ANALYSIS OF GROUNDWATER LEVEL TIME SERIES AND THE RELATION TO RAINFALL AND RECHARGE

R Meyer

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Water Research Commission

ANALYSIS OF GROUNDWATER LEVEL TIME SERIES AND THE RELATION TO RAINFALL AND RECHARGE

Report to the

Water Research Commission

on the project

"Analysis of groundwater level time series and the relation to long-term climatic conditions, climate change and recharge"

by

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EXECUTIVE SUMMARY

Introduction

Groundwater levels in South Africa have been recorded routinely and on a national scale by the Department of Water Affairs and Forestry since the mid 1950s. Since that time this task has been expanded significantly and currently a few hundred boreholes are monitored on a regular basis. Knowledge of long-term rainfall variability and the associated response of the country's groundwater resources are essential for efficient and sustainable groundwater resource and land management. Despite the relatively short period for which water level records are available, these records contain valuable information that can be used beneficially in the development of technologies to assist in the responsible management of our limited groundwater resources.

With this in mind, some South African groundwater level time series information was selected and studied using a new and novel approach based on a recently developed technique to monitor drought conditions. The results are presented in this report.

Aims and objectives

The main aims of the project were three fold:

- To collate long-term groundwater level information and investigate new methods that can be used to correlate these long term groundwater level fluctuations with rainfall and climatic cycles;
- To determine whether the apparent long-term declining trends observed in South African groundwater level data is indicative of a current and/or longer term groundwater drought cycle(s) or whether other factors are contributing to this trend; and
- To document the analytical techniques available and used to analyse relevant geohydrological information to assist planners in the longer term planning of groundwater utilization as part of the envisaged national Integrated Water Resource Management plans.

A methodology to simultaneously analyse groundwater level and rainfall information of southern Africa and correlate this information to drought and other long-term climatic indicators or cycles is proposed in this report. It is envisaged that the further development of the concepts expressed in this report, may eventually lead to the development of indicators that can be used to improve the current groundwater recharge estimations and thereby the long-term management of the important national groundwater resources.

In view of the international research emphasis on climatic change, it was believed to be important to assess the status of knowledge on climatic variability in southern Africa over recent geological times and specifically the last few thousands years. This review highlighted the large variations in climatic conditions that have occurred over time and allows one to consider the climatic changes that have taken place over the last 50 to 100 years, and the changes that are predicted for the next centuries, in perspective.

Brief description of some results

Based on the documented record and numerous studies on the palaeo-climatic conditions in southern Africa, climatic cycles of different length and intensity appear to have been present during the last approximately 200 000 years and more specifically the last few centuries. These can be summarised as:

- an approximately 23 000 year cycle of major wet and dry periods during the last approximate 200 000 years;
- a possible 400 – 500 year "cold/warm" or "wet/dry" cycle;
- an ~120 year cycle;
- an ~18 year cycle; and
- an ~11 year cycle.

In the documented South African groundwater level information, a number of different water level fluctuation cycles or trends are present. These are classified as

- Short term (~1 year) fluctuations in the groundwater level data;
- Medium term (~10 years+) cycle in the groundwater level data; and
- Longer term trend which may be of a cyclic nature, but due to the short time series, it is not clear whether it may perhaps be part of a longer cyclic period.

Of particular interest are the declining trends, often extending for 10 or more years that are observed in some of the data sets. These do not appear to be associated with a particular geohydrological, geological or climatological region, but are present throughout the country. Another important observation is the rapid response of groundwater levels to periods of excessive rainfall, often by several metres over a period of a few months.

Closely linked to periodicity in water levels, is the concept of "groundwater drought", which may have important management implications, but has not yet received sufficient attention. Researcher from the United States used the Palmer Drought Index (PDI) and the more recent Standardized Precipitation Index (SPI) to formulate a "Drought Index" that provides information on drought duration, frequency and time scales. Selected groundwater level and monthly rainfall time series from South Africa were analysed by correlating the groundwater level records with the Standarised Precipitation Index (SPI) values derived for South African rainfall data. An example illustrating the correlation between a water level record of more than 40 years from a borehole near De Aar and the associated SPI is given below Figure 1. The correlation between the two datasets is remarkable over the entire record period and both the larger and smaller anomalies (amplitude and duration) correlate well, especially for the first section of the record. Where groundwater levels follow even the small variations in SPI values, indicates that in selected cases, at least some groundwater recharge occurs during almost every year.

In the second example sudden groundwater level changes of around 25m (rapid recharge) correlate well with periods of high SPI values (consistently wet years), while extended periods of declining water level again correlate with extended periods of low SPI values (consistently dry years). However, not all examples analysed during this research project showed similar high correlations. The reasons for this are not apparent.

Figure 1: Groundwater level response at recording station D6N500 (borehole 3024CA00328) on the farm Caroluspoort, De Aar district with the associated SPI using the rainfall record of Rainfall District 54.

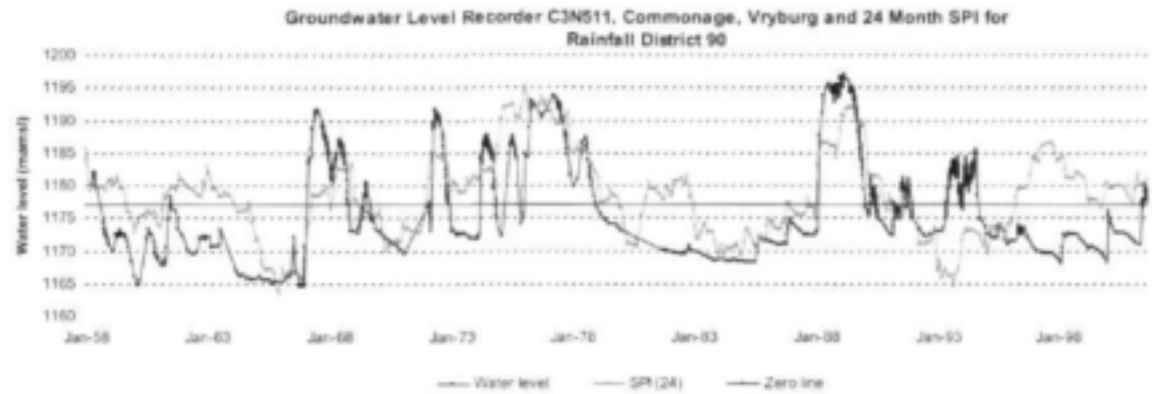

Figure 2: Groundwater level response at recording station C3N511 (borehole 2624DC00032) on the farm Commonage, Vryburg district with the associated SPI using the rainfall record of Rainfall District 90.

