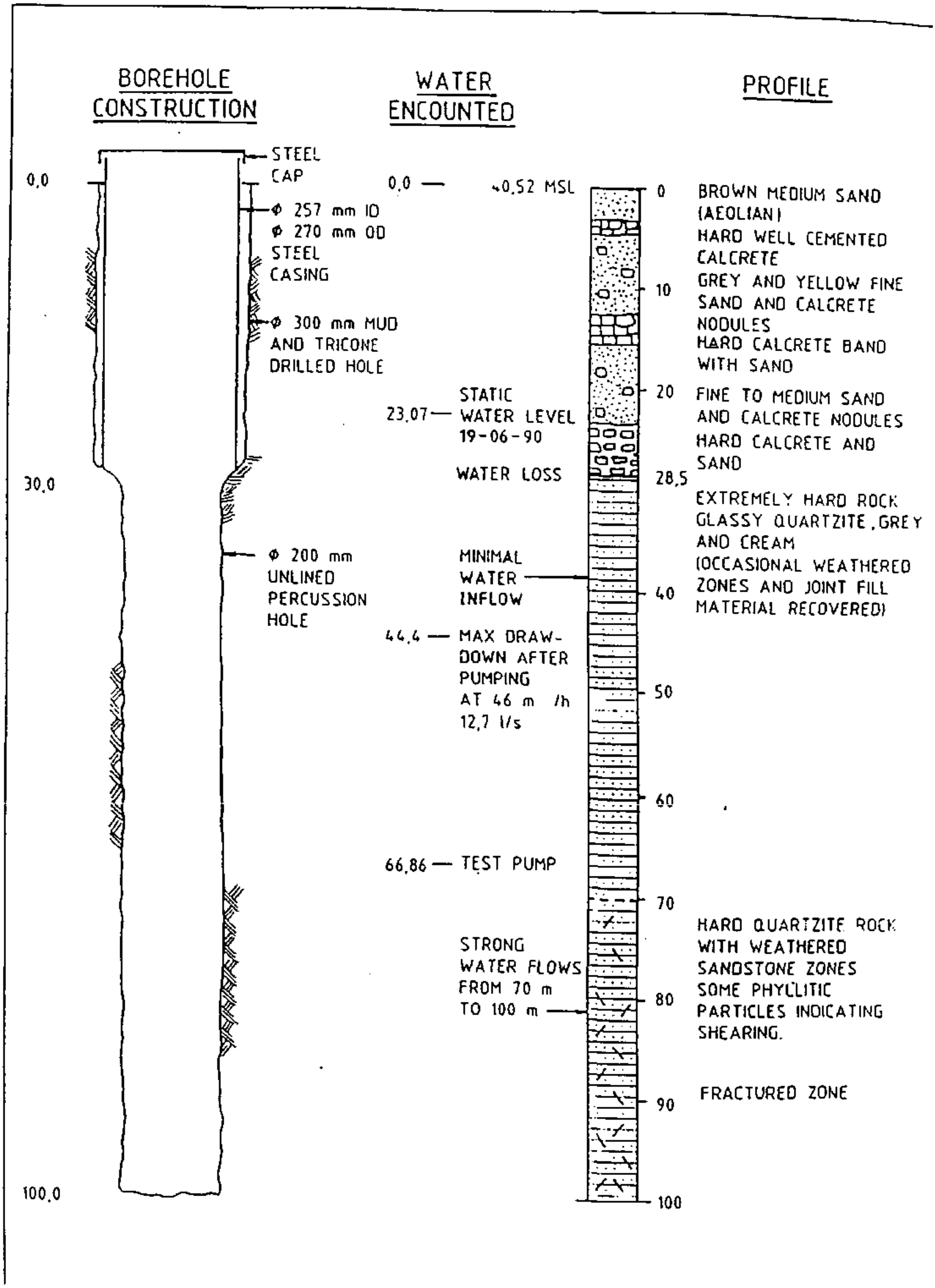
* ESTIMATED FLOWS

DATE DRILLED : 20 - 25 MAY 1990

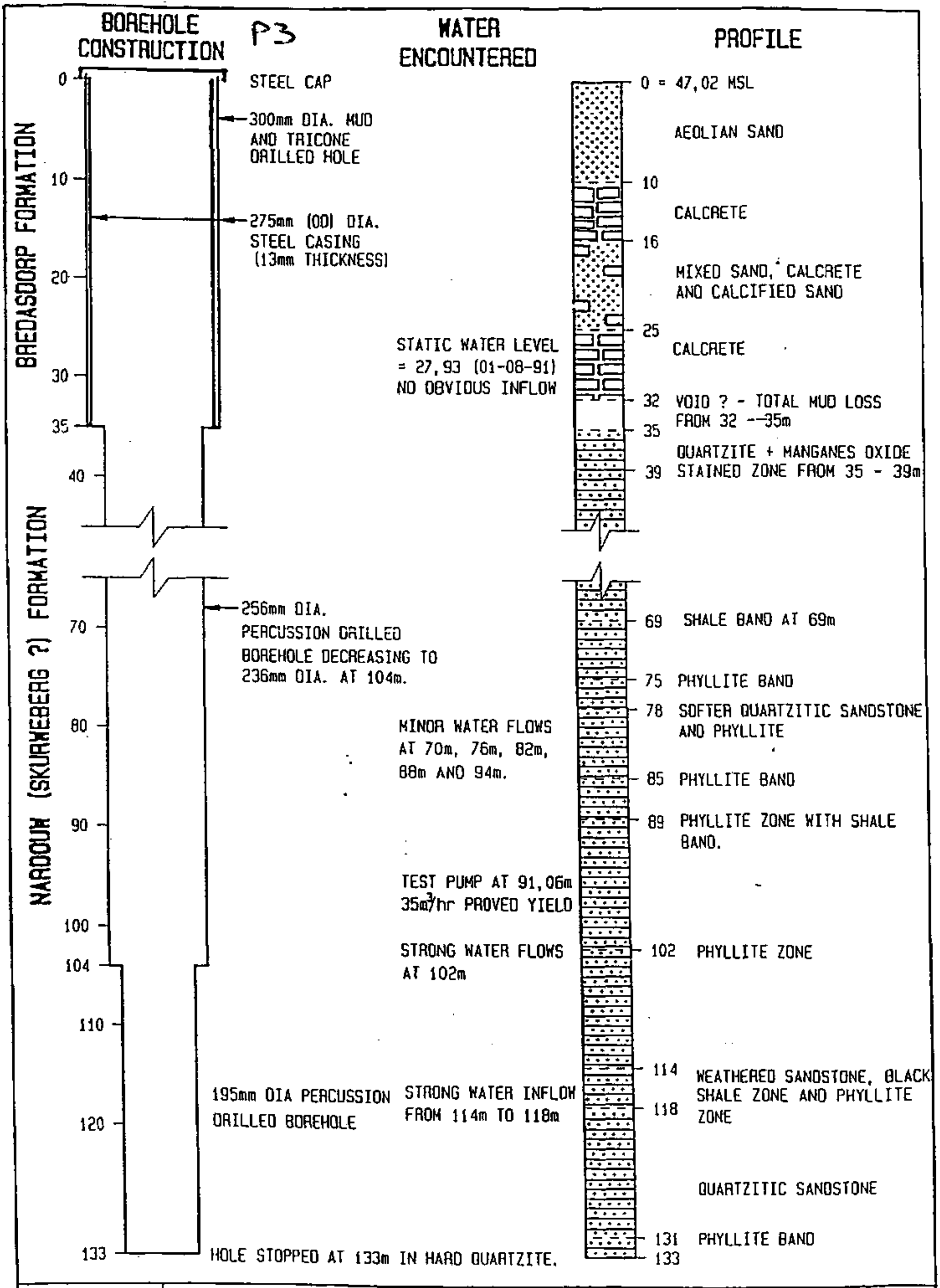
DATE TESTED : 5 - 8 JUNE 1990

CO-ORDINATES
X : 51 886,96
Y : 90 753,35

P2


BOREHOLE CONSTRUCTION
WATER ENCOUNTED
PROFILE
0,0
30,0
100,0
STEEL CAP
Φ 257 mm ID
Φ 270 mm OD
STEEL CASING
Φ 300 mm MUD AND TRICONE DRILLED HOLE
Φ 200 mm UNLINED PERCUSSION HOLE
0,0 — +0,52 MSL
23,07 — STATIC WATER LEVEL 19-06-90
WATER LOSS
MINIMAL WATER INFLOW
44,4 — MAX DRAW-DOWN AFTER PUMPING AT 46 m /h 12,7 l/s
66,86 — TEST PUMP
STRONG WATER FLOWS FROM 70 m TO 100 m
0
10
20
28,5
40
50
60
70
80
90
100
BROWN MEDIUM SAND (AEOLIAN)
HARD WELL CEMENTED CALCRETE
GREY AND YELLOW FINE SAND AND CALCRETE NODULES
HARD CALCRETE BAND WITH SAND
FINE TO MEDIUM SAND AND CALCRETE NODULES
HARD CALCRETE AND SAND
EXTREMELY HARD ROCK GLASSY QUARTZITE, GREY AND CREAM (OCCASIONAL WEATHERED ZONES AND JOINT FILL MATERIAL RECOVERED)
HARD QUARTZITE ROCK WITH WEATHERED SANDSTONE ZONES SOME PHYLLITIC PARTICLES INDICATING SHEARING.
FRACTURED ZONE

P3



STEEL CAP

300mm DIA. MUD AND TRICONE DRILLED HOLE

275mm (OD) DIA. STEEL CASING (13mm THICKNESS)

256mm DIA. PERCUSSION DRILLED BOREHOLE DECREASING TO 236mm DIA. AT 104m.

195mm DIA PERCUSSION DRILLED BOREHOLE

HOLE STOPPED AT 133m IN HARD QUARTZITE.

STATIC WATER LEVEL = 27,93 (01-08-91) NO OBVIOUS INFLOW

MINOR WATER FLOWS AT 70m, 76m, 82m, 88m AND 94m.

TEST PUMP AT 91,06m 35m³/hr PROVED YIELD

STRONG WATER FLOWS AT 102m

STRONG WATER INFLOW FROM 114m TO 118m

0 = 47,02 MSL

AEOLIAN SAND

CALCRETE

MIXED SAND, CALCRETE AND CALCIFIED SAND

CALCRETE

VOID ? - TOTAL MUD LOSS FROM 32 - 35m

QUARTZITE + MANGANES OXIDE STAINED ZONE FROM 35 - 39m

SHALE BAND AT 69m

PHYLLITE BAND

SOFTER QUARTZITIC SANDSTONE AND PHYLLITE

PHYLLITE BAND

PHYLLITE ZONE WITH SHALE BAND.

PHYLLITE ZONE

WEATHERED SANDSTONE, BLACK SHALE ZONE AND PHYLLITE ZONE

QUARTZITIC SANDSTONE

PHYLLITE BAND

STRUISBAAI ERF 920 PRODUCTION BOREHOLE P3	SHEET No. A1

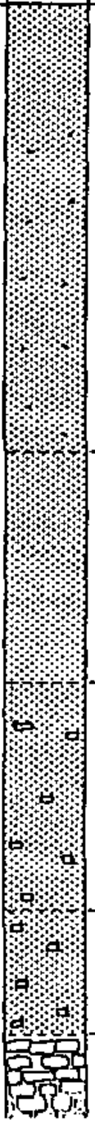
BOREHOLE LOG

BOREHOLE No. : T 1
SHEET : 1 OF 2

DRILL METHOD	SIZE	DEPTH
ROTARY TRICONE	100mm	18,3

MACHINE :
DRILLER : G Myburgh
DRILLING CONTRACTOR : Myburgh Bros

CLIENT : ESP
PROJECT : STRUISBAAI
SITE : STRUISBAAI - ERF 920
ORIENTATION : VERTICAL ELEVATION : 28,77
CO-ORDINATES : Y 90 773,14 X 51 823,93
DATE STARTED : 09/05/90 DATE COMPLETED : 09/05/90
DEPTH TO WATER TABLE : 11,86 LOGGED BY : RKM



DEPTH (m)	REC	DRILL METHOD	RQD %	REMARKS	PROFILE	MATERIAL DESCRIPTION	DEPTH (m)
1 2 3				Initial Water Level = 5,46 Blow out test after one hour = 0,15l/s (0,54 m³/hr) Final water level = 11,86 7/3/93 WL = 12,52 Drill = 18,63 below collar		Light grey, subrounded fine grained to medium grained SAND. Scattered broken shell particles.	4,00
4 5						Fine grained SAND.	6,00
6 7						Light grey and yellow medium grained SAND with calcareous nodules.	8,00
8 9						Grey and yellow medium grained calcareous SAND.	9,10
						Hard, well cemented CALCRETE, orange and yellow with some weaker bands	

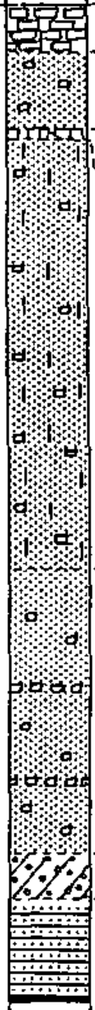
BOREHOLE LOG

BOREHOLE No. : T 1
SHEET : 2 OF 2

DRILL METHOD	SIZE	DEPTH
ROTARY TRICONE	100mm	18,3

MACHINE :
DRILLER : G Myburgh
DRILLING CONTRACTOR : Myburgh Bros

CLIENT : ESP
PROJECT : STRUISBAAI
SITE : STRUISBAAI - ERF 920
ORIENTATION : VERTICAL ELEVATION : 28,77
CO-ORDINATES : Y 90 773,14 X 51 823,93
DATE STARTED : 09/05/90 DATE COMPLETED : 09/05/90
DEPTH TO WATER TABLE : 11,86 LOGGED BY : RKM



DEPTH (m)	REC	DRILL METHOD	RQD %	REMARKS	PROFILE	MATERIAL DESCRIPTION	DEPTH (m)
						Hard, calcrete continued	10,40
11						Soft calcareous SAND	11,10
						Very hard, well cemented CALCRETE band	11,20
12 13 14						Soft calcareous gravel and silty SAND.	15,00
15 16 17						SAND with first signs of broken shell particles. Medium grained with some calcareous particles and zones of calcrete.	17,50
						WATER LOSS ZONE. Quarz pebbles and white clay zone.	17,90
18						Very hard rock, grey quartzite particles. Table Mountain Group. Peninsula formation ?	18,30
19							

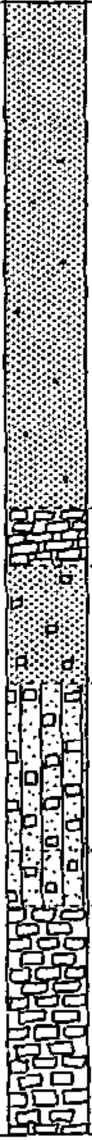
BOREHOLE LOG

BOREHOLE No. : T 2
SHEET : 1 OF 2

DRILL METHOD	SIZE	DEPTH
ROTARY TRICONE	100mm	0 - 12,5

MACHINE :
DRILLER : *G Myburgh*
DRILLING CONTRACTOR : *Myburgh Bros*

CLIENT : *ESP*
PROJECT : *STRUISBAAI*
SITE : *STRUISBAAI - ERF 920*
ORIENTATION : *VERTICAL* ELEVATION : *24,3*
CO-ORDINATES : *Y 91 137,17* *X 51 719,67*
DATE STARTED : *10/05/90* DATE COMPLETED : *10/05/90*
DEPTH TO WATER TABLE : *4,3* LOGGED BY : *RKM*



DEPTH (m)	REC	DRILL METHOD	RQD %	REMARKS	PROFILE	MATERIAL DESCRIPTION	DEPTH (m)
				Initial Water Level = 5,15 m. Blow out test after 1 hour = 0,085l/s (0,306 m^3/hr). Final Water Level = 10,05 m. Recovery to 5,0m in 14 minutes.		Fine to medium grained, subrounded SAND with fine grained shell particles.	4,50
						Zone of harder CALCRETE	5,00
						Fine grained SAND with scattered calcareous zones	6,00
						Layers of soft CALCRETE & CALCAREOUS SILT ± 100 to 200mm thick with harder well cemented CALCRETE.	7,50
						As above but yellow calcareous material from 7,5m.	8,00
10						Hard to medium hard rock CALCRETE.	

VAN NIEKERK, KLEYN & EDWARDS FIGURE NO: A 3

BOREHOLE LOG

BOREHOLE No. : T 2
SHEET : 2 OF 2

DRILL METHOD	SIZE	DEPTH
ROTARY TRICONE	100mm	0 - 12,5

MACHINE :
DRILLER : *G Myburgh*
DRILLING CONTRACTOR : *Myburgh Bros*

CLIENT : *ESP*
PROJECT : *STRUISBAAI*
SITE : *STRUISBAAI - ERF 920*
ORIENTATION : *VERTICAL* ELEVATION : *29,0*
CO-ORDINATES : *Y 91 137,17* *X 51 719,67*
DATE STARTED : *10/05/90* DATE COMPLETED : *10/05/90*
DEPTH TO WATER TABLE : LOGGED BY : *RKM*

DEPTH (m)	REC	DRILL METHOD	RQD %	REMARKS	PROFILE	MATERIAL DESCRIPTION	DEPTH (m)
				Water loss from this zone.		Hard to medium hard rock CALCRETE. Some shelly gravel	11,5
						Hard quartzitic sandstone. Table Mountain Group.	12,5

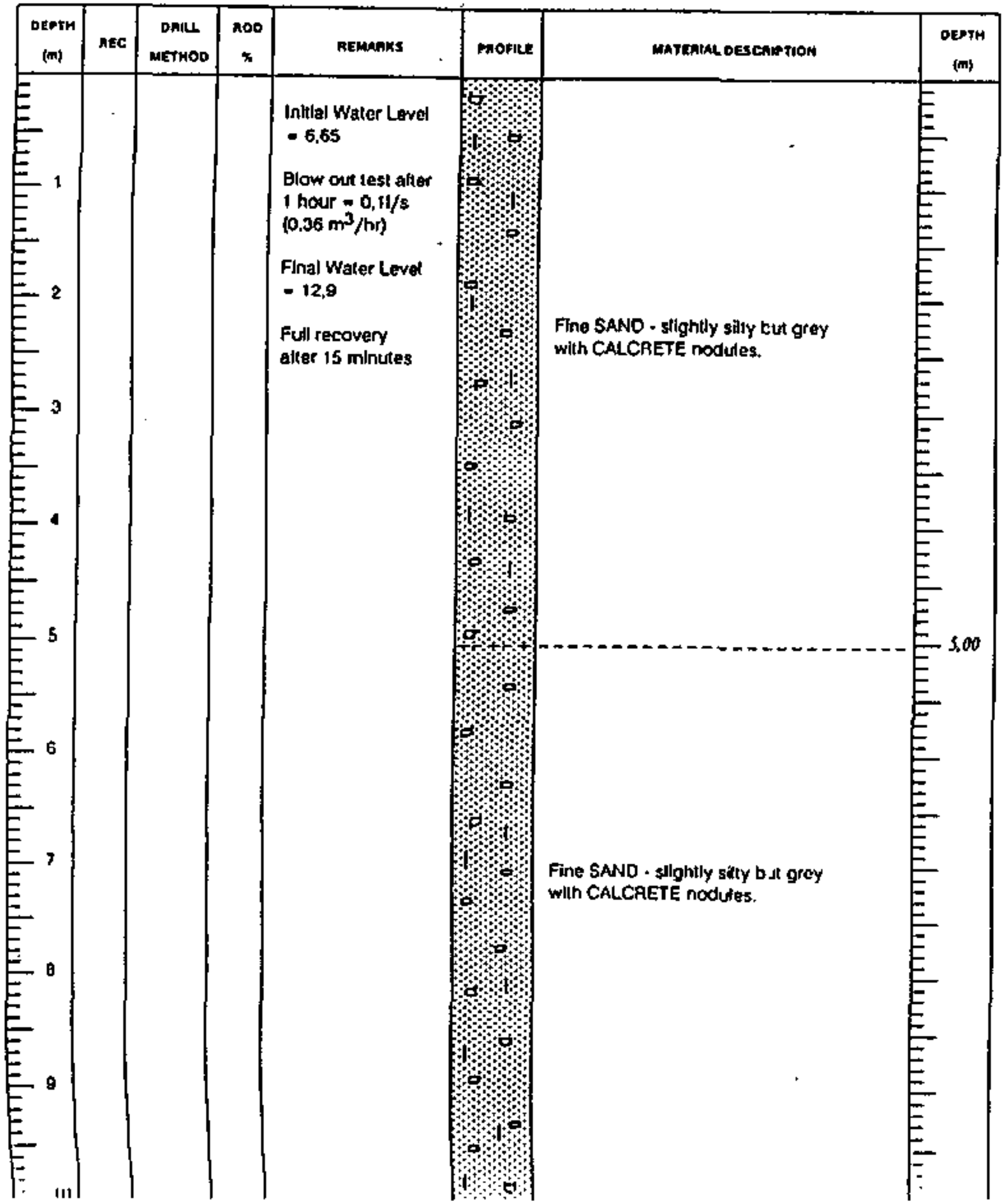
BOREHOLE LOG

BOREHOLE No. : *T 3*
SHEET : *1* OF *2*

DRILL METHOD	SIZE	DEPTH
ROTARY TRICONE	100mm	0 - 18,3

MACHINE :
DRILLER : *G Myburgh*
DRILLING CONTRACTOR : *Myburgh Bros*

CLIENT : *ESP*
PROJECT : *STRUISBAAI*
SITE : *STRUISBAAI - ERF 920*
ORIENTATION : *VERTICAL*
ELEVATION : *26,12*
CO-ORDINATES : *Y 91 422,97* *X 51 676,60*
DATE STARTED : *11/05/90*
DATE COMPLETED : *11/05/90*
DEPTH TO WATER TABLE : *6,65*
LOGGED BY : *RKM*



DEPTH (m)	REC	DRILL METHOD	ROD %	REMARKS	PROFILE	MATERIAL DESCRIPTION	DEPTH (m)
				Initial Water Level = 6,65 Blow out test after 1 hour = 0,1l/s (0.36 m^3/hr) Final Water Level = 12,9 Full recovery after 15 minutes		Fine SAND - slightly silty but grey with CALCRETE nodules.	5,00
						Fine SAND - slightly silty but grey with CALCRETE nodules.	