No evidence was found that a consistent and constantly declining trend in South African groundwater level information is present, at least over the approximately 50 years for which information is available. There are, however, in many of the long-term records periods of extended declining groundwater level. These were found to continue in some instances for up to 20 years. These long declining trends are also often terminated by sometimes abrupt rises or return of the groundwater level to the original reference level, or sometimes even higher. Depending on the intensity and duration of the rainfall event or the period over which above average rainfall is recorded, this return of the groundwater level occurs within months after the onset of the rainfall event. This can be explained by a combination of factors, such as the intensity and duration of the rainfall period, the geohydrological conditions in the vicinity of the recharge area for a particular aquifer of the monitoring borehole, the physical parameters of the unsaturated zone, and others. Further, no indication could be found that the current cycle of climatic change experienced throughout the world and that is predicted to intensify during the next decades, is reflected in any way in the South African groundwater level records. It must also be stressed that the predicted changes in climate for the southern part of Africa, are relatively minor compared to those that are documented in the geological record of the last few million years.

It is proposed that the observed correlations between SPI and groundwater level fluctuations can be used to calculate a generic "recharge index" for a region. Based on the way the SPI values were calculated and reported in this project, the "recharge index" could be representative of a rainfall district, and not necessarily a region of similar geohydrological conditions. When developed further, this approach may result in improved quantification of groundwater recharge on a regional basis in Southern Africa.

From an analysis of the SPI and long-term groundwater level graphs and its possible use in recharge calculations, the following observations were made:

- the SPI value has to be at least positive in order to cause recharge. In the context of this report, recharge is considered to occur when water levels are increasing. In many cases it would appear that the SPI value has to be in excess of +2 to have a meaningful impact on groundwater recharge.
- During a period of positive SPI values, water levels have to show an increasing trend for a period generally at least equivalent in duration to that of the SPI anomaly, otherwise limited or no recharge will take place.
- During periods where SPI values are close to zero or negative, no recharge takes place.
- For recharge to occur, the annual rainfall needs to be above the long term MAP.

A methodology has been proposed to calculate the "Recharge Index". A number of factors are calculated with each being given a weight. The total weight is then a relative indication of the rate of recharge. The method proposed is still very subjective and a great deal of additional work needs to be done to develop this into a reliable way to turn the "Recharge Index" into a realistic representation of effective recharge. The example in Figure 1 above was used to calculate the proposed recharge index for that specific rainfall district. Based on the outcome of the calculations it is suggested that the period between 1973 and 1978 was one of high groundwater recharge, that of 1978 to 1986 one of no or very low recharge, while the period between 1986 and 1992 was again one of high recharge. No attempt was made to express the "recharge index" value into a percentage of MAP or any other more quantitative way of expressing recharge.

Conclusions and recommendations

Some of the main conclusions and recommendations emerging from this research project can be summarised as follows:

- A number of different climatic cycles (cold/warm or wet/dry cycles) of different duration and intensity have been present or are postulated to have been present during the last 200 000 years. These range between a cycle of approximately 23 000 years, to one of approximately 11 years cycle of major wet and dry periods during the last approximate 200 000 years. For the purpose of this study, the 18 and 11 year cycles are perhaps those of most significance in assisting the groundwater resource planners.
- Although the present investigation has not investigated this issue in any great detail, it is concluded that when viewed from a geological perspective, the short documented record of the climatic conditions, including the groundwater level records, no conclusive statement can be made regarding changing geohydrological conditions as a result of changing hydrological or climatic conditions over say the last 50-100 years. The South African groundwater level

records cover a too short time period to make any conclusive statements whether a steady decline in our groundwater levels is present or not.

- The Standardized Precipitation Index (SPI) is a relatively new development in drought prediction technology. It has been proven in the United States and elsewhere in the world to be a reliable tool for this purpose. The application of this technique in the study of the impact of drought on groundwater resources as was done in this project, is as far as could be ascertained from the literature, unique. As such there are no well-proven methodologies developed yet according to which geohydrological information should be handled to obtain the most benefit from such a correlation between the two datasets.
- This limited study has shown that correlations between SPI values and water level fluctuations are present in South African data sets. The quality or degree of correlation however, varies. Examples are presented where excellent correlations exist, but on the other hand, some examples of poor correlations have also been recorded. The reasons for the presence of correlations, whether these are good or poor, are not well understood and warrant further investigation. It was shown that only water level data that are not impacted upon by external forces should be used when correlating SPI values and water level fluctuations.
- It is generally accepted that there is a relation between water level fluctuations and recharge. The numerous techniques developed in the past in this field are a proof of this. The results obtained during this project, have confirmed that the SPI methodology can also make a valuable contribution to this still challenging field of aquifer recharge estimation.
- A first attempt in developing a "Recharge Index" derived from SPI data is presented in this report. Although the concepts that have been formulated and included in the methodology may seem to be simplistic, it is believed that the development of such an index has merit and should be investigated further. The method on its own may not yet provide the required quantitative assessment of groundwater recharge, but together with other available methods to calculate recharge, may add the required information to provide more quantitative answers in future.

Some recommendations emerging from this research include:

- A more in depth analysis of the nature of groundwater level time series should be done to be able to explain the wide variety of response patterns to climatic conditions observed in the available South African groundwater level records.
- The fundamental theory behind the SPI analysis should be investigated and its possible application to geohydrological datasets should be given a theoretical basis.
- The development of the "Recharge Index" should be expanded and placed on a sound theoretical base.
- Once a sound calculation methodology for the Recharge Index has been developed, it should be calibrated in order to produce meaningful figures representing the actual recharge that contributes to our groundwater resources.
- The process of calculating a Recharge Index should be automated and the derived values should be given a reliability rating.

- Once a reliable methodology has been developed to calculate recharge, a groundwater recharge map of the country should be compiled based on for example the rainfall districts as defined by the Weather Bureau.

It is further recommended that the Department of Water Affairs and Forestry should consider the establishment of rainfall recording equipment close to the water level monitoring recorders. This would enhance the reliability of the correlation between rainfall and water level fluctuations. It is further also recommended that the Department reconsider any recommendations made to close down any of the existing monitoring programmes. Groundwater level records contain important information on the long-term behaviour of aquifers that have not been studied in any great detail, but could provide valuable information in future that will be beneficial to the managers of the national water resources.

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"THE ANALYSIS OF GROUNDWATER LEVEL TIME SERIES AND THE RELATION TO LONG TERM CLIMATIC CONDITIONS, CLIMATE VARIABILITY AND RECHARGE"

Contributions throughout the duration of the project by members of the Steering Committee during individual discussions and at official Steering Committee meetings are gratefully acknowledged. The Steering Committee responsible for this project consisted of the following persons:

Dr K Pietersen	Water Research Commission (Chairman)
Dr M Rouault	Oceanography Department, University of Cape Town
Prof G van Tonder	Institute for Groundwater Studies, University of the Free State
Mr E van Wyk	Hydrological Services, Department of Water Affairs and Forestry, Pretoria

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The Water Research Commission is thanked for financially supporting this interesting project and it is hoped that it would support further research in this field.