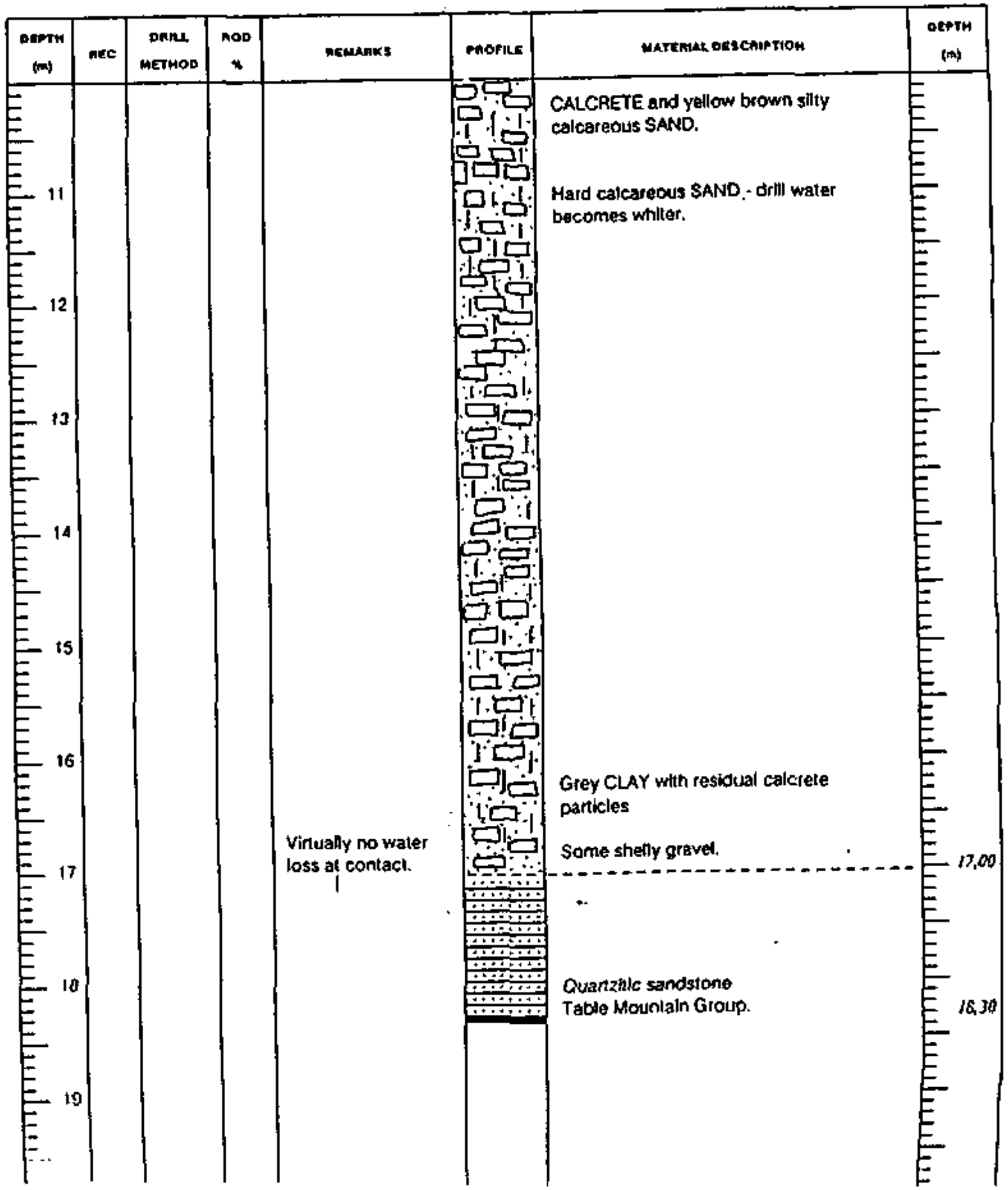
BOREHOLE LOG

BOREHOLE No. : *T 3*
SHEET : *2* OF *2*

DRILL METHOD	SIZE	DEPTH
ROTARY TRICONE	100mm	0 - 18,3

MACHINE :
DRILLER : *G Myburgh*
DRILLING CONTRACTOR : *Myburgh Bros*

CLIENT : *ESP*
PROJECT : *STRUISBAAI*
SITE : *STRUISBAAI - ERF 920*
ORIENTATION : *VERTICAL*
ELEVATION : *26,12*
CO-ORDINATES : *Y 91 422,97* *X 51 676,6*
DATE STARTED : *11/05/90*
DATE COMPLETED : *11/05/90*
DEPTH TO WATER TABLE : *11,86*
LOGGED BY : *RKM*



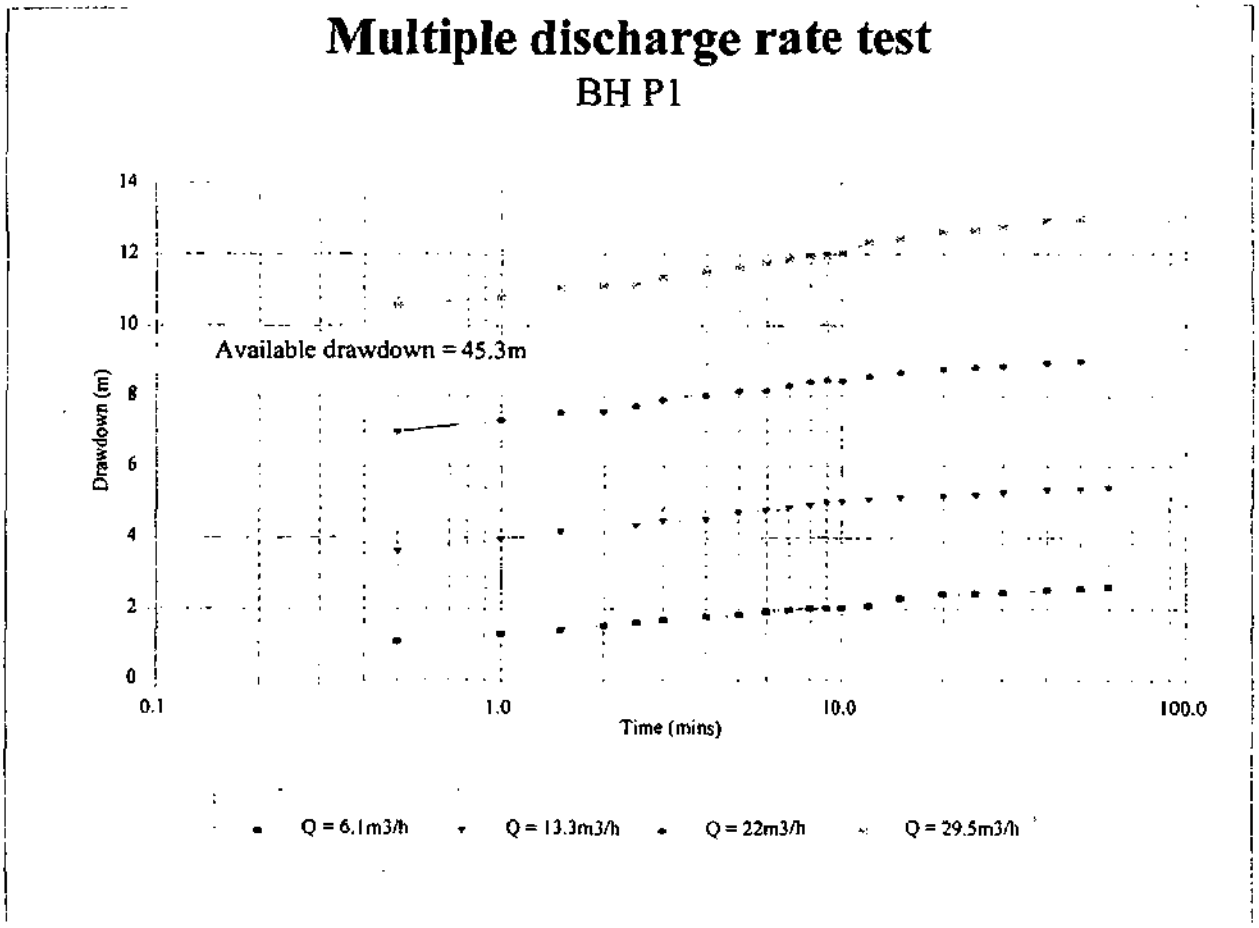
DEPTH (m)	REC	DRILL METHOD	ROD %	REMARKS	PROFILE	MATERIAL DESCRIPTION	DEPTH (m)
						CALCRETE and yellow brown silty calcareous SAND.	
						Hard calcareous SAND - drill water becomes whiter.	
						Grey CLAY with residual calcrete particles	
				Virtually no water loss at contact.		Some shelly gravel.	17,00
						Quartzitic sandstone Table Mountain Group.	18,30

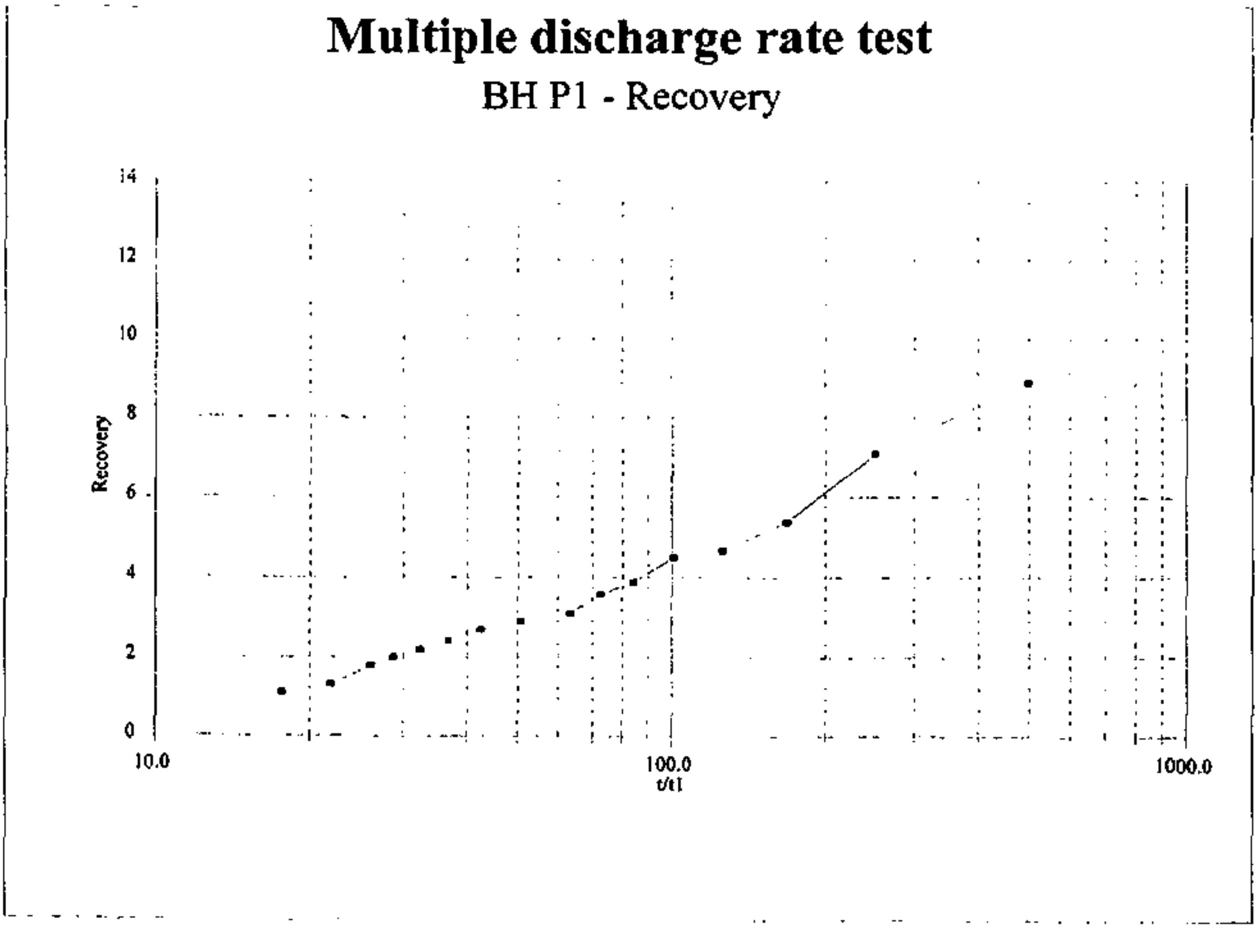
APPENDIX 2

TEST-PUMPING DATA

- Test-Pumping Graphs
- Boreholes P1, P2, P3 at Struisbaai

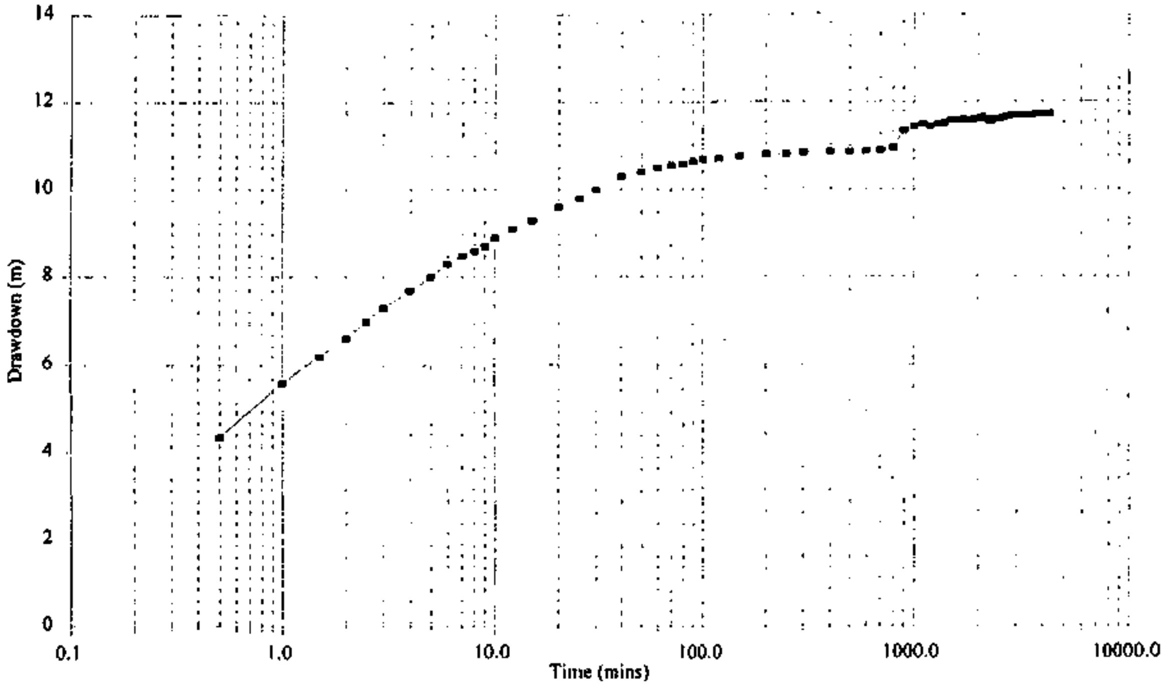
Data from McClea (1990 and 1991)


Multiple discharge rate test
BH P1
Available drawdown = 45.3m
Drawdown (m)
0
2
4
6
8
10
12
14
0.1
1.0
10.0
100.0
Time (mins)
Q = 6.1m3/h
Q = 13.3m3/h
Q = 22m3/h
Q = 29.5m3/h


Multiple discharge rate test
BH P1 - Recovery
Recovery
0
2
4
6
8
10
12
14
10.0
100.0
1000.0
t/t1

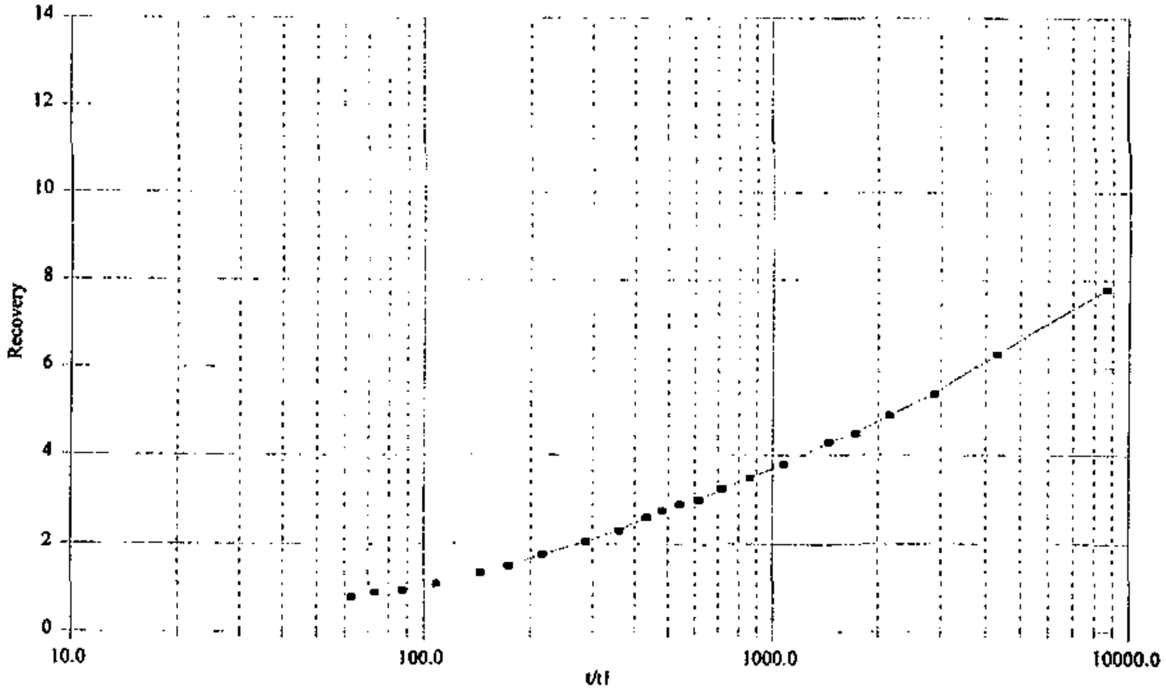
Constant discharge test: BH P1

Abstraction rate = 25.20m3/h



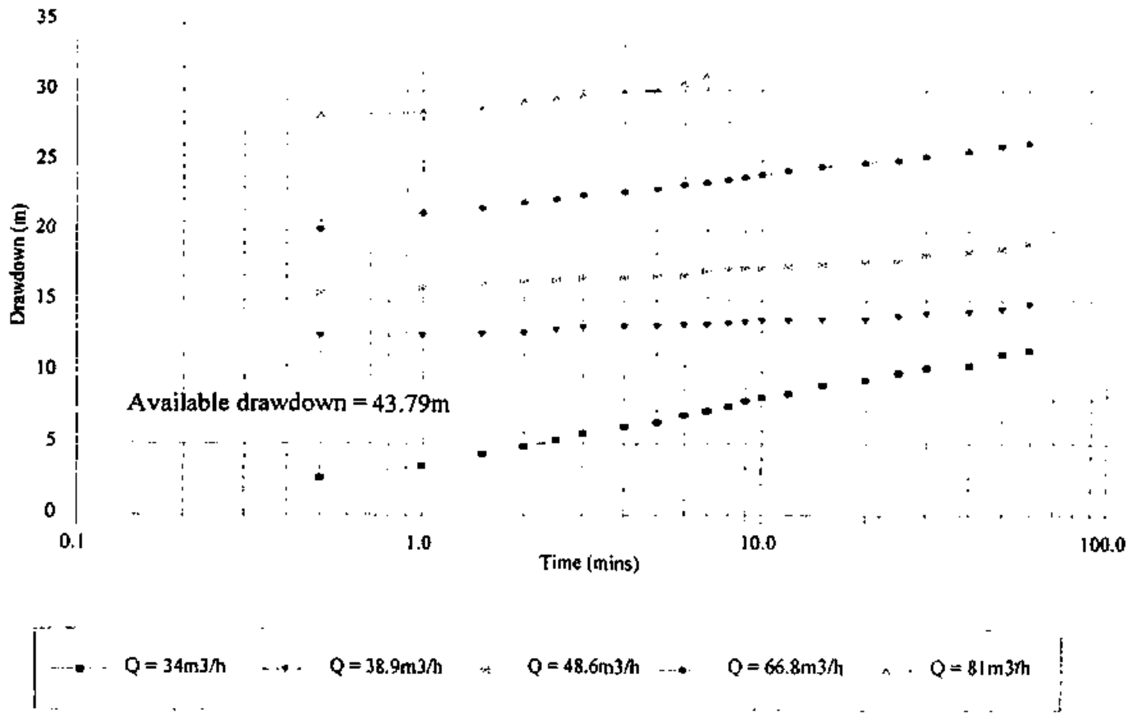
Constant discharge test

BH P1 - Recovery



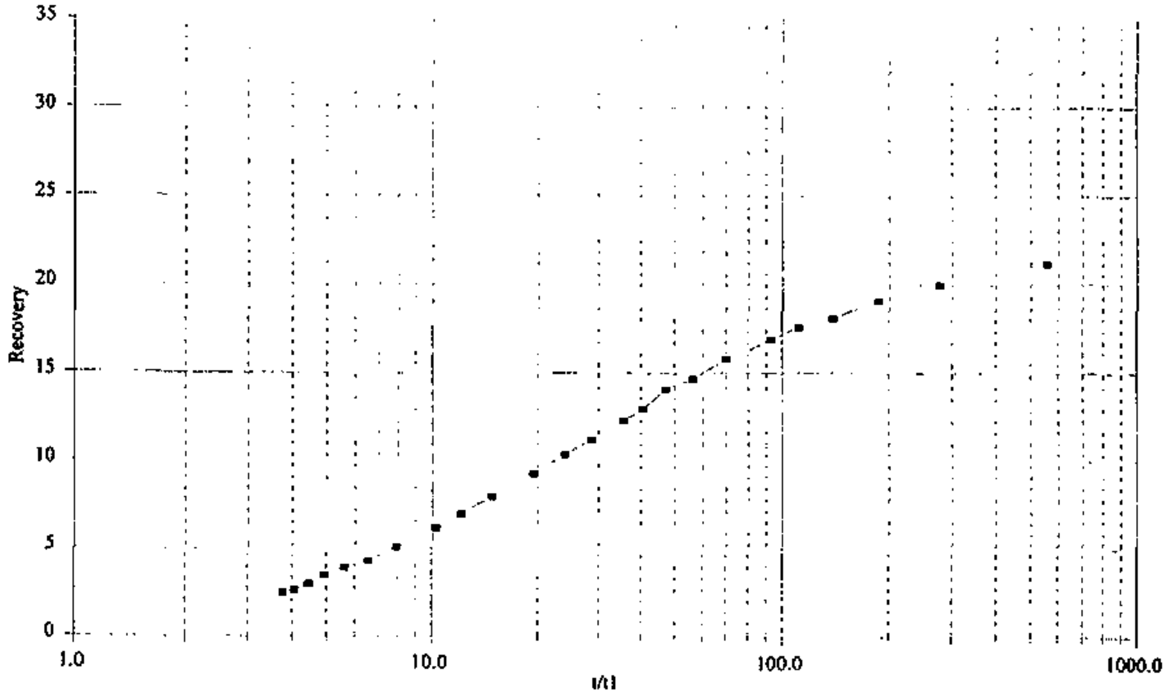
Multiple discharge rate test

BH P2



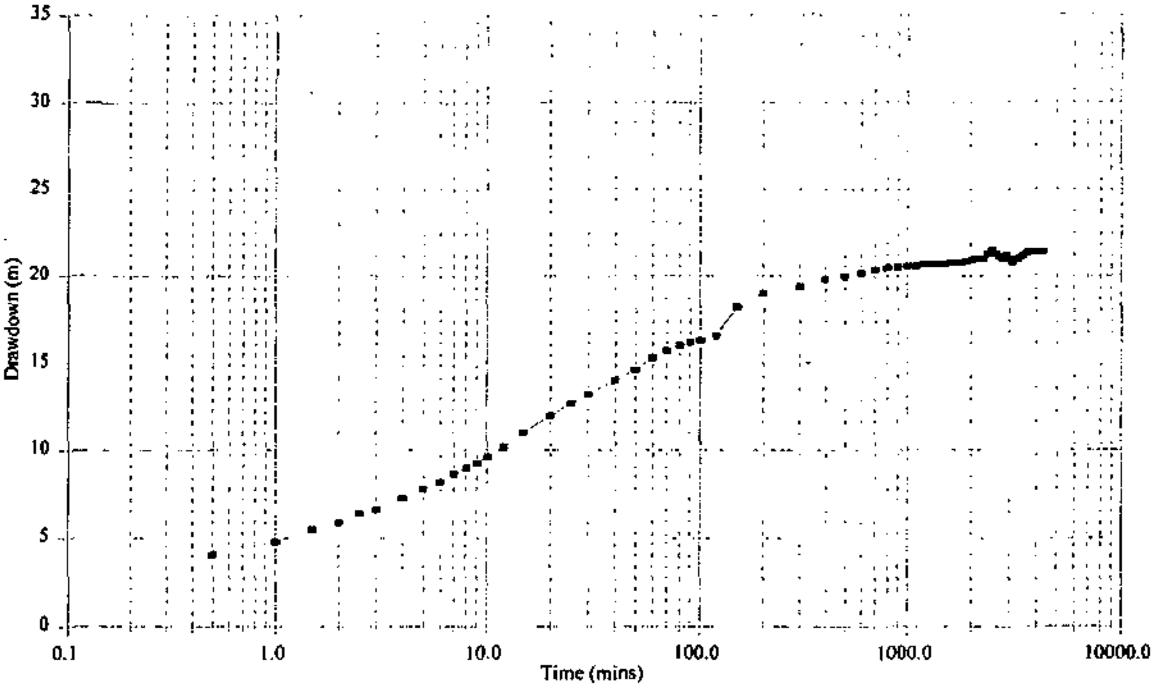
Multiple discharge rate test

BH P2 - Recovery



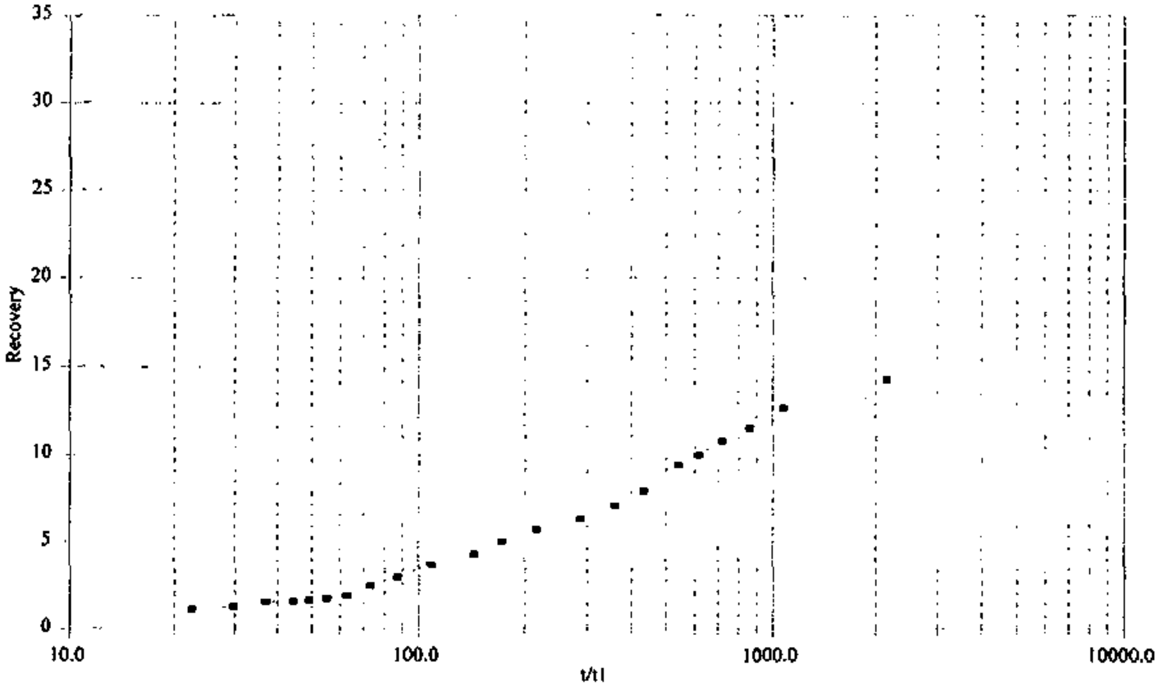
Constant discharge test: BH P2

Abstraction rate = 46.10 m3/h



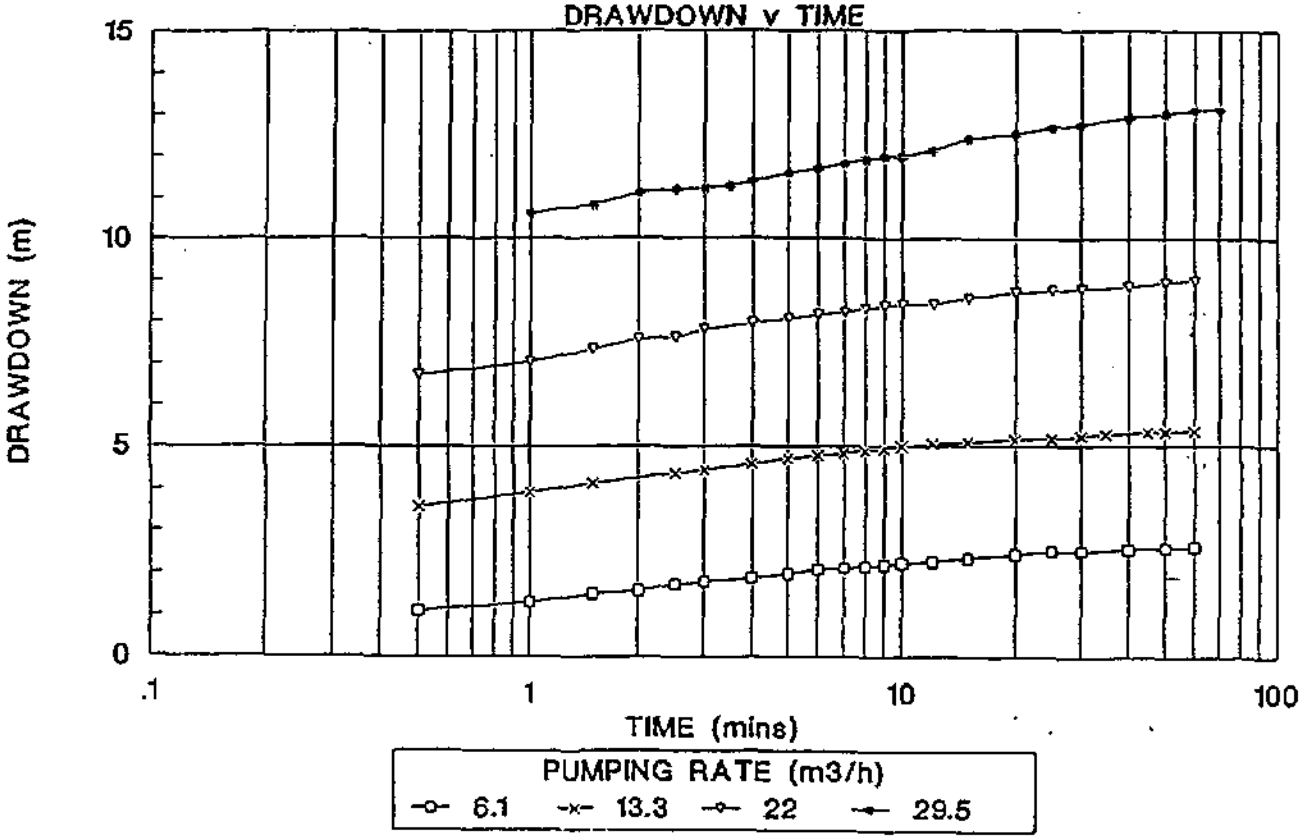
Constant discharge test

BH P2 - Recovery



STRUISBAAI WATER BOREHOLES
BOREHOLE 1 - STEP TEST

DRAWDOWN v TIME



Q = 25,2 m³/h

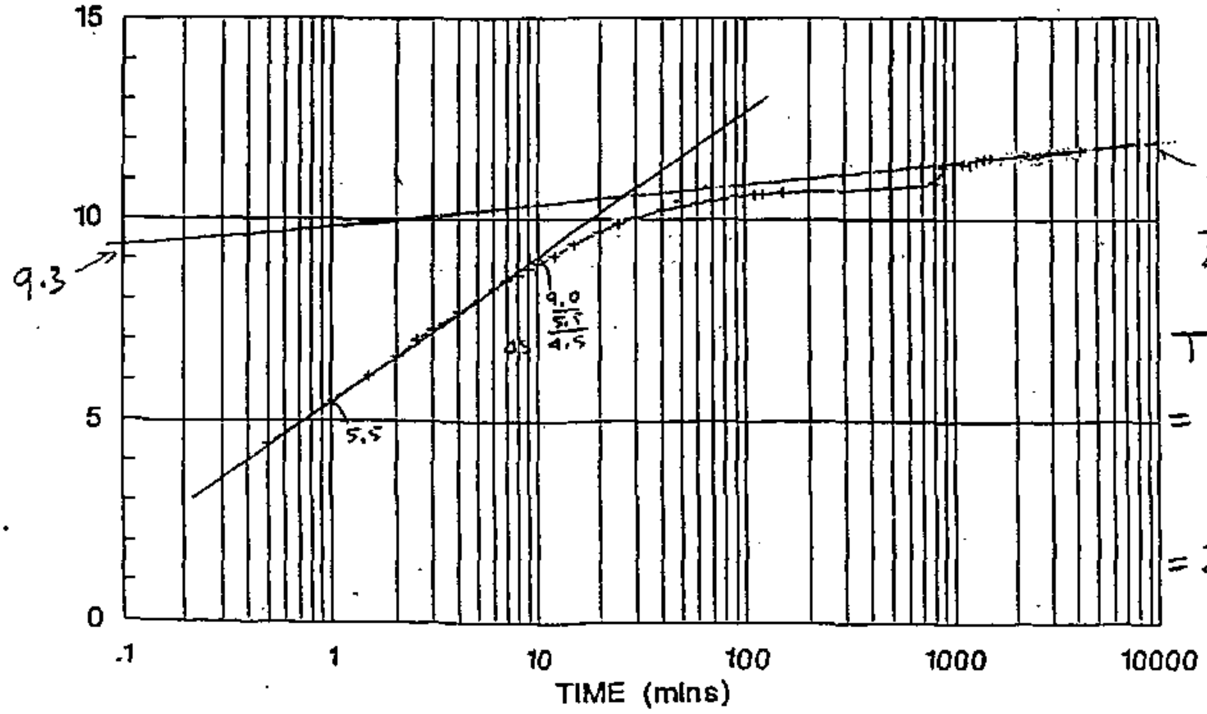
STRUISBAAI WATER BOREHOLES
BOREHOLE 1
72hr CONSTANT DELIVERY TEST

DRAWDOWN v TIME

$T = \frac{2.3Q}{4\pi \Delta s}$

= 24,6 m²/day

= 25 m²/day



12,0

9.3

2,7 m / 5 cycles

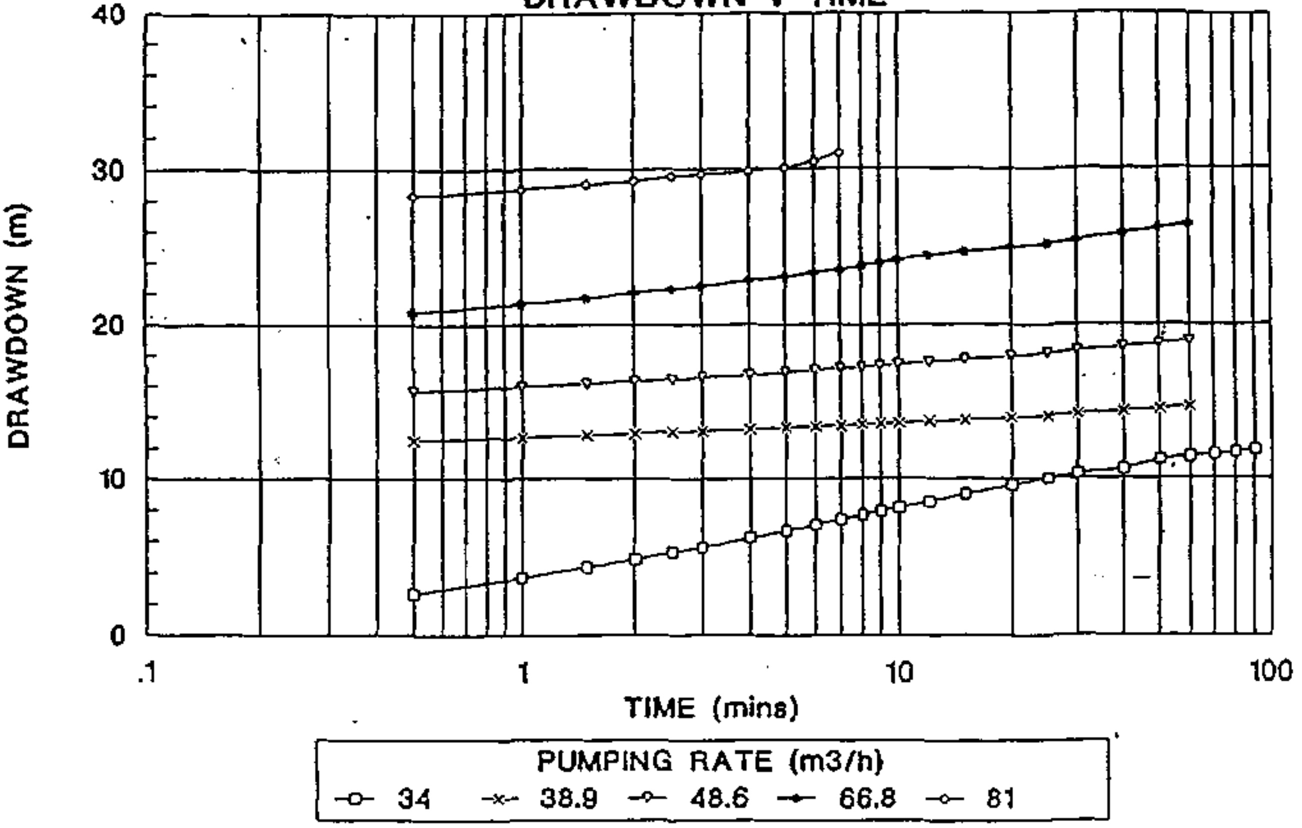
T LATE STAGE

$= \frac{2\cdot3 \times 25\cdot2 \times 24}{4\ \pi\ 2\cdot7/5}$

= 205 m²/d

PUMP RATE 25.2 m3/Hr

STRUISBAAI WATER BOREHOLES
BOREHOLE 2 - STEP TEST
DRAWDOWN v TIME

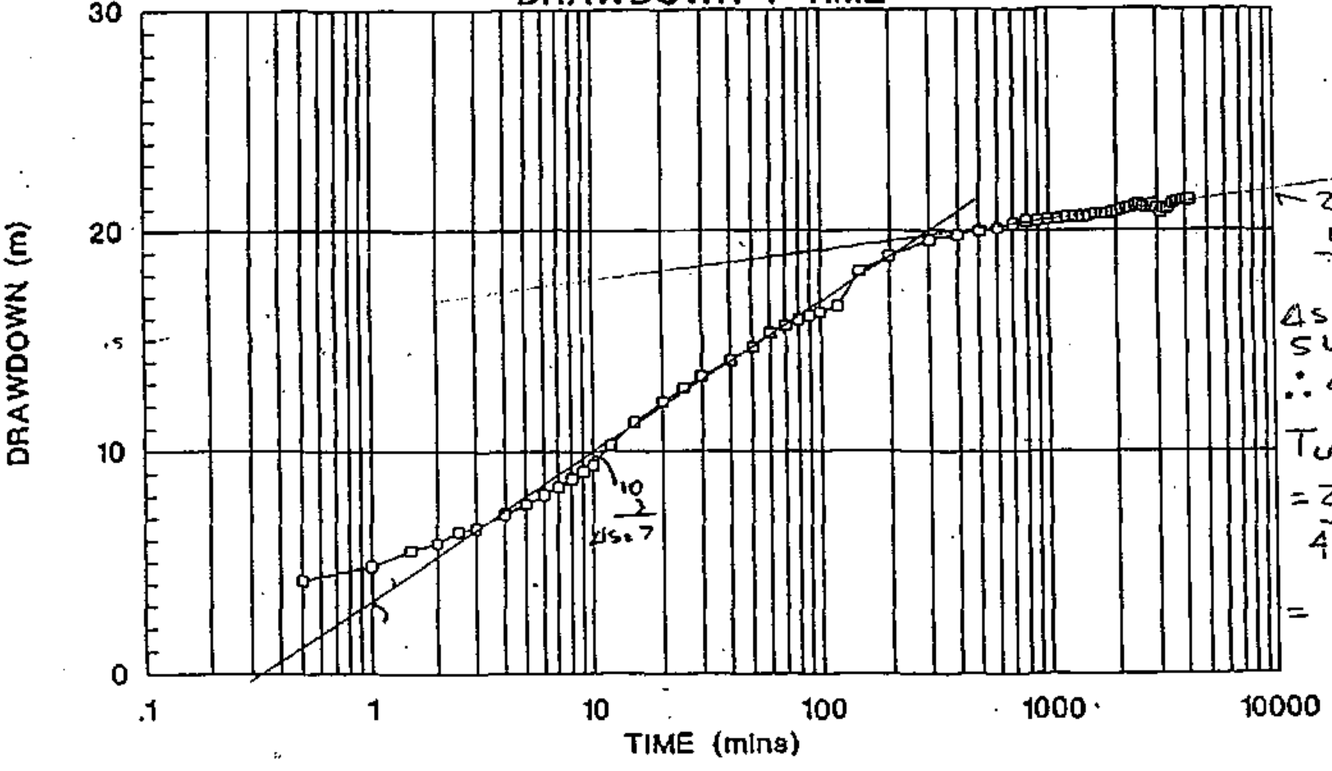


$Q = 46,1\ m^3/hr$

STRUISBAAI WATER BOREHOLES
BOREHOLE 2
72hr CONSTANT DELIVERY TEST