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1. BACKGROUND TO AND MOTIVATION FOR THIS RESEARCH PROJECT

The Department of Water Affairs and Forestry (DWAF) has been and still is monitoring groundwater levels and water quality in some 400 boreholes countrywide. Water level monitoring records are in some cases available since the early 1950s. In most cases at least monthly records are available, however, in some instances daily water level recordings are kept, and lately since digital water level recorders have become available, even more detailed records are available in selected cases.

It is not always clear why certain boreholes, and especially those with very long records, were selected for monitoring, as the original motivation for the selection is nowhere documented. It can however, be accepted that some were originally selected purely for background water level monitoring and are therefore located in relatively undisturbed hydrogeological environments, upstream of major catchment developments or groundwater abstraction schemes. It is also not certain whether many of these monitoring boreholes can still be regarded as true background monitoring boreholes unaffected by more recent developments. During the course of some longer term projects selected boreholes were equipped with water level recorders and eventually became part of the national groundwater monitoring network.

The need to document the historical water level records systematically was recognised by Mr Bill Orpen of the DWAF in the early 1990s and a project was initiated in this regard. The work culminated in the DWAF report GH 3829 published in 1995 (Zietsman and Nienaber, 1995) and entitled *"Inventory of groundwater levels as recorded at operational groundwater level monitoring stations and possible correlations with causative monthly rainfalls to December 1994."*

It is unfortunate that the majority of cases water level information is only available since the early 1970s. There are however a few boreholes were water level data since the mid-1950s is available. Hydrographs of water level fluctuations in dolomitic palaeo-sinkholes and water discharge records for some of the dolomitic springs, both of which can be regarded as indirect measures of the potentiometric groundwater level, are fortunately available for much longer periods. Some of these date back to the early part of the 20th century. Examples are the Wondergat sinkhole, Maloneys Eye, Turffontein Spring and the Fountains at Pretoria. Flow from and water level fluctuations at springs have however, were not included in the analyses described in this report. A large section of the "Manual on quantitative estimation of groundwater recharge and aquifer storativity" by Bredenkamp *et al.* (1995) was devoted to the analysis of groundwater level information specifically from the dolomite aquifers, due to the availability of long groundwater level and spring flow time series for these aquifers.

Knowledge of long-term rainfall variability is essential for efficient and sustainable groundwater resource and land management. In the DWAF report by Zietsman and Nienaber (1995) the water level data were correlated with rainfall records by using a modified version of the Cumulative Rainfall Departure (CRD) technique originally developed by Wenzel (1936). In South Africa Smit (1977), Temperley (1980), Kok (1981) and Taylor (1983) applied this technique. Bredenkamp *et al.* (1995) developed this technique further specifically for application to South African aquifers.

However, following the publication of the DWAF Zietsman and Nienaber (1995) report, unfortunately no further analysis of the initial results was done.

When paging through the graphs assembled in the 1995 DWAF report, it is immediately apparent that a number of different water level fluctuation cycles or trends are present. These are provisionally classified as:

- Short term (~1 year) fluctuations in the water level data;
- Medium term (~10 years+) cycle in the water level data; and
- Longer term trend which may be of a cyclic nature, but due to the short time series, it is not clear whether it does reflect a specific cycle.

On both the last two categories, shorter cycles and/or fluctuations are usually superimposed on the data.

Of particular interest are the declining trends, often extending for several years, that can be observed in some of the data sets. These do not appear to be associated with a particular geohydrological, geological or climatological region, but occur throughout the country. Admittedly, there are clear indications of recharge events in these records, but the impression is often created that there appears to be a continued and gradual lowering of the groundwater levels. A second important observation that is apparent from these groundwater level data sets, is the rapid response that can be observed in the records of many boreholes. These are mostly of the order of several metres, although even tens of metres are observed, and occur generally over a period of a few months. In most cases such events can be correlated to extreme rainfall events. Whilst the data for these boreholes are collected, documented and managed by the Department of Water Affairs and Forestry, an analysis of these data sets is due. Bredenkamp *et al.* (1995) and Bredenkamp (1999) used some of this information for the quantitative estimation of recharge of mainly dolomitic aquifers and other selected geohydrological regions , but did not specifically address the apparent declining longer term trends in their analyses. When trying to analyse these declining trends, care has to be taken that these are not due to the impact of large abstraction schemes, or other external influences impacting on the water level behaviour. In the case of the Witwatersrand mining region, water levels have definitely been impacted upon by the massive and systematic dewatering that has taken place over the years, and therefore these mining areas have been excluded during this investigation. In other areas of the country prolonged over abstraction of groundwater for irrigation purposes, can also result in long-term declining groundwater level trends.

However, in many of the cases country wide, no obvious cause for a declining trend is apparent. A number of possibilities come to mind including over exploitation of the resource, changes in land use impacting on recharge, and changing rainfall patterns possibly associated with longer term climatic changes. In proposing this project it was believed that an analysis of this information could present valuable information that may point towards the possible causes for this apparent trend, both on a local as well as a regional scale. In particular the possible link to long-term climatic changes is of interest. A possible explanation for this declining trend can be the role or effect of, or the link to longer term climatic *changes* over the last few decades, and even centuries.

Closely linked to this is the concept of "groundwater drought", which may have important management implications, but has not been properly explored. The "groundwater drought" concept is not new and has previously been addressed in an African context by the British Geological Survey in association with staff from the Department of Water Affairs and Forestry (Calow *et al.*, 1999a). The decreasing trends that have been recorded in some boreholes may also be explored as part of the longer-term fluctuations established by palaeo-geohydrological studies. Numerous studies have been documented over the last decade on palaeo-climatic conditions (covering the last say 3000 years) in southern Africa and Africa (Tyson and Lindesay, 1992; Stevenson *et al.*, 1999; Partridge, 1999; Partridge *et al.*, 1999; Verschuren *et al.*, 2000; Richard *et al.*, 2001)). By using the Palmer Drought Index (PDI) and the more recent Standardized Precipitation Index (SPI), also known as the Standardized Rainfall Anomaly (Agnew, 2000), several authors contributed to the formulation of a the concept *Drought Index* which provides information on drought duration, frequency and time scales (McKee *et al.*, 1993, 1995; Jones and Hulme, 1996; Hayes, 2000;, Svoboda, 2000; Agnew , 2000). Tyson (1988) developed rainfall and temperature indexes for predicting climatic events.

During the last decade the demand on the country's groundwater resources has been increasing steadily as more and more communities are being supplied from groundwater resources and large areas are irrigated with groundwater. The implications of a possibly steadily decreasing regional groundwater level coupled with increased utilization of and demand for this resource can have a significant impact on the management and use of groundwater resources. Declining regional water levels may lead to even more severe impacts during "groundwater drought" cycles.