DRAWDOWN v TIME

$T = \frac{2.3Q}{4\pi\Delta s}$ EARLY STAGE

$= 29\ m^2/d$



22 m

$\frac{15\ m}{7\ m}$

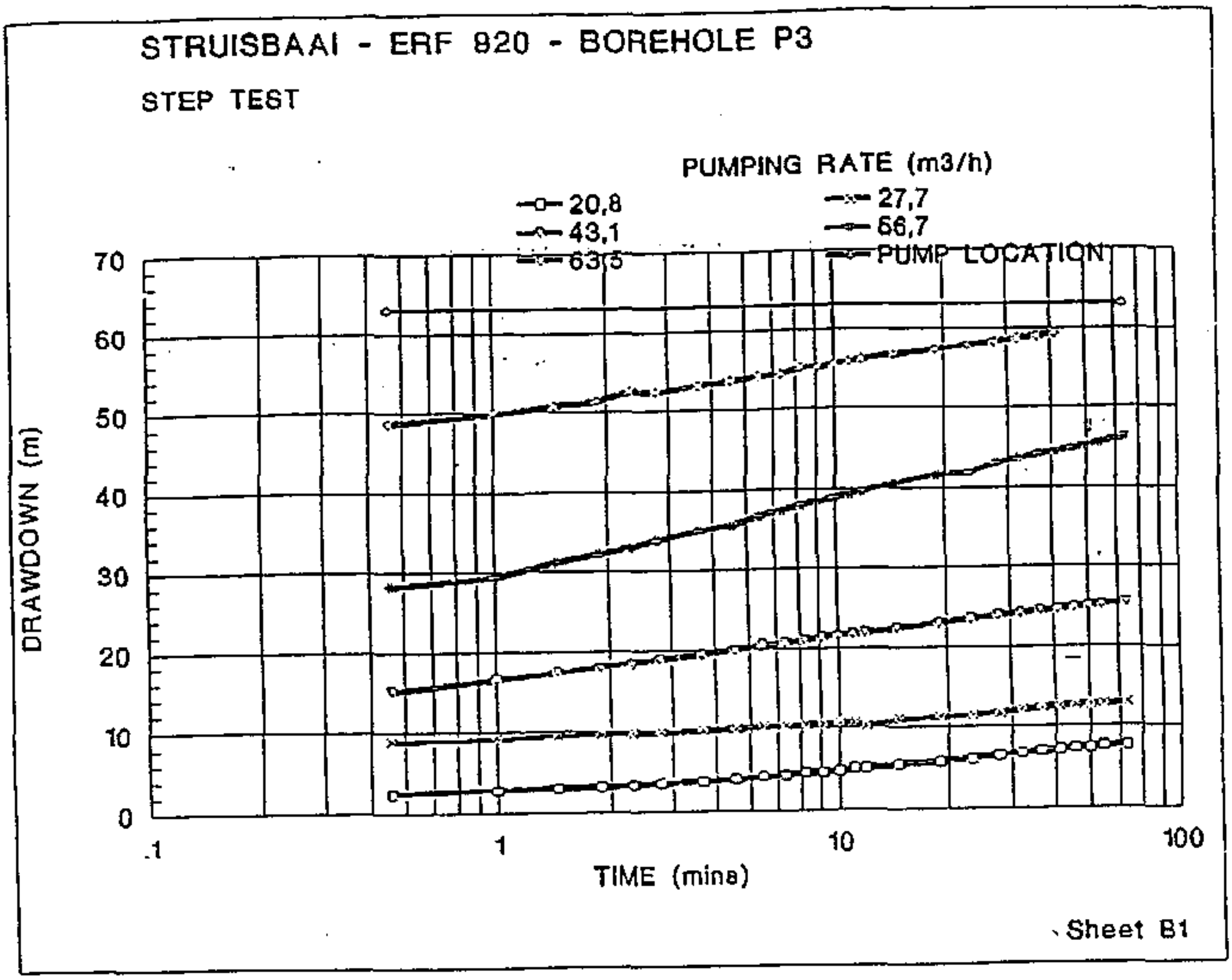
Δs OVER
5 LOG CYCLE
∴ Δs = 7/5

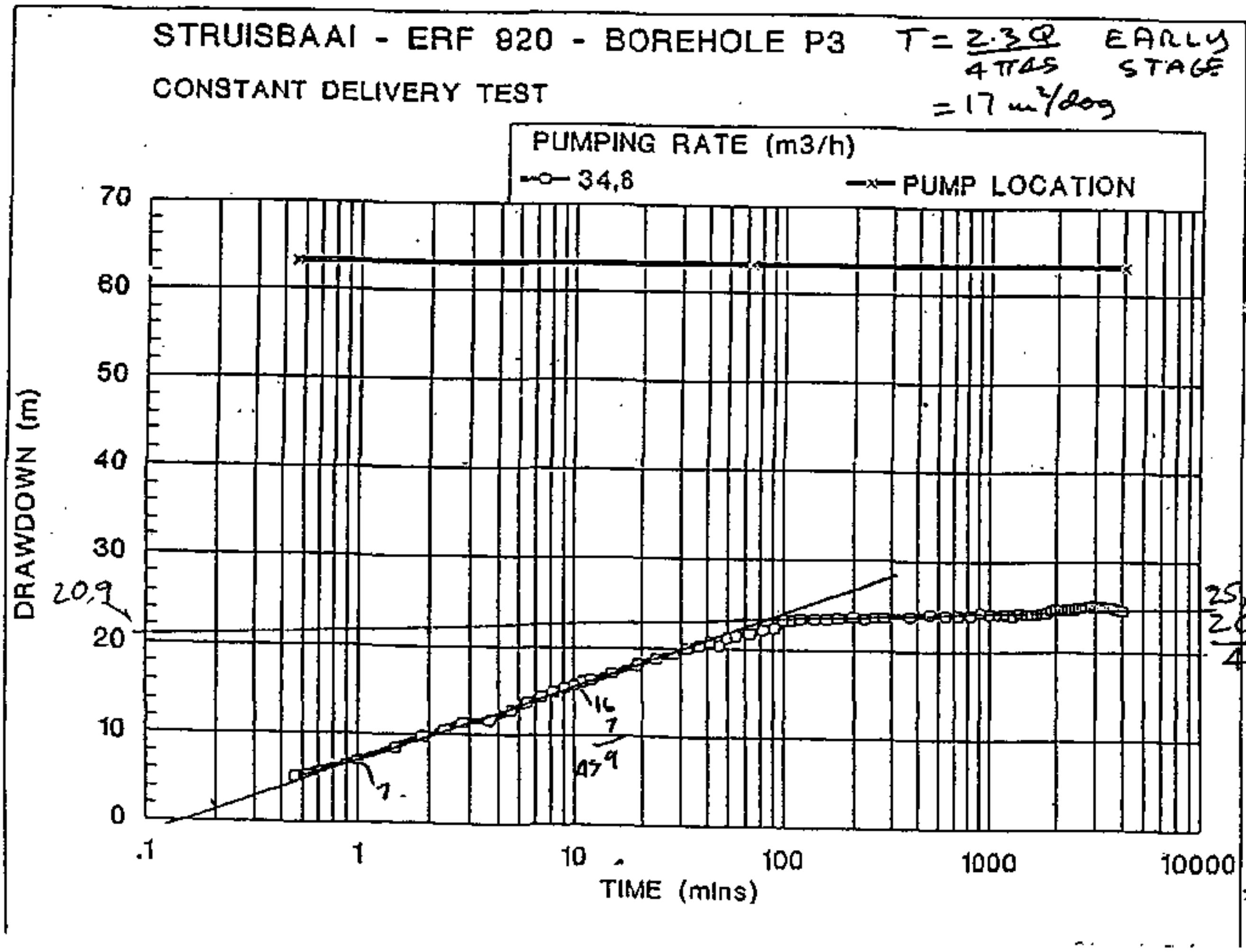
T LATE STAGE

$= \frac{2.3 \times 46. \times 24}{4\pi\ 7/5}$

$= 145\ m^2/d$

PUMP RATE 46.1 m3/Hr





$T = \frac{2.3Q}{4\pi\Delta s}$ EARLY STAGE

$= 17$ m²/day

25,1
20,9
4,2 / 5 LOG CYCLES

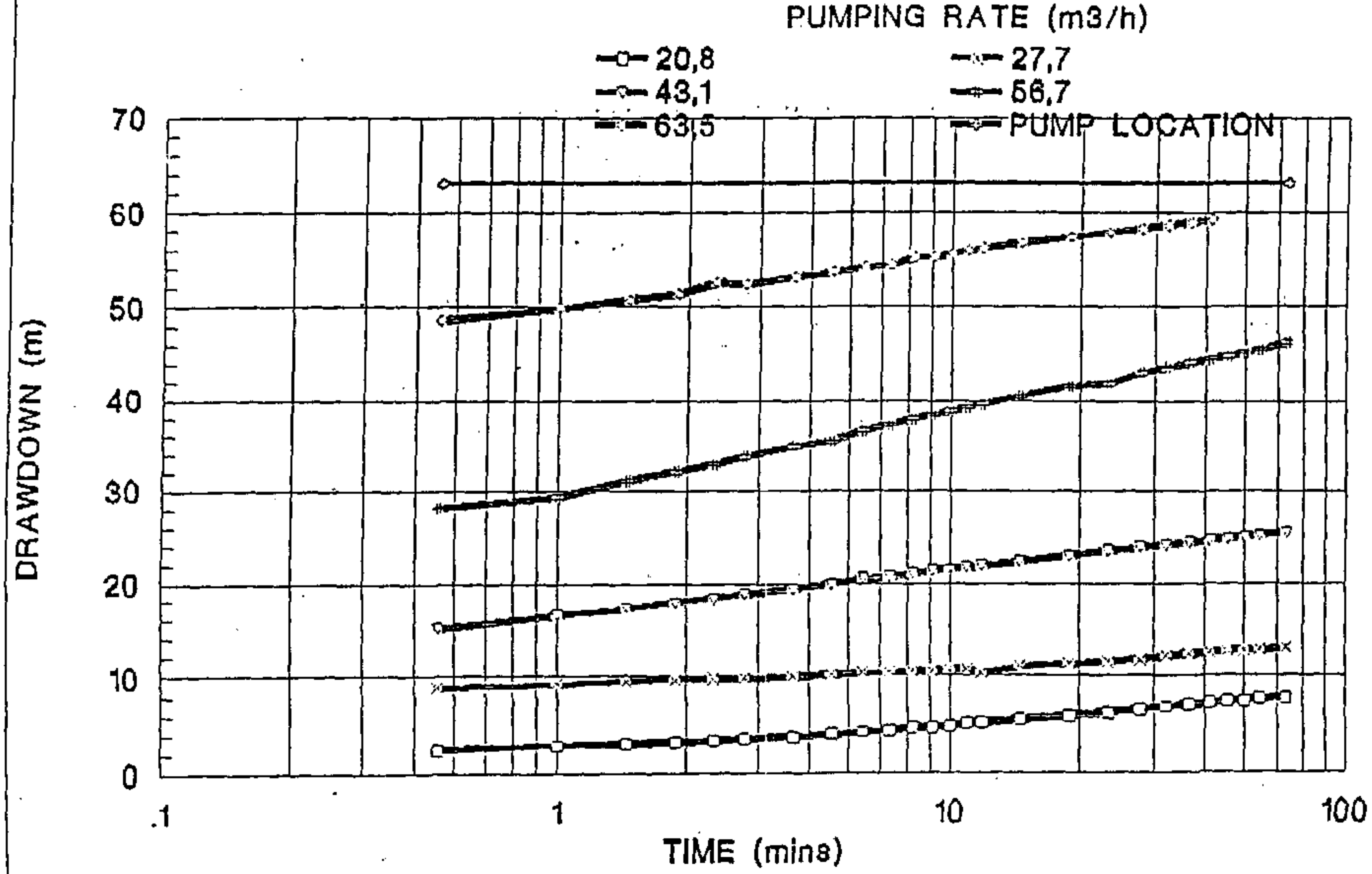
T LATE STA

$= \frac{2.3 \times 34.8 \times}{4\pi \; 4.2/5}$

$= 182$ m²/d

STRUISBAAI - ERF 920 - BOREHOLE P3

STEP TEST

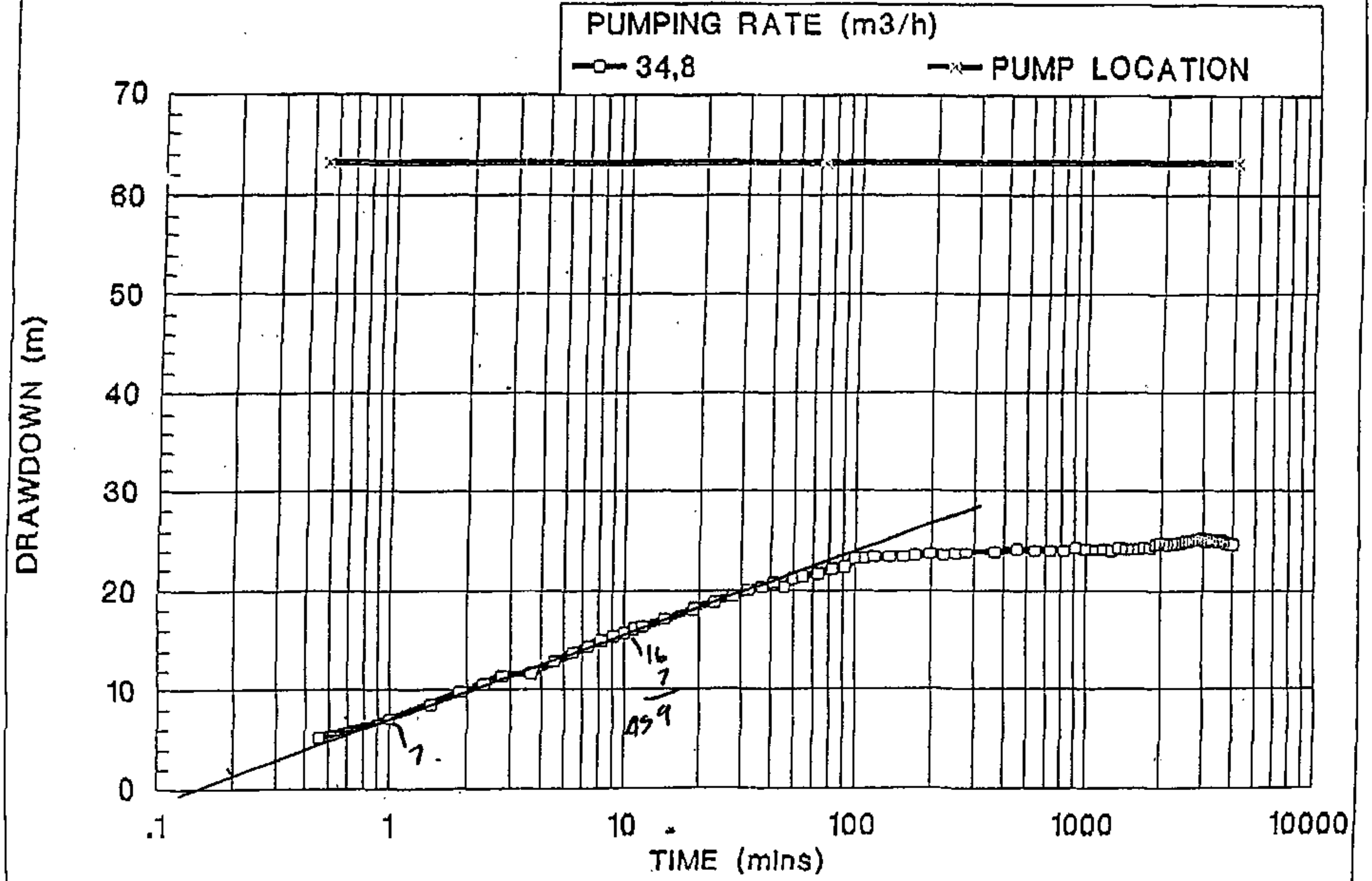


Sheet B1

STRUISBAAI - ERF 920 - BOREHOLE P3

CONSTANT DELIVERY TEST

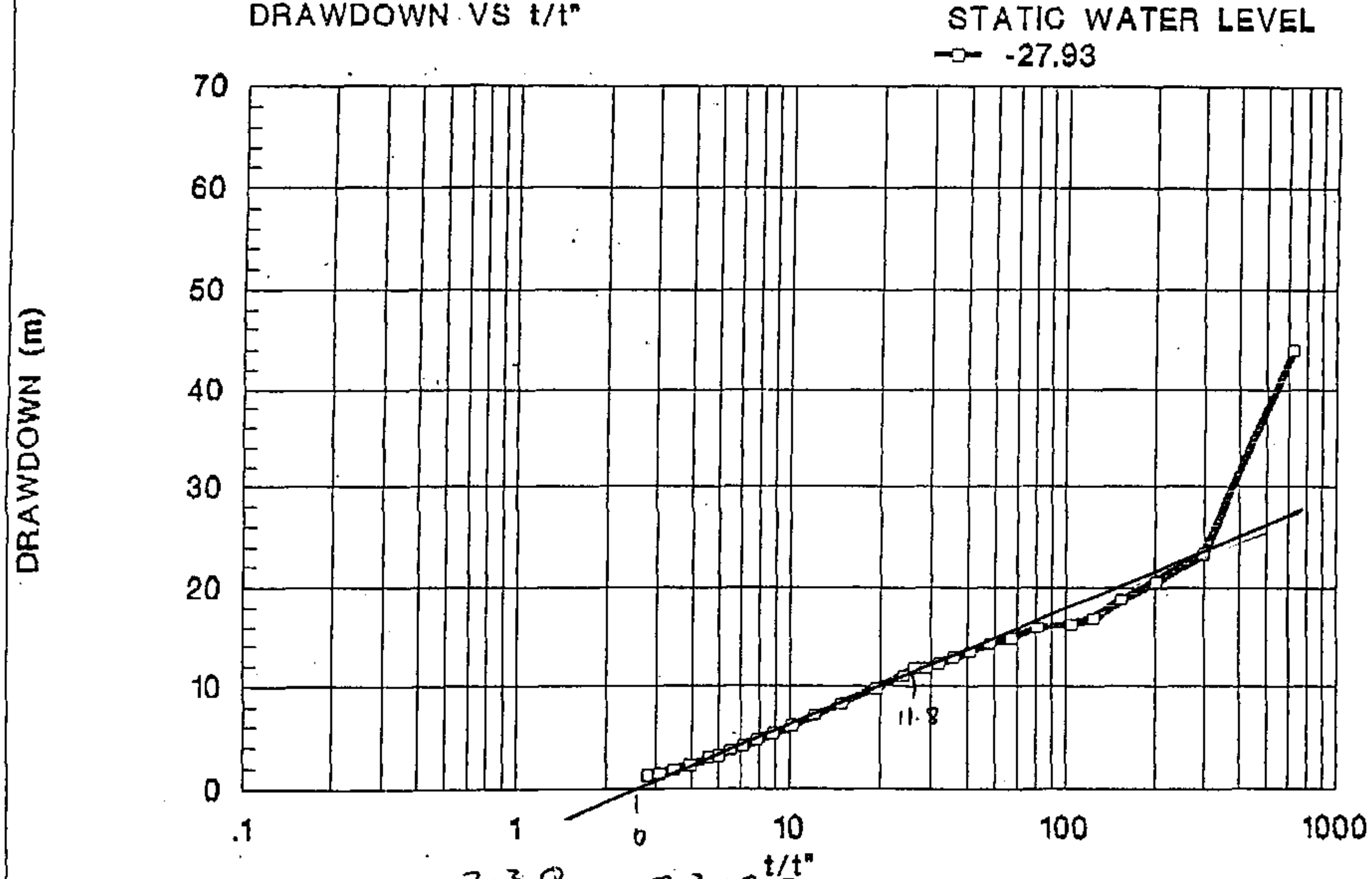
$$T = \frac{2.3Q}{4\pi\Delta s} = 17\ m^2/day$$



Sheet B4

STRUISBAAI - ERF 920 - BOREHOLE P3

STEP TEST - RECOVERY
DRAWDOWN VS t/t"



$$T_R = \frac{2.3\,Q}{4\pi\,\Delta s} = \frac{2.3 \times 835}{4\pi\ 11.8} = 13\ m^2/d$$

Sheet B3

APPENDIX 3

CHEMISTRY AND ISOTOPIC DATA

- ➡ Struisbaai Groundwater Chemistry
- ➡ Struisbaai Groundwater Isotopic Composition
- ➡ Struisbaai Rainfall Chemistry
- ➡ CSIR Chemistry Laboratory Precision and Recovery Data