The relation between rainfall and groundwater recharge is a topic that is still debated and no clear answer as to the exact relationships exists. Bredenkamp *et al.* (1994) further developed a concept initially described by Temperley (1978) to correlate rainfall and water level changes. This method is referred to as the Cumulative Rainfall Departure (CRD) technique. The subject is also addressed in a recently published book on different techniques used in the estimation of groundwater recharge in southern Africa by Xu and Beekman (2003).

2. AIMS OF THE RESEARCH

The aims of the research described in this report were to

- investigate methods that can be used to correlate long term water level fluctuations with rainfall and climatic cycles;
- determine whether the long term declining trends observed in SA groundwater level data is indicative of a current and/or longer term groundwater drought cycle(s) or whether other factors are contributing to this trend.
- Document the analytical techniques used to analyse relevant geohydrological information to assist planners in the longer term planning of groundwater utilization as part of IWRM.

In this project it is intended to develop a methodology to analyse groundwater level and rainfall information of southern Africa and correlate this information to drought and other long-term climatic indicators or cycles. In doing this, it is envisaged that this could lead to the formulation of indicators that can be used in groundwater recharge estimations and the long-term management of this important national water resources.

3. METHODOLOGY FOLLOWED

During the literature review the focus was predominantly on the following aspects:

- aspects of the southern African climate during recent geological times and specifically the last few thousands years;
- techniques used to correlate water level information with rainfall;
- indicators of drought,
- the concept of "groundwater drought", climate change and its impact on groundwater, and
- climatic records of the last few millennia, drought indexes, groundwater recharge, long term analysis of drought, and related topics.

The literature review was followed by an analysis of a selected number of available groundwater level and rainfall time series, especially using the Standardized Precipitation Index (SPI) method. The groundwater level information was obtained from the Department of Water Affairs and Forestry National Groundwater Database. Rainfall information for the districts where groundwater levels were analysed, were also provided by DWAF, while the SPI calculations were done in collaboration with Dr M Rouault of the University of Cape Town. In this project the comparison of SPI values and groundwater levels was only done by visual correlations and no rigorous statistical analysis of the two datasets was conducted.

The results reported here should be treated as preliminary as a theoretical basis for such correlations has not been investigated nor proven at this stage. The investigation into the possible correlation between groundwater levels and SPI is seen as a possible method to further analyse groundwater level information and may lead to the prediction of longer term groundwater level behaviour and to determine closer relationships between rainfall and groundwater recharge.

4. LITERATURE REVIEW

Only a summarised version of the full literature review is included in the main report. A more detailed description of the literature review is included in Appendix A at the end of this report. Occasionally reference is made in the main text to figures that are included in Appendix A.

4.1 Climatic periods in southern Africa during the Pleistocene and Holocene

Climatic change is a subject of studies that receives attention of researchers worldwide. Not only are climatologists involved in this research (IPCC, 2001), but in other disciplines where the effect of the predicted changing climate may have an impact, for example plant diversity and groundwater resources, research is ongoing (SA National Botanical Institute, 2001; Beekman and Cave, 2003). In the geological record there is overwhelming evidence that significant climatic changes occurred throughout the geological history of the earth and more specifically also southern Africa. Dingle *et al.* (1983) published a sea level curve graph showing sea level changes during the Upper Cretaceous and Tertiary (last approximately 100 Ma**; Figure 1**). Based on geological evidence, these authors concluded that fluctuations from –300m to +200 m relative to the present day sea level occurred.

More detailed information on sea level fluctuations during the last 200 000 years is provided by W R Miller in a report on a study of Lake Sibaya in Northern Kwazulu Natal (Miller, 2001). What is interesting is that sea level dropped by more than 130m during a period of approximately 80 ka, starting around 100 ka ago to 18 ka (Last Glacial Maximum). What is even more remarkable is that, following this decline, the sea level recovered to its present level within about 10 000 years (**Figure A-2, Appendix A**). Since that recovery (8 000 years to present) fluctuations were of the order of 5 m maximum (**Figure A-3, Appendix A**). The oscillations between glacial and interglacial climate conditions over the last three million years have been characterised by a transfer of immense amounts of water between two of the largest reservoirs on Earth – the ice sheets and the oceans. Since the most recent of these oscillations, referred to as the Last Glacial Maximum (LGM) that occurred between 30 000 and 19 000 years ago, approximately 50 million cubic kilometres of ice has melted, causing a rise in sea level of ~130 m (Lambeck *et al.*, 2002). Evidence for this rise in sea level is present in the geological record in several places along the southern African coastline (Dingle *et al.*, 1983; Vogel, 1989; Tyson, 1999; Wright, 2002). The Cenozoic climates of southern Africa have been subject to global influences; these include orbitally controlled cycles of change as well as a number of stepwise coolings that characterised the last 65 Ma. The evolution of ocean current systems that dictated the distribution of sea surface temperatures around the southern African coastline, coupled with differential uplift of the landmass in the interior, have modified patterns of atmospheric circulation to create the unique climate system of today (Tyson and Partridge, 2000).

According to a publication on climate change and its effect on plant diversity in South Africa (NBI, 2001), the earth has experienced at least 20 warm and cool periods over the last half million years resulting in glaciers retreating and advancing and sea levels rising and falling. These changes have been rapid and extreme with mean temperatures fluctuating by more than 2°C in 50-100 years. Recently developed computer models for the prediction of climatic conditions known as General Circulation Models or GCMs, predict that climatic changes will not occur uniformly across the globe. In general it is predicted that land areas will warm faster than the oceans and polar latitudes faster than temperate latitudes. According to the South African Country Study referred to in this publication, and which is based on research done at the Hadley Centre in the United Kingdom and the National Centre for Atmospheric Research (NCAR) in the USA, temperatures are predicted to increase during the next 50 years over the whole of South Africa with January temperatures increasing most in the central interior and Northern Cape (2.5-4.5°C) and least at the coast (0.5-1.0°C). It is further predicted by these models that summer rainfall will decrease by between 5% in the northern regions and 25% in the Eastern and Southern Cape while parts of the Western Cape may lose a significant portion of its winter rainfall.

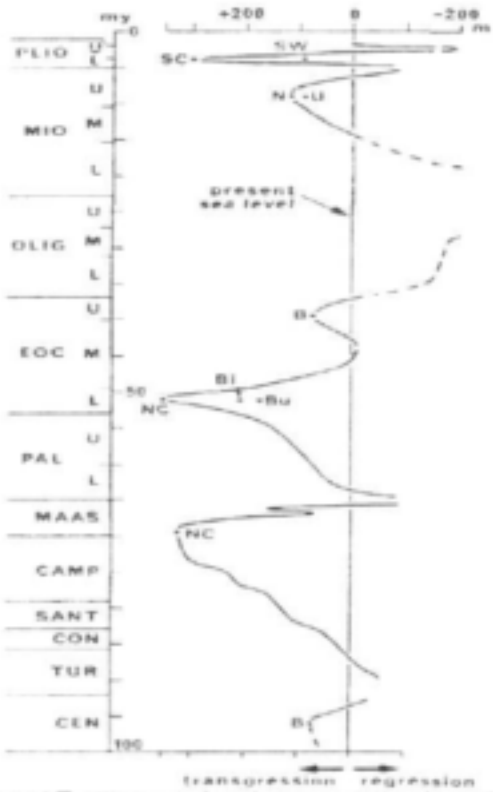


Figure 1: Upper Cretaceous and Tertiary sea level movements along the southern African coast relative to present day sea level from: Dingle *et al.*, 1983).