GROUNDWATER CHEMISTRY DATA

AG1

DATE	03/04/93	10/28/93	04/14/94	08/28/94	12/07/94
K (mg/L)	6.4	6.0	6.4	5.6	5.9
Na (mg/L)	195	206	210	213	209
Ca (mg/L)	91	93	94	89	86
Mg (mg/L)	24	25	26	25	25
NH4 (mg/L N)	<0.05	<0.05	<0.1	<0.1	<0.1
SO4 (mg/L)	52	56	50	53	52
Cl (mg/L)	347	359	356	364	367
Alk (mg/L CaCO3)	215	228	216	217	212
NOx (mg/L N)	2.40	4.70	3.10	2.30	2.30
P (mg/L)	<0.05	<0.05	<0.1	<0.1	<0.1
Si (mg/L)	4.4	3.8	3.8	3.9	3.9
Cu (mg/L)	<0.02	<0.02	<0.03	<0.03	<0.03
Fe (mg/L)	<0.02	<0.02	<0.03	<0.05	<0.05
Mn (mg/L)	<0.02	<0.02	<0.03	<0.05	<0.05
Zn (mg/L)	<0.01	<0.02	<0.03	<0.03	<0.03
Sr (mg/L)	1.14	1.17	1.0	1.17	1.09
Rb (mg/L)	-	-	-	<0.03	<0.03
Ba (mg/L)	-	-	-	<0.25	<0.25
Li (mg/L)	0.008	0.006	0.010	0.008	0.009
DOC (mg/L C)	4.4	6.9	3.0	1.4	0.8
EC - field (mS/m)	-	168	-	-	-
EC - lab (mS/m)	155	170	165	160	160
pH - field	-	6.5	-	7.3	-
pH - lab	7.7	7.7	7.2	7.7	-
Cations (meq/l)	15.16	15.81	16.08	15.88	15.63
Anions (meq/l)	15.33	16.19	15.63	15.86	15.83
% balance	1.07	2.42	2.91	0.13	1.32
Carbon-13 (‰ PDB)	-10.6	-10.6	-10.5	-10.6	-10.5
TIC (mmol/L)	4.4	4.6	4.4	4.4	4.4
Carbon-1 pMC	45.5	46.3	45.1	45.3	44.7
Oxygen-18 (‰ SMOW)	-4.6	-4.7	-4.7	-	-5.0
87-Sr/86-Sr	0.709196	0.709224	0.709156	0.709203	0.709145

ICP-MS Microchemistry Data (concentrations in ppb)

Borehole AG1

Date	03/04/93	04/14/94	Date	03/04/93	04/14/94
Li	23.700	30.723	I	-	8.731
Be	0.070	0.327	Te	-	-
B	-	371.649	Cs	-	-
Al	-	17.393	Ba	6.060	5.186
Sc	7.570	6.139	La	-	1.758
Ti	-	159.200	Ce	-	-
V	5.810	43.388	Pr	-	0.776
Cr	10.300	3.378	Nd	-	-
Mn	-	-	Sm	-	0.057
Fe	1657.000	956.167	Eu	-	1.515
Co	0.390	0.344	Gd	-	-
Ni	2.170	2.093	Tb	-	0.013
Cu	3.020	2.522	Dy	-	-
Zn	2.890	4.223	Ho	-	-
Ga	0.250	0.775	Er	-	-
Ge	-	-	Tm	-	0.019
As	-	0.594	Yb	-	-
Se	15.200	5.008	Lu	-	-
Br	-	1410.216	Hf	-	-
Rb	3.680	3.905	Ta	-	0.003
Sr	1503.000	1638.937	W	0.180	-
Y	-	0.022	Re	-	0.065
Zr	-	0.005	Os	-	-
Nb	-	0.742	Ir	-	0.009
Mo	0.300	-	Pt	-	-
Ru	-	-	Au	-	-
Rh	-	0.028	Hg	-	-
Pd	-	0.088	Tl	-	-
Ag	-	-	Pb	-	-
Cd	-	0.053	Bi	-	-
In	-	-	Th	-	0.020
Sn	2.850	1.867	U	0.350	2.512
Sb	0.060	0.029			

GROUNDWATER CHEMISTRY DATA

BH10

DATE	03/03/93	10/28/93	04/15/94	08/26/94	12/06/94
K (mg/L)	7.0	5.9	6.2	5.6	6.0
Na (mg/L)	291	274	269	250	280
Ca (mg/L)	143	120	123	111	126
Mg (mg/L)	37	33	34	29	35
NH4 (mg/L N)	<0.05	<0.05	0.12	<0.1	<0.1
SO4 (mg/L)	81	67	65	55	71
Cl (mg/L)	616	508	508	455	575
Alk (mg/L CaCO3)	217	241	236	238	228
NOx (mg/L N)	1.1	1.4	2.3	1.3	1.1
P (mg/L)	<0.05	<0.05	<0.1	<0.1	<0.1
Si (mg/L)	4.7	3.9	4.1	4.2	4.2
Cu (mg/L)	<0.02	<0.02	<0.03	<0.03	<0.03
Fe (mg/L)	0.05	0.06	0.11	<0.05	<0.05
Mn (mg/L)	<0.02	<0.02	<0.03	<0.05	<0.05
Zn (mg/L)	0.05	<0.02	<0.03	<0.03	<0.03
Sr (mg/L)	1.35	1.16	1.07	0.93	1.12
Rb (mg/L)	-	-	-	<0.25	<0.03
Ba (mg/L)	-	-	-	<0.03	<0.25
Li (mg/L)	0.011	0.008	0.010	0.009	0.011
DOC (mg/L C)	4.5	9.6	3.3	4.0	0.8
EC - field (mS/m)	-	-	-	-	-
EC - lab (mS/m)	230	220	215	190	225
pH - field	-	8.2	-	6.9	-
pH - lab	7.4	7.8	6.8	7.5	-
Cations (meq/l)	23.03	20.80	20.80	18.88	21.52
Anions (meq/l)	23.48	20.64	20.50	18.83	22.34
% balance	1.96	0.79	1.50	0.28	3.85
Carbon-13 (‰ PDB)	-12.0	-13.2	-12.6	-13.0	-12.5
TIC (mmol/L)	4.7	5.1	4.9	5.1	5.0
Carbon-14 (pmc)	76.9	87.9	86.2	86.6	84.0
Oxygen-18 (‰ SMOW)	-4.9	-4.7	-4.7	-	-5.0
87-Sr/86-Sr	0.709246	0.709272	0.709200	0.709245	-

ICP-MS Microchemistry Data (concentrations in ppb)

Borehole BH10

Date	03/03/93	04/15/94	Date	03/03/93	04/15/94
Li	26.400	-	I	-	0.930
Be	0.120	-	Te	-	0.065
B	-	39.056	Cs	-	11.033
Al	-	-	Ba	10.200	14.463
Sc	8.320	318.592	La	-	0.001
Ti	-	318.592	Ce	-	6.892
V	9.460	20.897	Pr	-	-
Cr	10.400	234.306	Nd	-	0.727
Mn	17.300	46.244	Sm	-	-
Fe	2601.000	3.099	Eu	-	9.614
Co	0.640	19.933	Gd	-	2.721
Ni	2.870	1179.641	Tb	-	0.026
Cu	2.680	0.474	Dy	-	-
Zn	96.500	3.028	Ho	-	0.012
Ga	0.290	3.476	Er	-	0.123
Ge	-	0.637	Tm	-	0.007
As	0.240	0.218	Yb	-	0.036
Se	23.600	0.229	Lu	-	0.012
Br	-	1.153	Hf	-	-
Rb	4.480	37.077	Ta	-	0.026
Sr	1716.000	1573.786	W	0.280	-
Y	-	4.352	Re	-	-
Zr	-	1600.103	Os	-	-
Nb	-	1.719	Ir	-	0.010
Mo	0.440	-	Pt	-	2.335
Ru	-	2.720	Au	-	0.041
Rh	-	-	Hg	-	-
Pd	-	-	Tl	-	-
Ag	-	1.692	Pb	0.590	10.737
Cd	-	0.054	Bi	-	0.008
In	-	5.419	Th	-	-
Sn	0.370	13.345	U	0.430	-
Sb	0.190	-			

GROUNDWATER CHEMISTRY DATA

	BH6			BH8
DATE	10/29/93	04/15/94	12/07/94	03/03/93
K (mg/L)	5.3	4.8	5.1	10.9
Na (mg/L)	213	200	209	604
Ca (mg/L)	107	105	103	240
Mg (mg/L)	28	28	26	78
NH4 (mg/L N)	<0.05	<0.1	<0.1	<0.05
SO4 (mg/L)	54	49	49	196
Cl (mg/L)	384	365	392	1333
Alk (mg/L CaCO3)	237	229	227	205
NOx (mg/L N)	1.4	1.1	0.9	1.2
P (mg/L)	<0.05	<0.1	<0.1	<0.05
Si (mg/L)	3.9	4.0	4.2	4.6
Cu (mg/L)	<0.02	<0.03	<0.03	<0.02
Fe (mg/L)	1.67	0.12	<0.05	0.08
Mn (mg/L)	<0.02	<0.03	<0.05	<0.02
Zn (mg/L)	0.13	<0.03	<0.03	<0.01
Sr (mg/L)	1.03	1.03	0.95	2.35
Rb (mg/L)	-	-	-	-
Ba (mg/L)	-	-	-	-
Li (mg/L)	0.007	0.011	0.009	0.016
DOC (mg/L C)	9.1	2.8	0.8	4.5
EC - field (mS/m)	174	-	-	-
EC - lab (mS/m)	180	167	170	420
pH - field	6.4	-	-	-
pH - lab	7.6	7.2	-	7.3
Cations (meq/l)	16.99	16.18	16.51	44.94
Anions (meq/l)	16.81	15.97	16.66	45.89
% balance	1.07	1.26	0.95	2.10
Carbon-13 (‰ PDB)	-12.1	-12.4	-12.4	-12.5
TIC (mmol/L)	4.8	4.8	4.9	4.5
Carbon-14 (pmc)	83.2	80.8	81.6	81.0
Oxygen-18 (‰ SMOW)	-4.7	-4.9	-5.1	-4.6
87-Sr/86-Sr	0.709299	0.709177	0.709226	0.709260

ICP-MS *Microchemistry Data (concentrations in ppb)*

	BH6	BH8		BH6	BH8
Date	04/15/94	03/03/93	Date	15/04/94	03/03/93
Li	31.351	39.200	I	7.184	-
Be	18.199	0.130	Te	5.016	-
B	296.518	-	Cs	-	-
Al	-	-	Ba	5.633	21.100
Sc	6.511	7.120	La	-	-
Ti	184.606	-	Ce	6.318	-
V	34.682	12.900	Pr	0.042	-
Cr	3.602	8.700	Nd	26.851	-
Mn	25.589	3.400	Sm	36.91	-
Fe	958.894	3592.000	Eu	-	-
Co	0.232	0.820	Gd	23.15	-
Ni	2.825	5.170	Tb	0.019	-
Cu	1.488	4.470	Dy	-	-
Zn	10.053	9.780	Ho	-	-
Ga	0.332	0.430	Er	30.378	-
Ge	-	-	Tm	-	-
As	0.730	2.710	Yb	-	-
Se	3.974	55.500	Lu	0.012	-
Br	1458.955	-	Hf	19.089	-
Rb	3.382	6.160	Ta	-	-
Sr	1448.358	2647.000	W	4.039	0.160
Y	5.700	-	Re	0.031	-
Zr	-	-	Os	15.972	-
Nb	3.689	-	Ir	0.061	-
Mo	-	0.370	Pt	-	-
Ru	-	-	Au	-	-
Rh	2.659	-	Hg	2.845	-
Pd	0.232	-	Tl	-	-
Ag	15.426	-	Pb	-	0.260
Cd	13.231	-	Bi	-	-
In	-	-	Th	2.232	-
Sn	0.989	0.350	U	0.034	0.450
Sb	-	0.090			

GROUNDWATER CHEMISTRY DATA

G33427

DATE	10/29/93	04/18/94	08/29/94	12/08/94
K (mg/L)	13.4	13.8	13.0	13.4
Na (mg/L)	446	430	447	448
Ca (mg/L)	122	123	114	124
Mg (mg/L)	53	54	54	54
NH4 (mg/L N)	<0.05	0.20	<0.1	<0.1
SO4 (mg/L)	92	93	88	68
Cl (mg/L)	777	751	757	831
Alk (mg/L CaCO3)	303	285	284	282
NOx (mg/L N)	1.5	4.3	1.2	1.2
P (mg/L)	<0.05	<0.1	<0.1	<0.1
Si (mg/L)	3.9	4.1	4.2	4.2
Cu (mg/L)	<0.02	<0.03	<0.03	<0.03
Fe (mg/L)	<0.02	<0.03	<0.05	<0.05
Mn (mg/L)	<0.02	<0.03	<0.05	<0.05
Zn (mg/L)	<0.02	<0.03	<0.03	<0.03
Sr (mg/L)	0.93	0.81	0.77	0.94
Rb (mg/L)	-	-	<0.03	<0.03
Ba (mg/L)	-	-	<0.25	<0.25
Li (mg/L)	0.009	0.012	0.009	0.011
DOC (mg/L C)	-	4.1	2.7	0.9
EC - field (mS/m)	272	-	-	-
EC - lab (mS/m)	315	295	295	305
pH - field	6.9	-	7.1	-
pH - lab	7.7	7.0	7.6	-999.0
Cations (meq/l)	30.22	29.60	28.90	30.44
Anions (meq/l)	30.00	29.10	28.95	31.00
% balance	0.76	1.71	3.29	1.83
Carbon-13 (%o PDB)	-12.4	-12.3	-12.3	-12.2
TIC (mmol/L)	6.2	5.9	5.9	6.0
Carbon-14 (pmc)	66.8	67.0	68.3	69.8
Oxygen-18 (%o SMOW)	-4.7	-4.9	-	-4.9
87-Sr/86-Sr	0.709466	0.709209	0.709257	0.709211

ICP-MS Microchemistry Data (concentrations in ppb)

Borehole G33427

Date	04/18/94	Date	04/18/94
Li	-	I	13.813
Be	20.677	Te	-
B	353.574	Cs	0.794
Al	287.707	Ba	8.888
Sc	4.010	La	-
Ti	286.701	Ce	0.106
V	134.415	Pr	2.974
Cr	1.306	Nd	0.135
Mn	2.018	Sm	0.139
Fe	1330.011	Eu	-
Co	1.105	Gd	-
Ni	3.467	Tb	-
Cu	2.659	Dy	-
Zn	20.424	Ho	-
Ga	1.071	Er	-
Ge	0.914	Tm	-
As	3.179	Yb	0.139
Se	13.442	Lu	1.007
Br	2702.593	Hf	0.082
Rb	9.595	Ta	1.011
Sr	1564.195	W	0.003
Y	0.123	Re	0.004
Zr	5.864	Os	0.021
Nb	0.086	Ir	3.496
Mo	16.403	Pt	6.366
Ru	9.280	Au	-
Rh	0.073	Hg	-
Pd	0.065	Tl	0.012
Ag	0.039	Pb	-
Cd	0.214	Bi	0.004
In	-	Th	0.008
Sn	0.404	U	0.031
Sb	0.020		

GROUNDWATER CHEMISTRY DATA

G39940

DATE	10/28/93	04/15/94	08/19/94	12/08/94
K (mg/L)	41	36	40	40
Na (mg/L)	892	876	874	901
Ca (mg/L)	144	144	141	139
Mg (mg/L)	99	98	91	99
NH4 (mg/L N)	0.2	0.6	0.1	<0.1
SO4 (mg/L)	229	229	227	232
Cl (mg/L)	1479	1422	1486	1482
Alk (mg/L CaCO3)	452	416	418	415
NOx (mg/L N)	<0.05	0.4	<0.1	<0.1
P (mg/L)	<0.05	<0.1	<0.1	<0.1
Si (mg/L)	5.3	5.7	6.0	5.9
Cu (mg/L)	<0.02	<0.03	<0.03	<0.03
Fe (mg/L)	0.29	0.75	0.45	0.24
Mn (mg/L)	<0.02	<0.03	<0.05	<0.05
Zn (mg/L)	<0.02	<0.03	<0.03	0.03
Sr (mg/L)	3.41	2.48	2.15	2.44
Rb (mg/L)	-	-	0.03	0.04
Ba (mg/L)	-	-	<0.25	<0.25
Li (mg/L)	0.020	0.026	0.020	0.027
DOC (mg/L C)	-	-	-	7.1
EC - field (mS/m)	499	-	-	-
EC - lab (mS/m)	550	540	520	540
pH - field	6.5	-	7.0	-
pH - lab	7.8	7.2	7.6	-
Cations (meq/l)	55.17	54.29	43.54	55.31
Anions (meq/l)	55.52	53.25	55.01	54.94
% balance	0.64	1.94	2.75	0.67
Carbon-13 (%o PDB)	-11.6	-11.5	-11.4	-11.2
TIC (mmol/L)	9.2	8.7	8.6	8.7
Carbon-14 (pmc)	87.6	84.6	86.4	85.8
Oxygen-18 (%o SMOW)	-4.1	-4.2	-	-4.4
87-Sr/86-Sr	0.709301	0.709341	0.709270	0.709279

ICP-MS Microchemistry Data (concentrations in ppb)

Borehole G39940

Date	04/15/94	Date	04/15/94
Li	46.232	I	226.471
Be	-	Te	-
B	617.781	Cs	-
Al	-	Ba	15.177
Sc	-	La	4.224
Ti	149.912	Ce	19.155
V	107.819	Pr	-
Cr	-	Nd	-
Mn	21.184	Sm	21.530
Fe	1623.368	Eu	-
Co	12.139	Gd	-
Ni	-	Tb	-
Cu	42.938	Dy	-
Zn	1.54	Ho	0.040
Ga	96.397	Er	120.518
Ge	-	Tm	-
As	12.944	Yb	-
Se	-	Lu	0.082
Br	5104.244	Hf	-
Rb	13.011	Ta	-
Sr	2737.036	W	-
Y	23.171	Re	-
Zr	-	Os	0.114
Nb	-	Ir	18.404
Mo	-	Pt	0.355
Ru	-	Au	-
Rh	0.1	Hg	188.505
Pd	-	Tl	-
Ag	-	Pb	-
Cd	36.009	Bi	0.040
In	-	Th	0.073
Sn	-	U	60.307
Sb	28.337		

GROUNDWATER CHEMISTRY DATA

G39941

DATE	10/28/93	04/15/94	08/30/94	01/12/95
K (mg/L)	6.5	5.4	5.5	5.5
Na (mg/L)	265	184	202	172
Ca (mg/L)	101	90	87	89
Mg (mg/L)	34	28	30	26
NH4 (mg/L N)	<0.05	<0.1	<0.1	<0.1
SO4 (mg/L)	89	69	62	61
Cl (mg/L)	458	320	362	292
Alk (mg/L CaCO3)	236	214	218	212
NOx (mg/L N)	0.7	0.4	0.6	0.8
P (mg/L)	<0.05	<0.1	<0.1	<0.1
Si (mg/L)	4.0	4.0	4.2	3.7
Cu (mg/L)	<0.02	<0.03	<0.03	<0.03
Fe (mg/L)	<0.02	<0.03	<0.05	<0.05
Mn (mg/L)	<0.02	<0.03	<0.05	<0.05
Zn (mg/L)	<0.02	<0.03	0.04	0.07
Sr (mg/L)	0.98	0.67	0.69	0.68
Rb (mg/L)	-	-	<0.03	<0.03
Ba (mg/L)	-	-	<0.25	<0.25
Li (mg/L)	0.007	0.008	0.007	0.008
DOC (mg/L C)	7.9	3.1	1.1	1.9
EC - field (mS/m)	199	-	-	-
EC - lab (mS/m)	205	150	160	143
pH - field	6.4	-	7.3	7.2
pH - lab	7.8	7.3	7.7	7.4
Cations (meq/l)	19.54	14.94	15.66	14.20
Anions (meq/l)	19.53	14.78	15.91	13.71
% balance	0.02	1.12	1.54	3.57
Carbon-13 (%o PDB)	-11.2	-11.6	-11.4	-11.3
TIC (mmol/L)	4.4	4.3	4.5	3.9
Carbon-14 (pmc)	67.6	67.7	61.8	63.6
Oxygen-18 (%o SMOW)	-4.7	-4.8	-	-5.1
87-Sr/86-Sr	0.709262	0.709134	0.709240	0.709260

ICP-MS Microchemistry Data (concentrations in ppb)

Borehole G39941

Date	04/15/94	Date	04/15/94
Li	30.049	I	12.663
Be	16.047	Te	-
B	282.863	Cs	-
Al	18.253	Ba	12.403
Sc	5.398	La	0.162
Ti	223.362	Ce	-
V	25.170	Pr	0.016
Cr	3.317	Nd	-
Mn	7.327	Sm	-
Fe	1095.103	Eu	0.102
Co	0.553	Gd	-
Ni	16.388	Tb	0.022
Cu	0.798	Dy	3.447
Zn	3.430	Ho	-
Ga	1.098	Er	0.021
Ge	0.108	Tm	-
As	0.459	Yb	-
Se	2.803	Lu	0.015
Br	1514.323	Hf	-
Rb	4.819	Ta	3.343
Sr	1475.115	W	-
Y	0.058	Re	-
Zr	0.048	Os	-
Nb	0.008	Ir	0.011
Mo	-	Pt	10.400
Ru	-	Au	-
Rh	0.025	Hg	-
Pd	-	Tl	1.402
Ag	-	Pb	-
Cd	0.614	Bi	-
In	-	Th	-
Sn	2.375	U	-
Sb	3.301		