The current worldwide changes in climatic patterns should not be viewed in isolation, but in the context of our existing and increasing knowledge of climatic patterns and cycles during modern geological times observed in southern Africa. One of the greatest impacts on climate during the Cenozoic would be the regional uplift of the landmass that occurred during the Miocene (23 Ma – 5 Ma) and most notably also during the Pliocene (5 Ma – 1.6 Ma) on the east coast of South Africa (of the order of 900m to 600m) coupled with subsidence in the Pliocene (in the order of 400m) in the Northern Cape (Partridge, 1997). Another independent influence on climate was *"a significant period of global oceanic warming, which began late in the Oligocene (35 Ma – 23 Ma) and persisted through much of the Lower Miocene"* (Tyson and Partridge, 2000).

Partridge (1997, 1999) calculated a relationship between soil texture on granitic bedrock and mean annual rainfall and used this to establish the palaeo-rainfall record of the last 200 000 years at the Pretoria Saltpan (Tswaing Crater). This 200 ka rainfall record is characterised by well-defined variations with a period of about 23 000 years (**Figure 2**). According to this analysis the rainfall varied between about 450mm/a and 900mm/a compared to the current annual average of 630mm/a.

Distinctive spatial palaeoclimatic gradients were present over southern Africa towards the end of the LGM period (Partridge, 1997). Compared to the present-day mean, the annual total rainfall over the Kalahari appears to have been approximately 40% lower during the period 21 000 – 18 000 BP, while temperatures were also 5-6°C during this period (Heaton *et al.*, 1986; Talma and Vogel, 1992, Stute and Talma, 1998). This was followed by rapid warming after 15 000 BP, cooling around 11 000 BP, and then again a general rise in temperatures over most of the subcontinent (Tyson and Partridge, 2000). Between 7 000 and 4 500 BP temperatures were 2°C higher than present. Considerable regional variation in rainfall occurred over the subcontinent during these times. Silt deposits from the Kuiseb Valley in Namibia indicate a dry period that lasted from about 8 300 to 4 200 BP (Vogel, 1989). While the northeastern part of South Africa and southern Zimbabwe experienced lower rainfall, wetter conditions were experienced in the Kalahari. Isotope studies on stalagmites from the Cold Air Cave at Makapansgat Valley, provided a detailed climatic record of the last 6 000 BP. Increasing ‰ $\delta^{18}O$ and $\delta^{13}C$ values represent warmer, wetter conditions, while lower values indicate cooler and drier environments. During the Little Ice Age (~1 300 – 1 850 AD) an increase in the frequency of flood events is evident from tree ring analyses from widely separated sites, and from palaeoflood hydrology of the Orange River (Zawada, 1996), borehole temperature profiles (Jones *et al.*, 1999). Evidence is mounting for a general warmer and wetter period in southern Africa between 1 320 and 880 BP. There is evidence in the palynological, palaeoflood, Cango Cave and Namibian offshore sediment records of a dry spell during the mid fifth century, a cooler period between 0 and 300 BC followed by a warm and wet period during 0-200 AD.

A more detailed climatic history over the last 200 ka as described and recorded by various authors is summarised in **Appendix A.**

4.2 Climatic variations during the last approximately 200 years

Several authors have published information relating to the climatic conditions in southern Africa over the last two centuries. These include Tyson *et al.*, 2002; Muller and Tyson, 1988; Tyson, 1980; Currie, 1993; Richard *et al.*, 2001; Tyson and Lindsay, 1992; J C Vogel, 1989; C Vogel, 1989, 1995; Huffman, 1996; Vogel and Fuls, 1999; Tyson and Partridge, 2000; Cockcroft *et al.*, 1987, and Nash and Endfield, 2002.

C H Vogel (1989) used missionary diaries, letters, newspapers, official documents and bank archival material to obtain information of the climatic conditions in the Cape Province since the early 1800s. She came to the following conclusions:

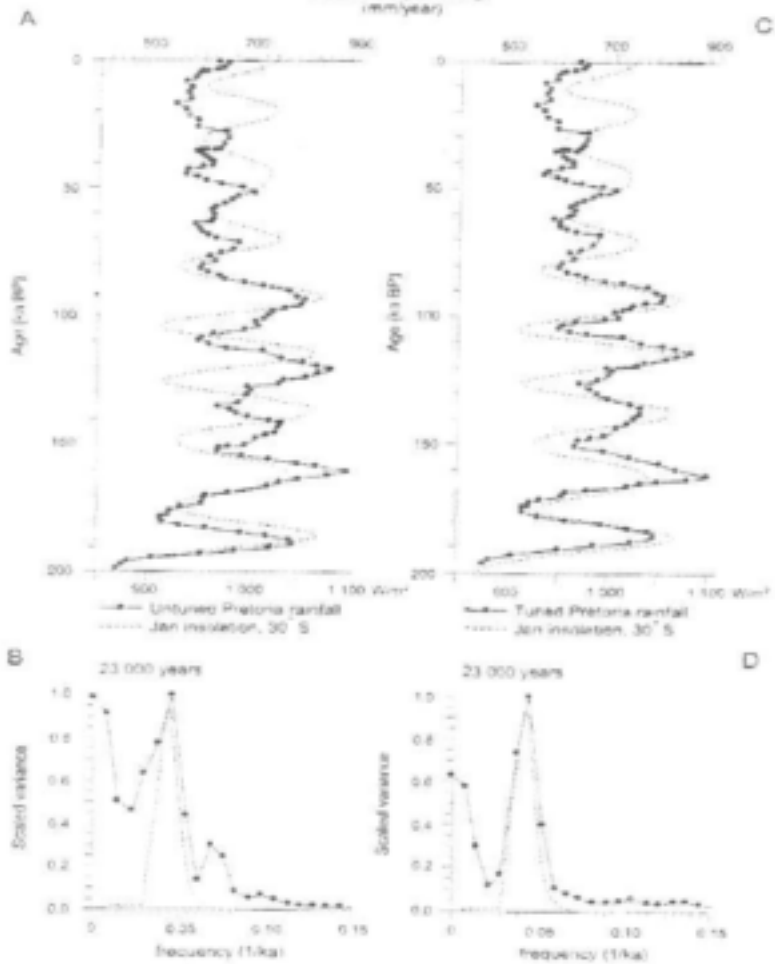


Figure 2: The Tswaing rainfall time series derived by Partridge (1997, 1999) from soil sediment texture and precipitation relation and Pretoria Saltpan textural and compositional data (from Partridge, 1999).

- notably wet periods span the years 1822-1823, 1831-1832, 1844-1848 1869-1871 and 1885-1900;
- notably dry of periods of below-normal rainfall include the years 1820-1822, 1824-1829, 1860, 1865, 1877-1885 and 1894-1896;
- areas of the eastern Cape were particularly affected by drought in 1862, 1865, 1877 and in the mid-1890s;
- the documentary derived-chronologies have been corroborated by using available dendrochronological data and meteorological instrumental data; and
- the 1890s were not as consistently wet as had been previously proposed, but rather, good rains were experienced at the outset and close of the decade, offset by severe drought conditions during the middle 1890s.

C H Vogel (1989) also observed that there appear to be particular associations between phases of the Southern Oscillation and periods of drought and below-normal rainfall in the 19th century. In addition there are indications of an inverse relationship when wet conditions are experienced in the southwestern Cape, the eastern areas are characterised by dry and drought conditions. No distinct periodicity of below- and above-normal rainfall years is discernable from the information presented by C H Vogel (1989). The information rather indicates that the frequency and type of rainfall event, including below- or above-normal events that prevailed at the Cape during the last century were essentially similar to those prevailing in the area at the present time. Periods of extreme drought were and are often followed by periods of abundant rains.

Archival material from the Council for World Mission (CWM) have been used by C H Vogel (1989) and Nash and Endfield (2002) to reconstruct climate patterns for the Kalahari region of Botswana and South Africa during the nineteenth century. Their findings are summarised in **Table 1**. Formal meteorological observations and records are available from around the start of the 20h Century. Tyson (1986) analysed the rainfall records and his conclusions for the 20^{th} century information is incorporated into **Table 1**.

4.3 Extreme weather conditions

Several authors refer to extreme weather, and especially rainfall seasons. From a groundwater perspective these are important, as it is known that during these periods increased recharge occurs. From an analysis done by Cockcroft *et al.*, (1987) and Muller and Tyson, 1986) it appears that when the summer rainfall region becomes drier, the winter region becomes wetter and, most importantly, the winter rainfall over the summer rainfall region tends to increase. Examples from the South African meteorological records are listed in **Appendix A.**

4.4 Climatic cycles

Cycles, periodicity or oscillations in the rainfall patterns of southern Africa have over the years have attracted the attention of many researchers and institutions from the early 1900s. Articles with titles such as "Is South Africa drying up?" (Barber, 1910), "Periodicity in rainfall" (Cox, 1925), and the more recent ones such as "20^{th} Century droughts in Southern Africa: Spatial and temporal variability, teleconnections with oceanic and atmospheric conditions" (Richard *et al.*, 2001), it is evident that the subject has been and still is of great interest and importance to the country.

A number of quasi-periodic rainfall oscillations have been reported of which, from a groundwater perspective, the 18-year period is perhaps the most noteworthy (**Figure 3**, Preston-Whyte and Tyson, 1988; Currie, 1993). A secondary frequency is at 10.5 years with other smaller amplitudes at 3.5 and 2.3 years (Tyson, 1980). The 10-12 year oscillation is seldom a strong component of the rainfall and its regional effect is confined to the southern Cape. Zucchini and Adamson (1984) concluded from their study of rainfall data that although the 18-year cycle is present in the data, its significance could not be established beyond doubt. Vines (1980) used selective mathematical filters and confirmed the existence and spatial dependence of both 18- and 11-year cycles in South African rainfall data. Oscillations around 18 years have also been confirmed from statistical analysis of data from Zimbabwe (Ngara, 1983;) and Mozambique (Reddy, 1986). Currie (1993) performed spectrum analysis on 59 South African rain-gauge records and found evidence for two peaks with periods of 18.2 ± 1.4 years and 10.3 ± 0.5 years that confirmed the work done by Tyson and his co-workers in the 1970s (**Figure 4**).

Whatever doubts may be attached to the statistical significance of the 18-year peak in the spectrum for the spatially-averaged data for the summer rainfall region, the sequence of alternating spells since 1906 in which preponderances of wetter and drier than normal years have occurred shows the physical reality of the oscillation during the twentieth century. Around the turn of the century the rhythm of change faltered (Tyson, 1980); instead of being wet, as backward extrapolation suggests, the period 1897-1905 (based on calendar year analysis) was dry and the oscillation underwent a phase shift. Since 1900 the oscillation has been stable for over 80 years (Tyson, 1980).

Table 1: Major wet and dry phases in the Kalahari during the nineteenth century identified from documentary sources (from C H Vogel, 1989) and Nash and Endfield, 2002), and for South Africa in general for the last two centuries.

Major wet periods	Major drought periods	Probable regional extent
1816/17		Southern Kalahari*
	1820-1822	Cape. Dry period of below normal rainfall.
	1820-27	Southern Kalahari plus parts of the former Eastern Cape*
1829/1830		Southern Kalahari plus adjacent parts of South Africa*
	1831-35	Southern Kalahari plus parts of the former Eastern Cape*
	1844-51	Entire Kalahari plus adjacent parts of Angola and Zambia*
1851/1852		Entire Kalahari plus large areas of South Africa
	1857-65	Middle and Southern Kalahari plus much of South Africa, with drought punctuated by widespread wetter conditions in 1863/64*
1863/64		Southern Kalahari plus areas of former Eastern Cape
1874/75		Middle and Southern Kalahari plus large areas of South Africa*
	1877-86	Entire Kalahari plus parts of South Africa
1889-91		Middle and Southern Kalahari plus large areas of South Africa*
	1894-99	Entire Kalahari plus large areas of neighbouring South Africa
1899/1900		Middle and Southern Kalahari plus adjacent parts of South Africa*
	1905/06-1915/16	Southern Africa
1916/17-1924/25		Southern Africa
	1925/26-1932/33	Southern Africa
1933/34-1943/44		Southern Africa
	1944/45-1952/53	Southern Africa
1953/54-1961/62		Southern Africa
	1962/63-1970/71	Southern Africa
1971/72-1980/81		Southern Africa
	1982/83-1992/93	Southern Africa
1993/94-2002/3*		Southern Africa

Note: * Last part of 2000 was, however, a dry period.

Tyson (1987) reiterates, "No evidence exists to show that southern Africa is becoming progressively drier. Some evidence is available to indicate that the quasi 18-year oscillation was present during the nineteenth century and earlier. However the evidence is based on proxy data and is somewhat tenuous. A phase shift occurred at the turn of the century." Others who support his view are Schumann and Thomson (1934). They stated that there was no evidence to support the idea that South African rainfall is undergoing a general long-period decline. This view was subsequently confirmed by the work of Kokot (1948) and Hofmeyr and Schulze (1963).