GROUNDWATER CHEMISTRY DATA

G39942

DATE	10/29/93	04/18/94	08/29/94	12/08/94
K (mg/L)	11.2	3.4	2.9	3.0
Na (mg/L)	83	78	79	81
Ca (mg/L)	56.8	73.6	78.1	78.5
Mg (mg/L)	1.7	11.2	11.1	11.3
NH4 (mg/L N)	<0.05	<0.1	<0.1	<0.1
SO4 (mg/L)	81	21	18	20
Cl (mg/L)	150	146	146	145
Alk (mg/L CaCO3)	72	172	185	188
NOx (mg/L N)	0.6	0.5	0.5	0.3
P (mg/L)	<0.05	<0.1	<0.1	<0.1
Si (mg/L)	4.0	4.3	4.3	4.0
Cu (mg/L)	<0.02	<0.03	<0.03	<0.03
Fe (mg/L)	<0.02	<0.03	<0.05	<0.05
Mn (mg/L)	<0.02	<0.03	<0.05	<0.05
Zn (mg/L)	<0.02	<0.03	<0.03	<0.03
Sr (mg/L)	1.82	0.84	0.77	0.82
Rb (mg/L)	-	-	<0.03	<0.03
Ba (mg/L)	-	-	<0.25	<0.25
Li (mg/L)	0.011	0.010	0.008	0.009
DOC (mg/L C)	4.2	2.7	1.3	0.9
EC - field (mS/m)	68	-	-	-
EC - lab (mS/m)	91	83	84	86
pH - field	9.3	-	7.6	-
pH - lab	10.9	7.5	7.9	-
Cations (meq/l)	6.85	8.09	8.34	8.47
Anions (meq/l)	6.99	8.03	8.23	8.28
% balance	2.00	0.76	1.30	2.26
Carbon-13 (%o PDB)	-11.1	-11.4	-11.2	-11.0
TIC (mmol/L)	1.5	3.4	3.6	3.7
Carbon-14 (pmc)	90.9	90.6	90.4	89.6
Oxygen-18 (%o SMOW)	-4.7	-4.9	-	-5.0
87-Sr/86-Sr	0.709393	0.709397	0.709227	0.709192

ICP-MS Microchemistry Data (concentrations in ppb)

Borehole G39942

Date	04/18/94	Date	04/18/94
Li	237.855	I	2.851
Be	-	Te	-
B	141.112	Cs	0.690
Al	1264.250	Ba	12.776
Sc	5.126	La	0.338
Ti	56.347	Ce	-
V	34.419	Pr	0.020
Cr	6.137	Nd	-
Mn	14.311	Sm	6.109
Fe	648.807	Eu	-
Co	0.551	Gd	-
Ni	3.593	Tb	-
Cu	2.361	Dy	0.035
Zn	2.234	Ho	-
Ga	1.894	Er	2.178
Ge	-	Tm	0.004
As	0.926	Yb	-
Se	3.433	Lu	0.017
Br	679.340	Hf	-
Rb	45.933	Ta	0.741
Sr	1387.553	W	-
Y	1.602	Re	0.059
Zr	-	Os	-
Nb	-	Ir	0.007
Mo	-	Pt	-
Ru	-	Au	-
Rh	1.577	Hg	0.023
Pd	-	Tl	0.024
Ag	3.155	Pb	-
Cd	0.041	Bi	0.880
In	-	Th	-
Sn	0.598	U	0.025
Sb	1.128		

GROUNDWATER CHEMISTRY DATA

G39943

DATE	10/29/93	04/18/94	08/29/94	12/08/94
K (mg/L)	6.5	4.1	3.5	3.3
Na (mg/L)	74	72	71	72
Ca (mg/L)	15.7	48.2	56.8	62.8
Mg (mg/L)	7.4	8.3	8.7	10.6
NH4 (mg/L N)	<0.05	0.2	1.2	0.7
SO4 (mg/L)	23	20	17	18
Cl (mg/L)	125	123	126	128
Alk (mg/L CaCO3)	36	120	146	162
NOx (mg/L N)	0.6	0.3	0.3	0.2
P (mg/L)	<0.05	<0.1	<0.1	<0.1
Si (mg/L)	4.1	3.3	6.3	5.8
Cu (mg/L)	<0.02	<0.03	<0.03	<0.03
Fe (mg/L)	<0.02	<0.03	<0.05	<0.05
Mn (mg/L)	<0.02	<0.03	<0.05	<0.05
Zn (mg/L)	<0.02	<0.03	<0.03	<0.03
Sr (mg/L)	1.20	0.97	0.94	0.95
Rb (mg/L)	-	-	<0.03	<0.03
Ba (mg/L)	-	-	<0.25	<0.25
Li (mg/L)	0.005	0.009	0.007	0.009
DOC (mg/L C)	5.4	4.0	1.2	0.8
EC - field (mS/m)	74	-	-	-
EC - lab (mS/m)	57	67	74	76
pH - field	10.0	-	8.2	-
pH - lab	9.5	9.0	8.3	-
Cations (meq/l)	4.76	6.35	6.83	7.27
Anions (meq/l)	4.79	6.30	6.89	7.24
% balance	0.32	0.77	0.93	0.46
Carbon-13 (%o PDB)	-11.9	-11.5	-11.4	-11.0
TIC (mmol/L)	0.9	2.7	3.1	2.7
Carbon-14 (pmc)	-999.0	89.0	90.8	88.0
Oxygen-18 (%o SMOW)	-4.7	-4.8	-	-5.0
87-Sr/86-Sr	*0.709373*	*0.709665*	*0.709290*	*0.709281*

ICP-MS Microchemistry Data (concentrations in ppb)

Borehole G39943

Date	04/18/94	Date	04/18/94
Li	41.328	I	13.919
Be	-	Te	-
B	168.545	Cs	0.073
Al	170.898	Ba	13.535
Sc	3.821	La	0.198
Ti	155.566	Ce	-
V	44.421	Pr	1.883
Cr	0.867	Nd	-
Mn	17.228	Sm	-
Fe	1010.857	Eu	0.042
Co	0.262	Gd	-
Ni	1.235	Tb	3.041
Cu	2.249	Dy	21.211
Zn	5.590	Ho	0.802
Ga	2.111	Er	0.019
Ge	0.771	Tm	3.111
As	1.717	Yb	-
Se	6.110	Lu	0.006
Br	664.294	Hf	-
Rb	8.906	Ta	2.026
Sr	1632.456	W	-
Y	0.034	Re	0.011
Zr	5.040	Os	-
Nb	0.025	Ir	5.426
Mo	-	Pt	13.582
Ru	-	Au	3.360
Rh	0.013	Hg	-
Pd	0.125	Tl	-
Ag	-	Pb	-
Cd	22.526	Bi	1.171
In	-	Th	-
Sn	18.248	U	0.014
Sb	0.104		

GROUNDWATER CHEMISTRY DATA

P2

DATE	03/04/93	10/27/93	04/14/94	08/26/94	12/06/94
K (mg/L)	3.0	2.6	2.6	2.4	1.3
Na (mg/L)	88	87	84	85	86
Ca (mg/L)	95	89	89	88	81
Mg (mg/L)	11.3	12.7	12.2	11.6	7.7
NH4 (mg/L N)	<0.05	0.1	0.1	<0.1	<0.1
SO4 (mg/L)	29	28	25	23	24
Cl (mg/L)	153	150	149	144	142
Alk (mg/L CaCO3)	222	230	213	213	211
NOx (mg/L N)	0.1	0.3	<0.1	0.3	<0.1
P (mg/L)	<0.05	<0.05	<0.1	<0.1	<0.1
Si (mg/L)	4.3	4.1	4.1	4.2	4.2
Cu (mg/L)	<0.02	<0.02	<0.03	<0.03	<0.03
Fe (mg/L)	0.13	0.08	0.09	0.07	<0.05
Mn (mg/L)	<0.02	<0.02	<0.03	<0.05	<0.05
Zn (mg/L)	<0.01	<0.02	<0.03	0.03	<0.03
Sr (mg/L)	1.13	0.98	0.89	0.98	0.92
Rb (mg/L)	-	-	-	<0.03	<0.03
Ba (mg/L)	-	-	-	<0.25	<0.25
Li (mg/L)	0.007	0.005	0.008	0.007	0.008
DOC (mg/L C)	4.7	7.0	2.9	1.6	0.8
EC - field (mS/m)	-	91	-	-	-
EC - lab (mS/m)	96	98	92	91	92
pH - field	-	6.4	-	-	-
pH - lab	7.6	7.7	7.4	7.2	-
Cations (meq/l)	9.54	9.34	9.19	9.14	8.46
Anions (meq/l)	9.37	9.43	9.00	8.84	8.72
% balance	1.91	0.91	2.12	3.50	3.09
Carbon-13 (%o PDB)	-11.2	-11.3	-11.2	-11.1	-11.0
TIC (mmol/L)	4.6	4.6	4.4	4.4	4.4
Carbon-14 (pmc)	80.6	79.6	81.7	80.5	81.6
Oxygen-18 (%o SMOW)	-4.6	-5.0	-4.9	-999.0	-5.1
87-Sr/86-Sr	0.709233	0.709244	0.709170	0.709215	-

ICP-MS Microchemistry Data (concentrations in ppb)

Borehole P2

Date	03/04/93	04/14/94	Date	03/04/93	04/14/94
Li	15.100	13.276	I	-	6.817
Be	0.010	0.090	Te	-	3.203
B	-	100.980	Cs	-	0.110
Al	-	-	Ba	3.450	3.203
Sc	7.970	4.758	La	-	0.110
Ti	-	204.365	Ce	-	-
V	268.000	19.583	Pr	-	-
Cr	9.650	3.195	Nd	-	28.094
Mn	0.690	1.725	Sm	-	-
Fe	1826.000	921.277	Eu	-	0.063
Co	0.490	0.465	Gd	-	-
Ni	2.230	2.930	Tb	-	2.166
Cu	1.850	6.543	Dy	-	-
Zn	24.100	1.633	Ho	-	-
Ga	0.130	-	Er	-	0.024
Ge	-	0.044	Tm	-	-
As	1.300	0.371	Yb	-	-
Se	4.820	44.721	Lu	-	-
Br	-	723.471	Hf	-	14.322
Rb	2.310	2.552	Ta	-	0.961
Sr	1357.000	1805.872	W	0.380	-
Y	-	0.033	Re	-	0.013
Zr	-	0.272	Os	-	-
Nb	-	0.032	Ir	-	-
Mo	0.710	-	Pt	-	3.007
Ru	-	-	Au	-	-
Rh	-	0.030	Hg	-	-
Pd	-	7.733	Tl	-	-
Ag	-	1.668	Pb	0.460	-
Cd	-	0.295	Bi	-	1.444
In	-	-	Th	-	-
Sn	0.660	13.282	U	0.210	0.017
Sb	0.300	0.266			

GROUNDWATER CHEMISTRY DATA

P3

DATE	03/04/93	10/27/93	04/15/94	08/28/94	12/06/94
K (mg/L)	2.8	2.4	2.6	2.3	2.6
Na (mg/L)	79	80	79	82	83
Ca (mg/L)	83	83	85	84	84
Mg (mg/L)	11.1	11.8	11.7	12.1	11.5
NH4 (mg/L N)	<0.05	0.1	0.1	<0.1	<0.1
SO4 (mg/L)	23	24	24	24	24
Cl (mg/L)	139	142	138	140	147
Alk (mg/L CaCO3)	208	220	209	238	208
NOx (mg/L N)	0.1	0.1	<0.1	0.1	<0.1
P (mg/L)	<0.05	<0.05	<0.1	<0.1	<0.1
Si (mg/L)	4.8	4.1	4.3	4.4	4.2
Cu (mg/L)	<0.02	<0.02	<0.03	<0.03	<0.03
Fe (mg/L)	0.03	0.04	0.06	<0.05	<0.05
Mn (mg/L)	<0.02	<0.02	<0.03	<0.05	<0.05
Zn (mg/L)	0.04	0.03	0.13	0.07	<0.03
Sr (mg/L)	0.89	0.97	0.83	0.86	0.85
Rb (mg/L)	-	-	-	<0.03	<0.03
Ba (mg/L)	-	-	-	<0.25	<0.25
Li (mg/L)	0.006	0.005	0.008	0.007	0.007
DOC (mg/L C)	4.1	7.2	2.9	1.4	0.8
EC - field (mS/m)	-999	85	-	-	-
EC - lab (mS/m)	88	90	88	87	88
pH - field	-	6.3	-	7.2	-
pH - lab	7.6	7.7	7.4	7.6	-
Cations (meq/l)	8.54	8.66	8.71	9.14	8.81
Anions (meq/l)	8.57	8.89	8.57	8.84	8.80
% balance	0.41	2.63	1.65	3.50	0.04
Carbon-13 (‰ PDB)	-11.1	-11.4	-11.3	-11.3	-11.1
TIC (mmol/L)	4.3	4.5	4.2	4.3	4.3
Carbon-14 (pmc)	84.1	83.2	82.6	84.1	82.3
Oxygen-18 (‰ SMOW)	-4.9	-4.8	-4.0	-	-5.1
87-Sr/86-Sr	0.709200	0.709291	0.709141	0.709202	0.709185

ICP-MS Microchemistry Data (concentrations in ppb)

Borehole P3

Date	03/04/93	04/15/94	Date	03/04/93	04/15/94
Li	12.900	10.389	I	-	5.576
Be	0.030	-	Te	-	-
B	-	124.045	Cs	-	-
Al	-	117.268	Ba	3.290	2.942
Sc	7.470	6.165	La	-	0.031
Ti	-	196.666	Ce	-	5.195
V	2.560	20.652	Pr	-	-
Cr	10.000	3.201	Nd	-	-
Mn	5.630	26.038	Sm	-	25.506
Fe	1613.000	630.848	Eu	-	0.015
Co	1.070	2.829	Gd	-	23.868
Ni	2.490	3.090	Tb	-	0.015
Cu	2.320	1.898	Dy	-	-
Zn	62.600	139.589	Ho	-	-
Ga	0.140	0.339	Er	-	24.685
Ge	-	11.389	Tm	-	0.038
As	3.550	1.092	Yb	-	-
Se	5.800	2.165	Lu	-	0.023
Br	-	596.697	Hf	-	-
Rb	2.440	2.329	Ta	-	-
Sr	1203.000	1628.538	W	0.660	-
Y	-	0.009	Re	-	0.024
Zr	-	3.262	Os	-	15.972
Nb	-	0.040	Ir	-	0.049
Mo	0.510	4.695	Pt	-	-
Ru	-	-	Au	-	-
Rh	-	-	Hg	-	0.075
Pd	-	0.069	Tl	-	-
Ag	-	0.052	Pb	-	-
Cd	-	0.140	Bi	-	-
In	-	-	Th	-	4.289
Sn	0.750	0.954	U	0.190	0.075
Sb	0.390	1.099			

RAINWATER CHEMISTRY DATA

	SBR1				SBR2				SBR3	
DATE	10/29/93	11/23/93	04/16/94	08/30/94	10/29/93	11/23/93	04/16/94	08/28/94	08/28/94	01/12/95
K (mg/L)	3.7	3.5	1.6	0.6	5.0	5.1	4.1	0.8	3.3	13.0
Na (mg/L)	67	74	51	11	46	38	23	7.7	11.2	15
Ca (mg/L)	20.3	17.8	14.6	1.3	26.1	19.8	14.4	4.2	3.1	7.5
Mg (mg/L)	6.6	9.1	7.0	1.2	5.9	4.9	3.4	0.9	1.4	1.8
NH4 (mg/L N)	0.3	<0.1	<0.1	<0.1	0.1	1.0	<0.1	<0.1	<0.1	18
SO4 (mg/L)	27	26	17	3	21	18	9	2	3	5
Cl (mg/L)	122	143	109	19	86	72	59	17	21	23
Alk (mg/L CaCO3)	34	12	6	1	49	41	16	5	6	24
NOx (mg/L N)	0.6	0.8	<0.1	<0.1	0.3	<0.1	<0.1	<0.1	<0.1	19.9
P (mg/L)	<0.05	<0.1	<0.1	<0.1	<0.05	<0.1	<0.1	<0.1	<0.1	2.33
Si (mg/L)	0.4	<0.5	<0.5	-	0.2	<0.5	<0.5	-	-	-
Cu (mg/L)	0.04	<0.03	<0.03	-	<0.02	<0.03	<0.03	-	-	-
Fe (mg/L)	0.06	<0.03	0.03	-	0.05	0.04	<0.03	-	-	-
Mn (mg/L)	<0.02	<0.03	<0.03	-	<0.02	<0.03	<0.03	-	-	-
Zn (mg/L)	0.07	0.51	0.13	-	0.03	0.03	0.03	-	-	-
Sr (mg/L)	0.14	0.09	0.05	-	0.14	0.08	<0.05	-	-	-
Rb (mg/L)	-	-	-	-						
Ba (mg/L)	-	-	-	-						
Li (mg/L)	<0.005	<0.005	<0.005	-	<0.005	<0.005	<0.005	-	-	-
DOC (mg/L C)	11	2.1	3.2	0.5	16	4.7	2.7	1.9	7.2	14
EC - field (mS/m)	-	-	-	-	-	-	-	-	-	-
EC - lab (mS/m)	56	59	34	9	45	37	24	8	-10	34
pH - field	-	-	-	-	-	-	-	-	-	-
pH - lab	7.7	6.5	7.0	5.9	7.8	6.8	7.2	6.6	6.9	6.9
Cations (meq/l)	4.77	4.92	3.56	0.64	3.90	3.23	2.13	0.64	0.84	2.77
Anions (meq/l)	4.73	4.87	3.58	0.62	3.88	3.22	2.15	0.62	0.81	2.88
% balance	0.68	1.00	0.55	3.66	0.55	0.20	0.65	2.65	3.33	3.94

CSIR DIVISION OF WATER TECHNOLOGY 10 OCTOBER 1995
ANALYTICAL SERVICES (STELLENBOSCH LABORATORY)
PRECISION AND RECOVERY DATA

	n	Avg mg/L	Addn mg/L	Std dev	CV %	Rec %	n	Avg mg/L	Adcn mg/L	Std dev	CV %	Rec %
Potassium as K mg/L	10	1.7	1.5	0.02	0.9	95	10	5.4	4.5	0.03	0.6	101
Sodium as Na mg/L	10	23.6	5	0.22	0.9	105	10	69.6	15	0.32	0.5	96
Calcium as Ca mg/L	10	12.5	5	0.21	1.7	102	10	37.2	15	0.75	2.0	100
Magnesium as Mg mg/L	10	3.6	1.5	0.04	1.1	108	10	10.7	4.5	0.12	1.1	104
Ammonia as N mg/L	10	1.0	0.25	0.01	1.3	100	10	4.6	1.5	0.09	1.9	105
Sulphate as SO4 mg/L	10	17.1	5	0.74	4.3	114	10	228	200	3.68	1.6	103
Chloride as Cl mg/L	10	53.6	10	1.51	2.8	115	10	488	400	7.32	1.5	101
Alkalinity as CaCO3 mg/L	10	25.1	5	0.44	1.8	101	10	250	50	0.82	0.3	97
Nitrate as N mg/L	10	1.0	0.25	0.04	3.6	90	10	4.6	1.5	0.05	1.1	109
Phosphate as P mg/L	10	1.0	0.25	0.01	1.0	109	10	4.5	1.5	0.02	0.0	96
Conductivity mS/m	*10*	-	-	-	-	-	*10*	88.3	-	0.75	0.9	-
Dissolved Organic Carbon as C mg/L	10	-	-	-	-	-	10	10.2	2.5	0.24	2.4	97
Fluoride as F mg/L	10	0.50	0.25	0.03	5.2	98	10	2.0	0.5	0.07	3.4	100
Aluminium as Al mg/L	10	0.35	0.25	0.02	4.8	102	10	1.25	0.25	0.02	1.8	90
Copper as Cu mg/L	10	0.35	0.25	0.01	3.0	100	10	1.25	0.25	0.01	0.7	98
Iron as Fe mg/L	10	0.35	0.25	0.01	2.5	101	10	1.25	0.25	0.01	1.1	95
Manganese as mn mg/L	10	0.35	0.25	0.01	2.7	104	10	1.25	0.25	0.01	1.0	95
Zinc as Zn mg/L	10	0.35	0.25	0.01	4.0	98	10	1.25	0.25	0.01	1.1	93
Chemical Oxygen Demand mg/L	10	75	25	1.8	2.4	100	10	525	25	6.5	1.2	102

APPENDIX 4

DOWN HOLE GEOPHYSICS

Boreholes

- ➡ G33427 - 79 m
- ➡ G39940 - 12 m
- ➡ G39941 - 69 m
- ➡ G39942 - 50 m
- ➡ G39943 - 35 m
- ➡ BH 7 - 49 m

APPENDIX 4

STRUISBAAI: DOWN-THE-HOLE GEOPHYSICAL LOGGING

(References Repsold, 1989 and Jorgensen, 1989)

1 INTRODUCTION

The logging was carried out by Mr Barry Venter of DWA&F. The probes used were:

Gamma-Ray Log (γ): Gamma-Ray measures the relative absence of presence of clay minerals. It is thus used to determine lithological boundaries and differentiation of shaly (clayey) and non-shaly rocks. Measurement is in counts per second with high clay registering high c.p.s.

Formation Resistivity Log (ρ and $\omega\rho$): This records the resistivity profile of the layers in Ω-metres. There are always two logs namely the short-spaced and long-spaced where the short-spaced has a shallow depth of rock measurement and the long-spaced a deeper rock measurement but a poorer layer resolution.

Neutron-neutron Log (N-n): The neutron probe is used to determine the rock density. Measurement is in counts per second.

Water Resistivity Log (R): This records the resistivity of the water in the borehole and is used to detect salinity layering.

Self-Potential Log (SP): This is recorded simultaneously with the resistivity log. This is a reflection of the salinity of the pore water in porous rock, recorded in Ω-m.

Temperature Log (T): This records the temperatures of the water in the borehole.

Note: For the Struisbaai boreholes the Caliper log was not available.

2 INTERPRETATION OF THE LOGS

The logs are attached. Each borehole log was interpreted as follows:

BH7: The self-potential log is very erratic and is probably due to the heavy corrosion of the casing, i.e. the log is "seeing" through the hole in the casing. No anomalies are seen below the end of the casing. No geological log is available for this borehole.