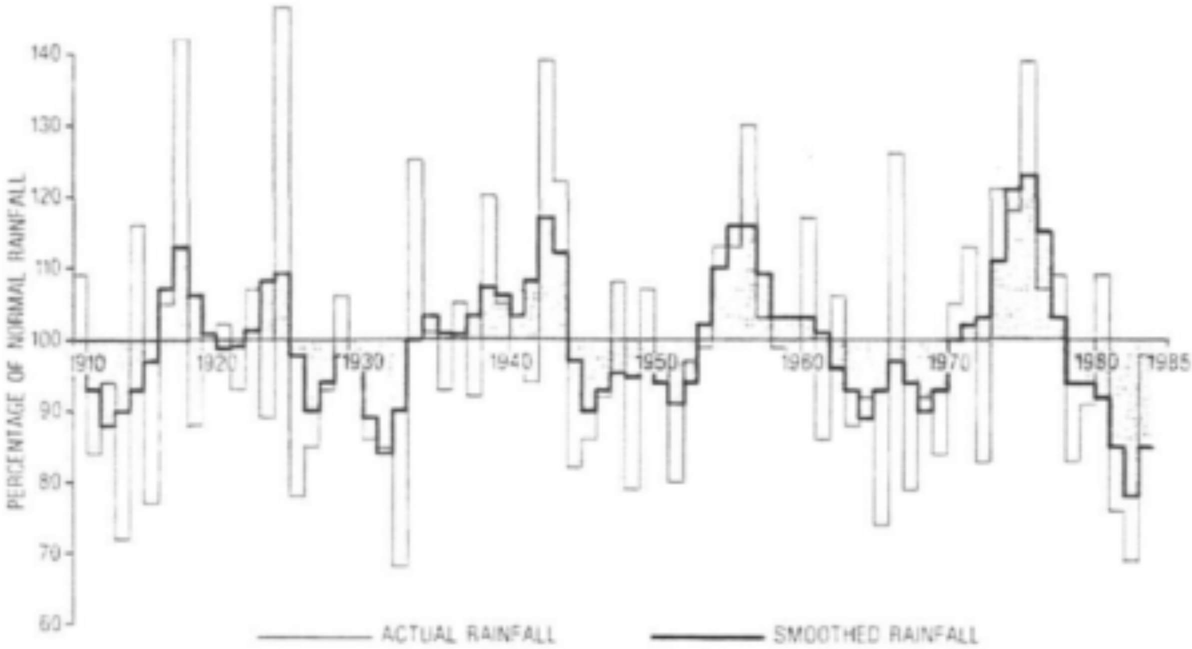


Figure 3: Averaged rainfall series for the hydrological year in the summer rainfall region of South Africa for the period 1910/11 to 1983/84 (from Preston-Whyte and Tyson, 1988).

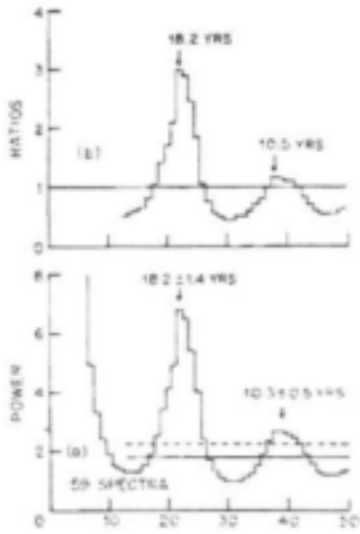


Figure 4: Maximum entropy power spectrum based on 59 rain-gauge records (from Currie, 1993).

Over the years, and before the detailed analyses made by Tyson and his co-workers since the 1980s, the southern African rainfall record has been analysed by many researchers, especially with regard to cyclic patterns or a steady diminution of the rainfall (Hutchins, 1889; Nevill, 1908; Barber, 1910; Agric. J of the Union of South Africa, 1913; Union of South Africa, 1914; Schwartz, 1919; South Africa, 1923; Cox 1925; Van Reenen, 1925; Peres, 1930). At the end of the extended drought period of the late 1920s and early 1930s, Schumann and Thompson (1934) concluded that there was no evidence to support the theory that South African rainfall was undergoing a general long-period decline. Kokot (1946) and Hofmeyr and Schulze (1963) came to a similar conclusion, while work by Tyson *et al.* (1975) and Dyer (1976) indicated that no statistical evidence exists to support the notion that South Africa has experienced a progressive decline in rainfall.

Using a model developed by Dyer and Tyson (1977), Tyson (1980) extrapolated the fitted curve backwards in time and postulated spells of about 9 years during which runs of dry and wet years have occurred during the nineteenth century. Documented evidence shows that the period 1897-1905 was dry over South Africa (instead of being wet as backward extrapolation suggests). However, for the period before 1880, there are suggestions that extended wet and dry spells of about nine years duration also occurred in the nineteenth century. The 1886-96 period was widely experienced as an above-normal rainfall period, and in fact the wettest period on record in southern Africa, occurred during this time period. The period 1880-86 was dry over much of South Africa south of about 29°. One can do little more than speculate about conditions prior to 1880. Of eleven stations with records going back to 1871, ten recorded above-average rainfalls over the period 1871-1879. Of the six stations with series beginning before 1862, all showed negative deviations during the supposed dry spell of 1862; of three stations for the possible wet period of 1853-61 all showed positive deviations.

Provisional backwards extrapolation, based on information from C H Vogel (1989), and Nash and Endfield (2002), would result in some changes to the dates of the dry and wet spells proposed by Tyson (1980). By linking these dates to those published by Tyson, results in the extended **Table 2** for the approximate period of 1800 to 2000. Alexander (1995, 2002) analysed South African river flow data and confirmed a 19 to 21 year periodicity in both rainfall and river flow records.

4.5 Conclusion

From the information presented in the previous sections, a number of different climatic cycles of different duration appear to have been present or are postulated to have been present during the last 200 000 years. These can be summarised as:

- An approximately 23 000 year cycle of major wet and dry periods during the last approximate 200 000 years (Partridge, 1999).
- A possible 400 – 500 year "cold/warm" or "wet/dry" cycle (this report).
- An ~120 year cycle.
- An ~18 year cycle (Schumann and Thompson, 1934; Hofmeyr and Schulze, 1963; Tyson, 1980; Ngara *et al.*, 1983; Dyer, 1976; Currie, 1993; Alexander, 1995, 2002).
- An 11 year cycle (Tyson, 1980; Currie, 1993).
- A 3.5 year cycle (Tyson, 1980).
- A 2.3 year cycle (Tyson, 1980).