G33427: At 57 m there is a drop in Formation Resistivity with a corresponding increase in Gamma indicating porous (fractured) rock. At 64 m is also a fracture although the Gamma log has a lower reaction than the 57 m fracture. At both 57 m and 64 m the water resistivity and formation resistivity (short) approach each other which indicates a large cavity with minimal influence of rock material on the formation resistivity log. At both 57 m and 64 m the Neutron-neutron log moves to the left, i.e. this is where the neutrons are "captured" by the water in the cavity. Below the 64 m fracture the temperature of the water increases and the formation resistivity (long) increases, both indicating solid rock. No geological log is available for this borehole.

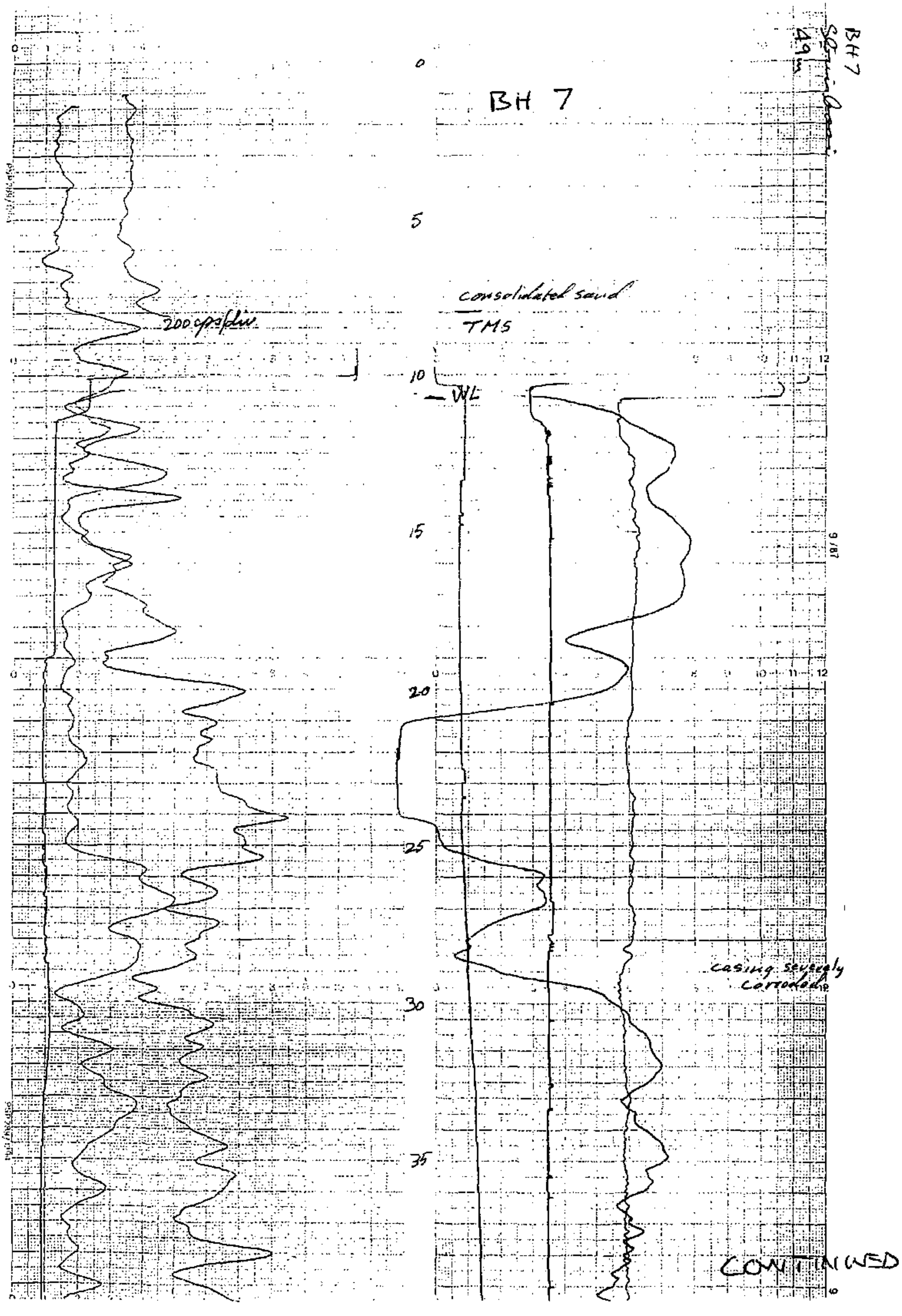
G39940: No anomalies are observed. However, note the position of the Neutron-neutron probe which is far to the left which shows this rock has a higher porosity than for any of the other boreholes. The geological log shows this is drilled in Enon Formation which confirms that this rock is more porous. Note too the low water resistivity, this borehole has the highest salinity water.

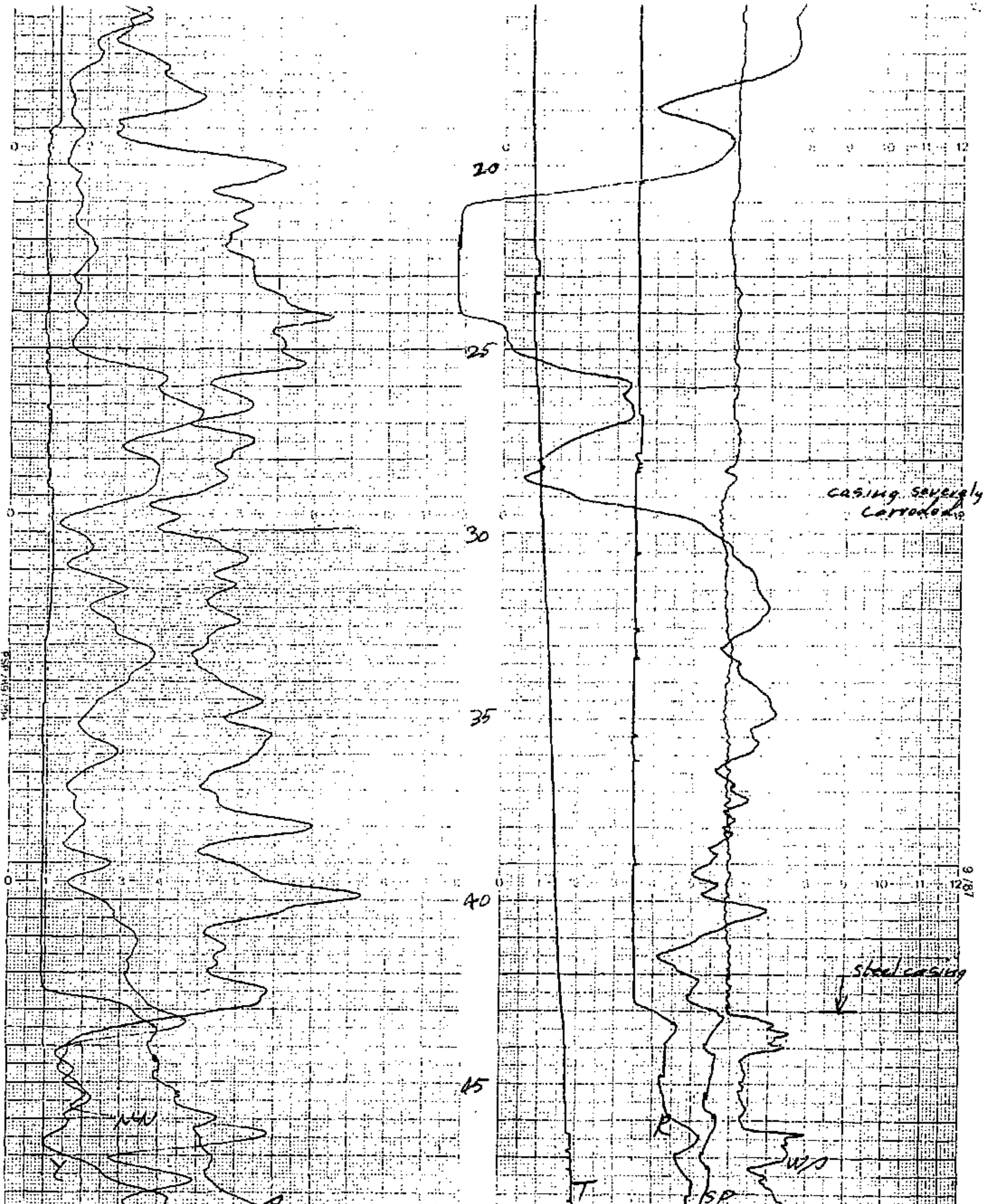
G39941: At 62.5 m there is a good cavity response by the Gamma and the Neutron-neutron probe moving in opposite directions. The drill log records a water strike at 63 m. A water strike at 53.2 m does not reflect in the geophysical log. At 48 m there is a sharp right spike of the Neutron-neutron. This could be some clay material which has deposited in the cavity at the calcrete-quartzite contact.

G39942: At 49 m is a cavity indicated by the Gamma log moving sharply to right with the Neutron-neutron moving to left. The geological log confirms a water strike at 49 to 51 m.

G39943: Fractures at 20 m at 23 m, at 26 m and at 33 m are indicated by the Neutron-neutron log moving left. The Gamma log only confirms the 20 m and 33 m fractures by moving right. The geological log does not record a water strike at 20 m, but does record water strikes at 23.2 m, at 27.2 m and at 33 m. The geophysical log shows a 35 m borehole, but the drill log shows the borehole was drilled to 42 m, but collapsing. The Gamma log shows an anomaly at 16 m to 18 m, however, the lack of response by the Neutron-neutron probe shows this is not a cavity.

In general the on-site geological logging of the boreholes and the geophysical logs show good agreement.

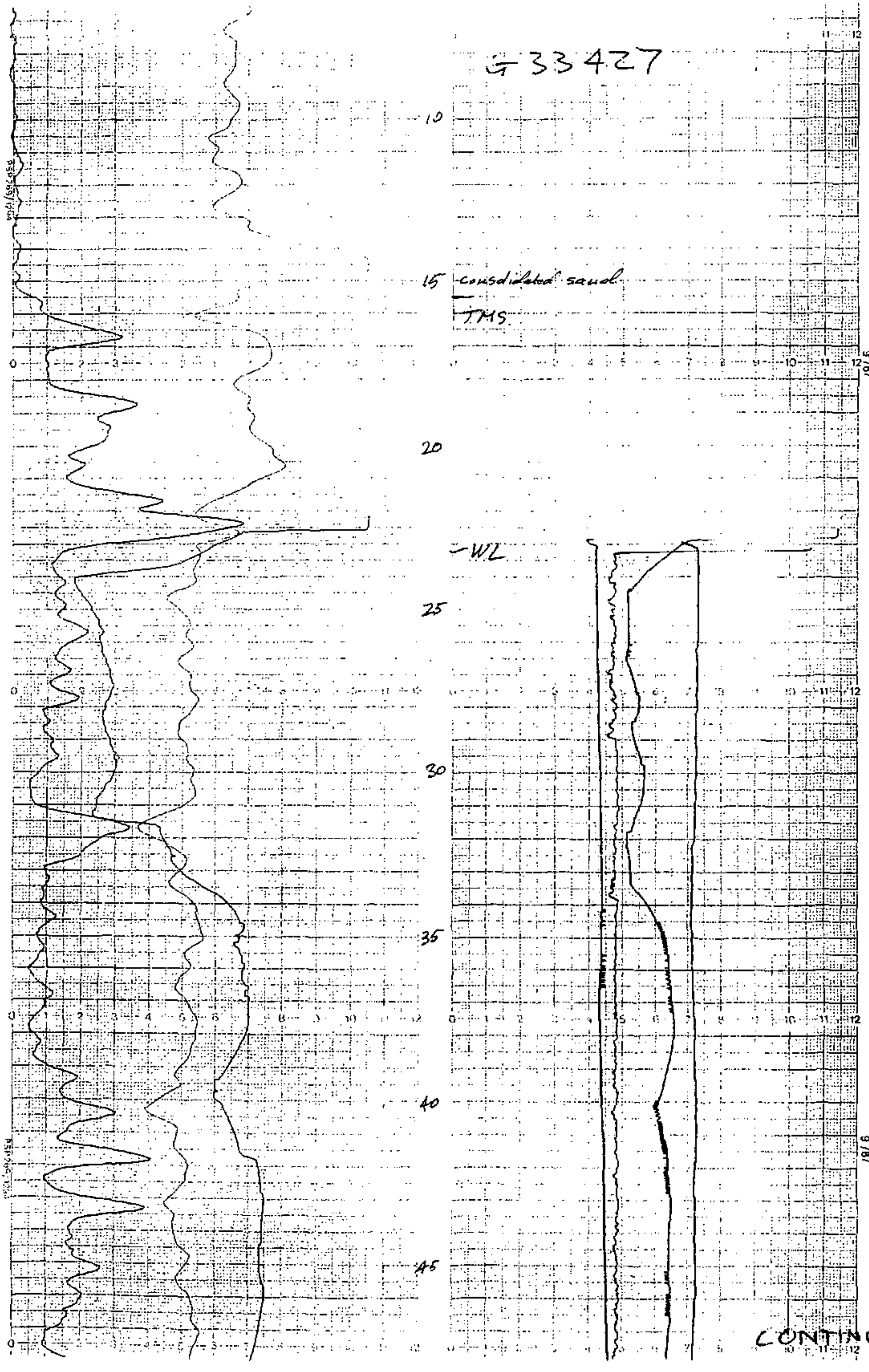

BH 7
[illegible]
49m
BH 7
0
5
10
15
20
25
30
35
consolidated sand
TMS
WL
200 cps/div.
casing severely corroded
CONTINUED



γ	ρ	N-N	R	SP	W/S	T
20cps/div Tc ½ sec disp. 0	50 Ωm/div	100 cps/div Tc ½ sec disp 0	50 Ω/div disp. 100	20 mV/div bias +450	1 Ωm/div	0,2°C/div 0 = 18°C

2118 Struisbaai Ou Pompgat #7 9310-12

G 33427



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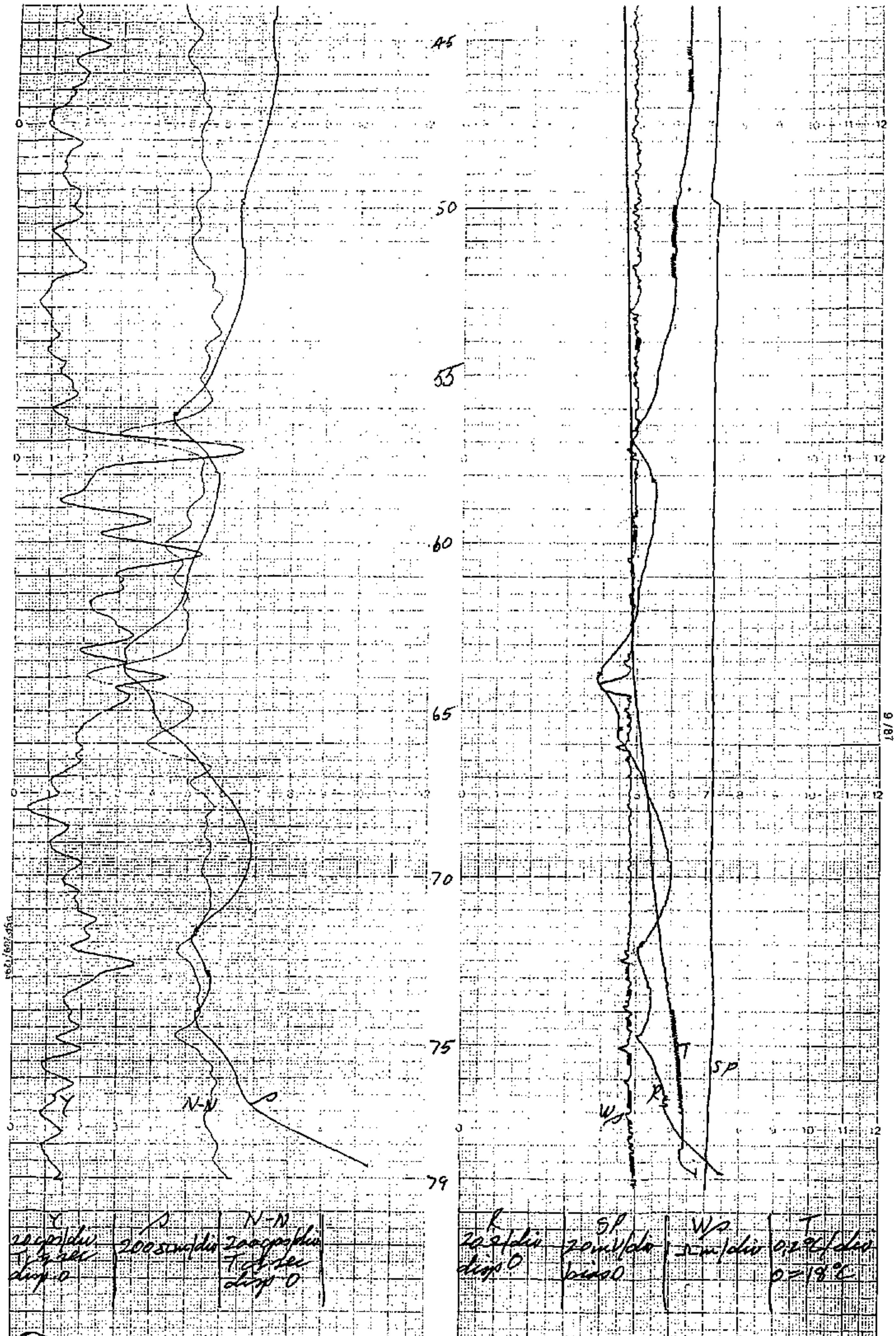
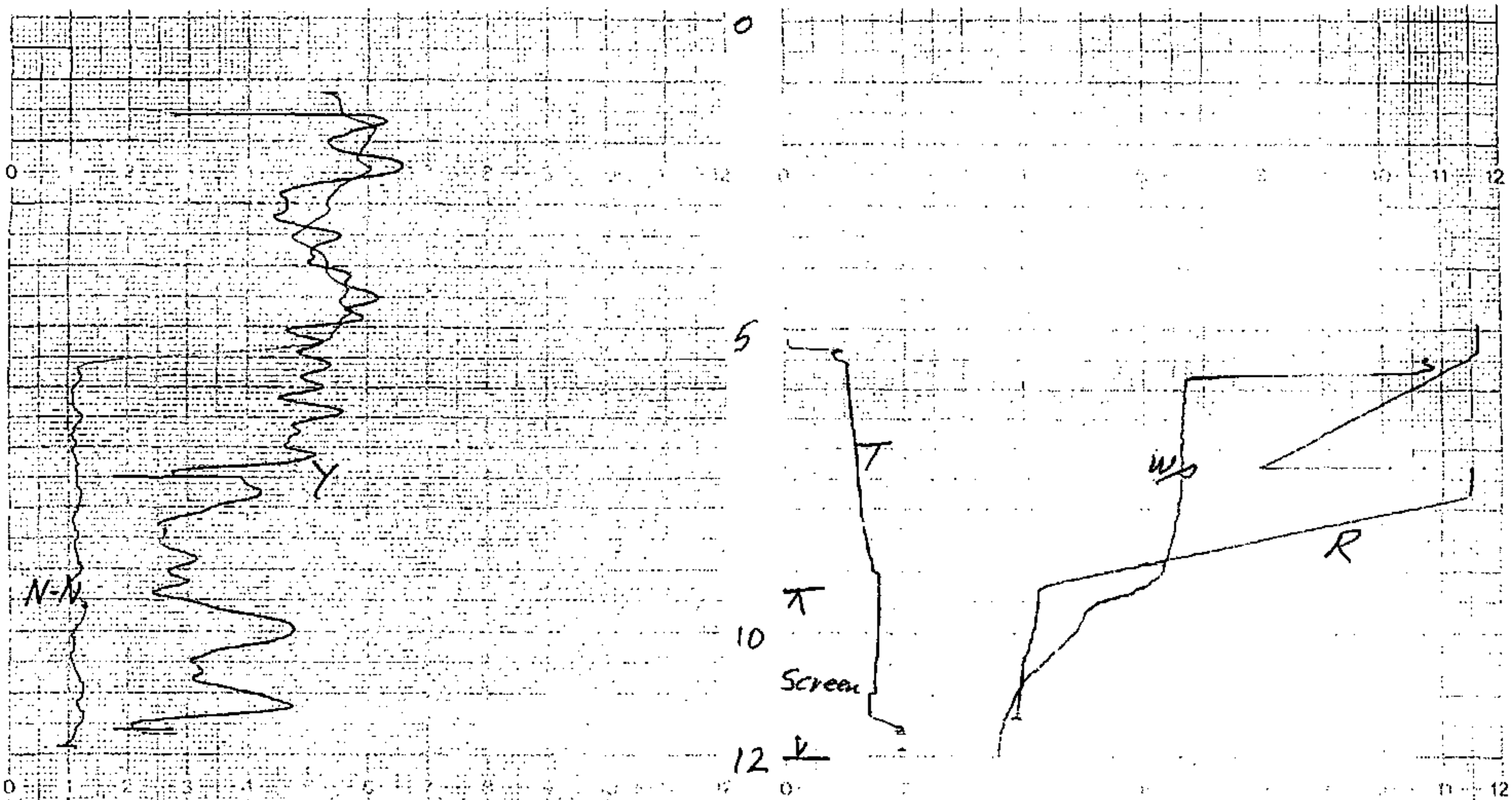


(2116) Struisbaai G33427 93-10-12



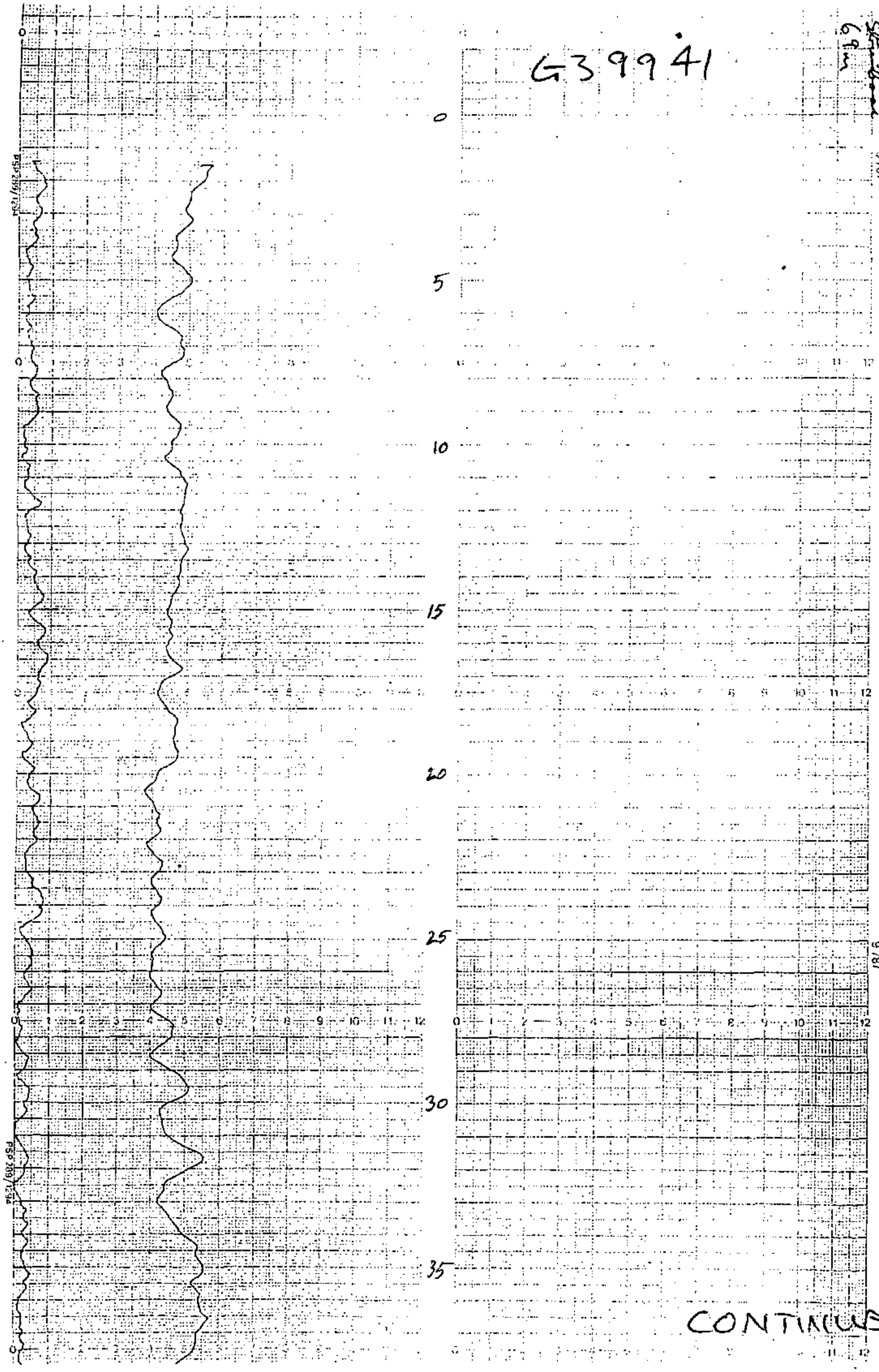
γ		N-N	R	W/S	T
5 cps/div T ½ sec disp. 0		100cps/div Tc ½ sec disp. 0	20Ω/div disp 270	0,5 Ωm/div	0,2°C/div 0 = 18°C

9/87

(2113) Struisbaai G39940 93-10-12

G39941

G39941



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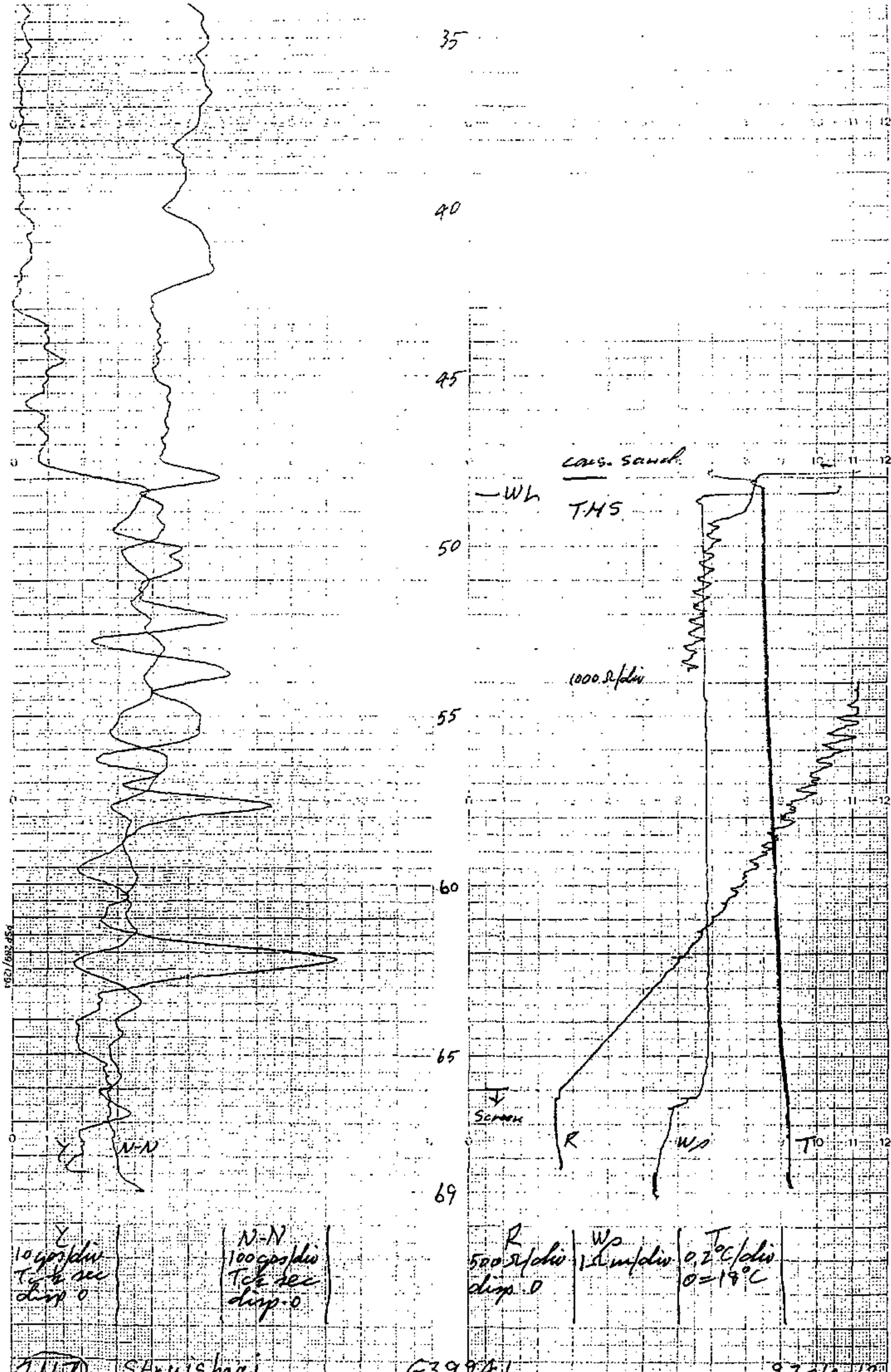
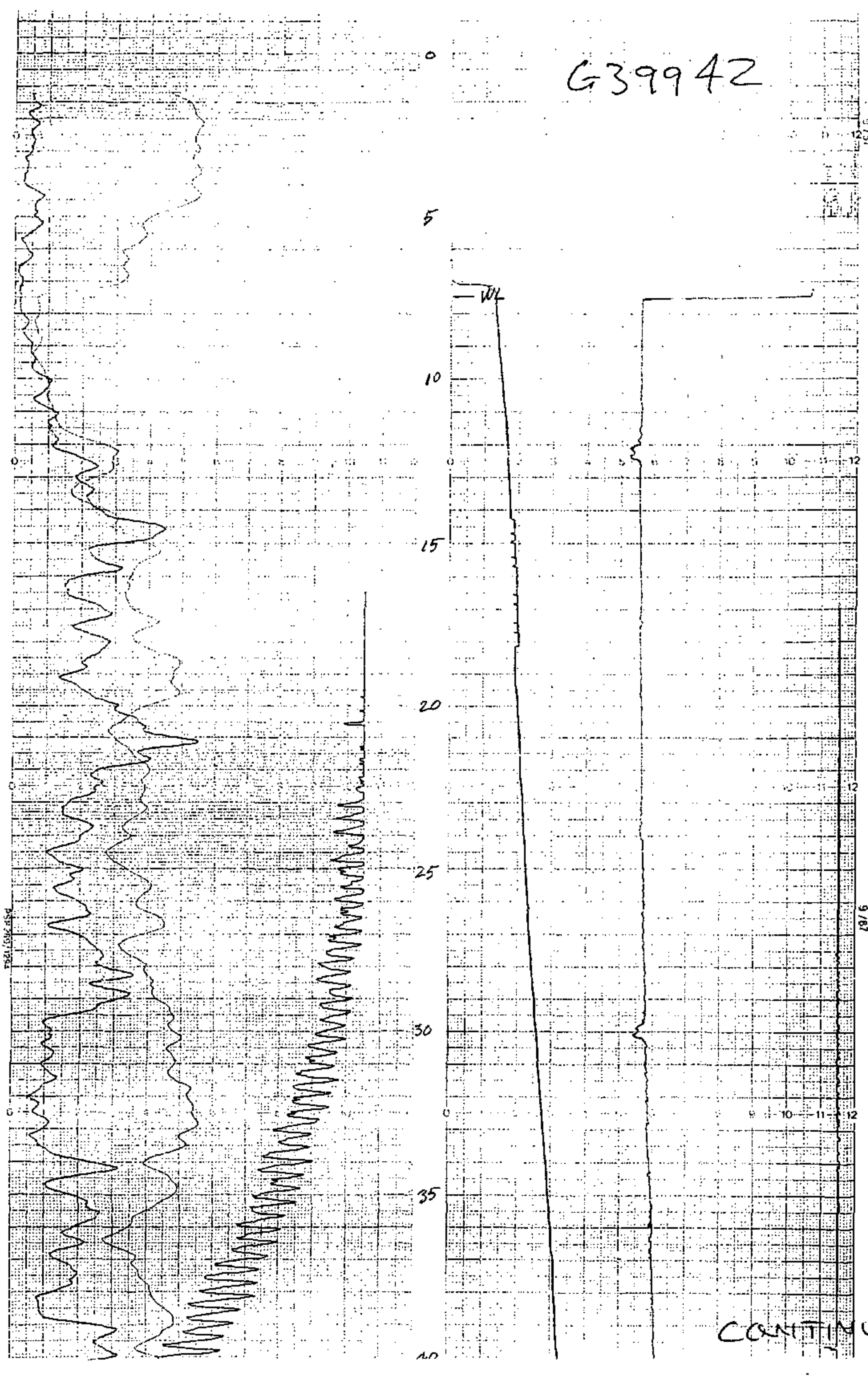


2117 Struisbaai G39941 93-10-12

G39942



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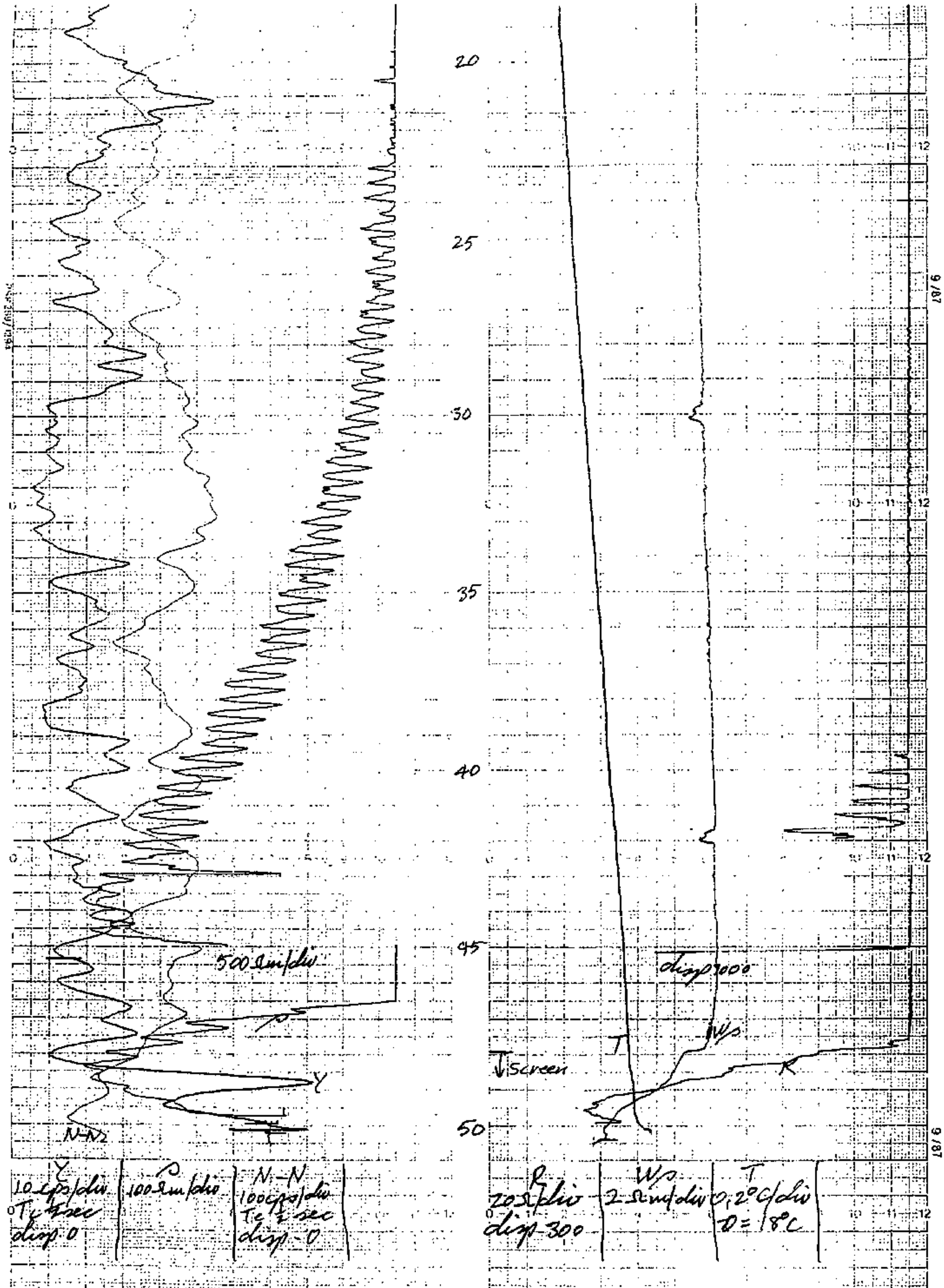

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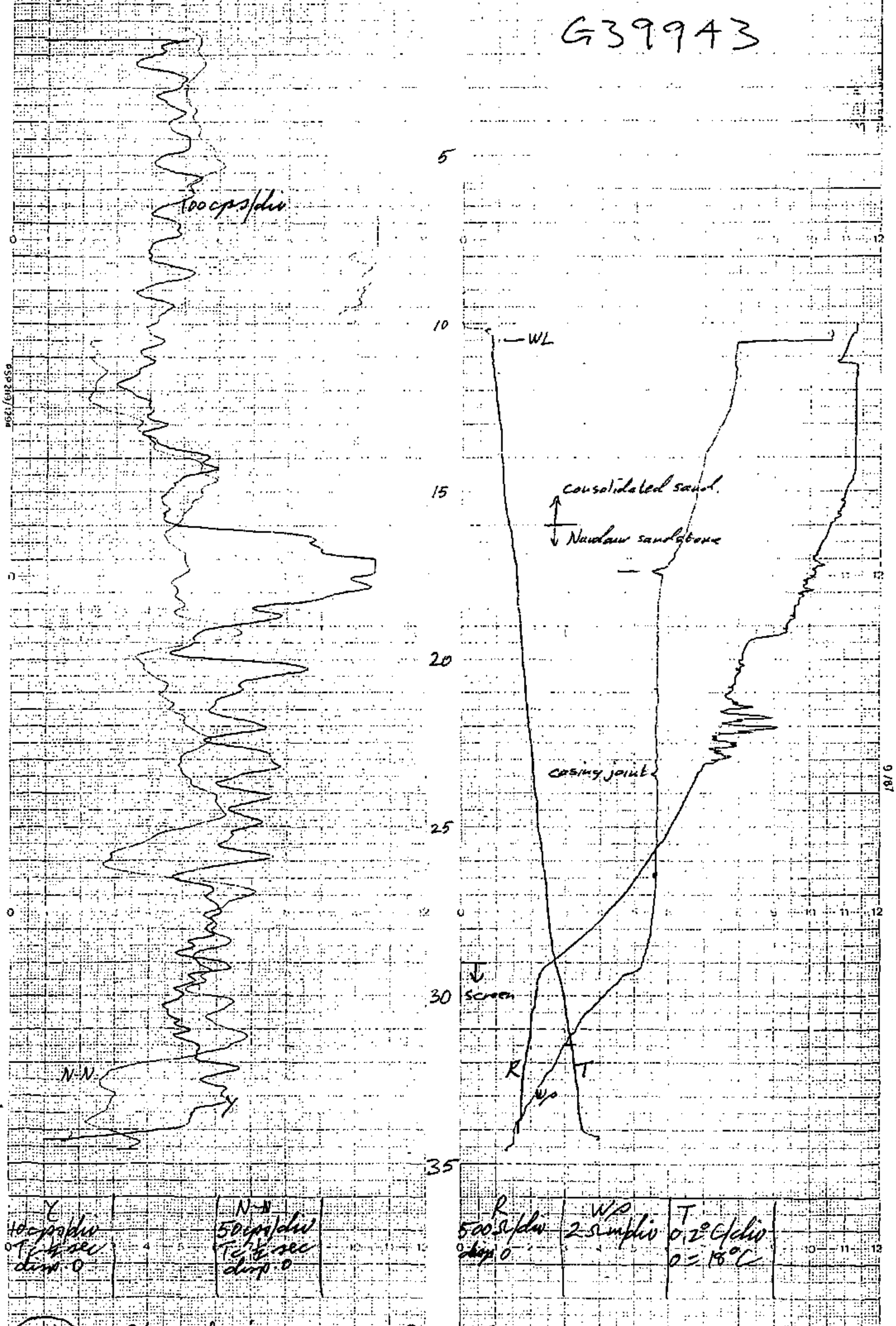
G39943



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APPENDIX 5

RECOMMENDATIONS FOR FUTURE GROUNDWATER MANAGEMENT

APPENDIX 5

RECOMMENDATIONS FOR FUTURE GROUNDWATER MANAGEMENT

The decision to replace the old wellfield with the new wellfield has been a fortuitous decision. By doing so two positive effects have occurred. Firstly the wellfield is now in an area where local recharge is slightly less saline due to it being further away from the sea and thus receiving less sea-spray. Secondly the possibility of over-pumping and inducing seawater intrusion is much reduced.

The current practice of satisfying summer peak demand by obtaining the extra water from the old wellfield is acceptable.

The danger with the current water-supply set-up is that complacency may set in with the belief that the water-supply and water-quality problems have been solved for now and also for the future. There is at present no scientifically calculated wellfield yield and wellfield management plan. The only calculation that has been carried out is individual borehole yield calculations. The potential danger is that as the demand for water increases, both from population increase and by increased use of the better quality water for gardening, this demand will be supplied by increasing the yield from the three production boreholes. When the maximum yield of the individual boreholes is increased beyond their capacity then additional boreholes will be drilled close by, the effect of which will be to further increase the local drawdown. This may induce seawater intrusion.

The modelling exercise that has been carried out is only the first step in developing a wellfield management and control plan. The hydraulic information available for this modelling exercise was minimal as the focus of this thesis was not the hydraulics of the system but the water quality. Pump-testing of the old boreholes and water level monitoring to obtain summer and winter regression curves is important additional information. The very big advantage that Struisbaai has compared to most other wellfields is that there is no apparent limit to inland development of the wellfield. As more water is needed so the wellfield can be extended inland. The important factor is to know at what stage must this inland extension occur.

The recommendations for future groundwater management are thus as follows:

- Carry out an investigation to obtain additional hydraulic information.
- Refine the groundwater model.
- Develop a series of water-demand scenarios and apply these to the model to determine the effect on water-levels.
- Determine the maximum water that can be obtained from the existing wellfield.
- Develop population growth and water demand forecasts to determine when the water demand and existing water yield are equal. This will ensure that wellfield expansion plans can be put into place before the need for additional water arises, thus preventing "emergency" overexploitation.
- Identify where the future wellfield expansion areas are and ensure that these are protected and reserved for groundwater abstraction.

★★★