Table 2: Wet and Dry cycles over the last 200 years

Spell	Period	Number. of years	Space mean deviation (%)	Wettest or Driest year	Max. or min. deviation (%)	Number of years with opposite sign
Wet	1807/08-1817/18	10				
Dry	1818/19-1826/27	8				
Wet	1827/28-1933/34	6				
Dry	1934/35-1943/44	9				
Wet	1844/45-1855/56	11				
Dry	1856/57-1865/66	9		1862/65		
Wet	1866/67-1876/77	10				
Dry	1877/78-1885/86	8		1877		
Wet	1886/87-1893/94	7				
Dry	1894/95-1904/05	10				
Dry	1905/06-1915/16	10	-4.3	1913/14	-30.0	5
Wet	1916/17-1924/25	9	+5.4	1924/25	+42.5	4
Dry	1925/26-1932/33	8	-14.7	1932/33	-33.5	1
Wet	1933/34-1943/44	11	+6.0	1942/43	+34.5	5
Dry	1944/45-1952/53	9	-9.4	1949/50	-23.0	2
Wet	1953/54-1961/62	9	+7.0	1956/57	+30.0	3
Dry	1962/63-1970/71	9	-6.0	1965/66	-24.5	3
Wet	1971/72-1980/81	10	+10.6	1975/76	+39.0	2
Dry	1982/83-1992/93	10				
Wet	1993/94-2002/3	9				

5. DROUGHT AND DROUGHT INDICATORS

5.1 Introduction

Scientifically, droughts are usually classified as *meteorological*, *agricultural* or *hydrological*, depending on the variables under consideration. The variables that indicate the presence and severity of agricultural and hydrological drought are derived from those associated with meteorological drought, or are directly influenced by them. When dealing with drought in southern Africa, a combination of the variables rainfall, temperature, soil moisture, evapotranspiration, river flow, status of reservoirs and underground water resources are usually the critical issues. If the popular definition of drought being a period of low rainfall, is applied to describe the climatic conditions in many parts of southern Africa, for example the Limpopo Basin, periods of drought would be common. Meteorologists, for example define drought solely on the basis of the degree of dryness and the duration of the dry period, whereas hydrologists link periods of shortfall to the effect on surface and subsurface water resources. Agriculturalists again link drought to soil water deficits and impacts on crops. From the social scientists view, drought is seen as a relative phenomenon, which varies according to the demand placed on the resource by the different uses. Rouault and Richard (2003) describe drought as a shortage of precipitation over an extended period. Central to all definitions, however, is the relative shortage of water (Calow *et al.*, 2002).

The term *groundwater drought* has been added during the last decade or two to this list describing different types of drought and can be described as occurring when groundwater sources fail as a direct consequence of drought. Groundwater drought may be regarded as a subset of a hydrological drought as replenishment of aquifers is largely driven by rainfall derived recharge. Aquifer response time is closely linked to local aquifer conditions, such as transmissivity, and different lag times in response will be encountered for different aquifers. Often failure of boreholes and springs during periods of (hydrological) drought, is incorrectly interpreted as regional depletion of aquifers. In the African context, and especially in the rural areas, this is not necessarily the case where abstraction from individual sources of boreholes is generally low and often sparsely distributed abstraction points. In such cases overall abstraction rarely exceeds long term rainfall derived aquifer recharge. Calow *et al* (2002) found that the ability of low transmissivity and therefore generally low yielding aquifers to transport sufficient water to the abstraction point to replenish the water being withdrawn, coupled to increased strain on the pumping mechanism and insufficient maintenance activities, resulting in general failure of boreholes, is often incorrectly described as groundwater drought. The identification of low permeability hydrological zones, low yielding boreholes and areas of high population density, coupled to a lack of alternative sources of water, requires more proactive aquifer management of drought preparedness (Calow *et al.*, 2002).

Water-related activities in a region should be in harmony with the amount of water that, under normal conditions, is available for those activities. "Normal" is often taken as to be the mean amount of water available, however, this notion of drought is rather inadequate. It is the occurrence of negative deviations from the required levels rather than from the mean that constitutes droughts. In other words, a drought occurs when there is less water available than is needed, and not when there is less than expected. Droughts are multi-facetted problems and require a developmental rather than a crisis management approach (UNESCO, undated)

What is more important is that a region affected by drought, experiences periodic times of water shortages that constitute a serious threat to life and livelihood. Four terms have been formulated to describe drought conditions, or the impact thereof, more clearly. These are *water shortage*, *water scarcity*, *water stress* and *water security*. Abrams (1997) described these four terms as follows:

- *Water shortage* is used to describe an absolute water shortage when the available water does not meet defined minimum requirements.
- *Water scarcity* focuses more on the relationship between demand for water and its availability and depends to a large degree on the sectoral use patterns within a region or country.
- *Water stress* is the symptomatic consequence of scarcity which may manifest itself as increasing conflict over sectoral use, crop failure, decline in service levels, etc, and
- *Water security* is a situation of reliable and secure access to water over time.

The single most important variable that defines drought in southern Africa is rainfall (Zucchini and Adamson, 1984). In terms of groundwater resources, rainfall is critical to the replenishment of the resource. For the following discussion drought periods will therefore be viewed in terms of the rainfall record and deviations from the long-term mean values.

5.2 Indicators of drought

Drought indicators or indices are designed for decision-making and often take the form of a single number. Typically they are derived from the analysis of raw rainfall, stream flow and other water supply indicators. There are several indices that measure how much precipitation for a given period of time has deviated from historically established norms. Although none of these indices are inherently superior to the rest in all circumstances, some indices are better suited than others for certain uses. Indices often used are (Hayes (2003):

- Percent of normal
- Palmer Drought Severity Index (PDSI)
- Standardized Precipitation Index (SPI)
- Crop Moisture Index (CMI)
- Surface Water Supply Index (SWSI), and
- Reclamation Drought Index (RDI).

It is important to note that no specific drought index has yet been developed to describe groundwater drought conditions. In the context of the current investigation into the relation between rainfall and groundwater levels, the Percent of normal, PDSI and SPI indices will be discussed in more detail in this report.

5.2.1 Percent of Normal

The percent of normal precipitation is one of the simplest measurements of rainfall for a location and is well suited to general discussions on drought. It is calculated by dividing actual (annual) precipitation by normal (annual) precipitation - typically considered to be a 30-year mean - and multiplying by 100. This can be calculated for a variety of time scales. Usually these time scales range from a single month to a group of months representing a particular season, to an annual or hydrological year.

One of the disadvantages of using the percent of normal precipitation is that the mean, or average, precipitation is often not the same as the median precipitation, which is the value exceeded by 50% of the precipitation occurrences in a long-term climate record. The reason for this is that precipitation on monthly or seasonal scales does not have a normal distribution. Use of the percent of normal comparison implies a normal distribution where the mean and median are considered to be the same.

5.2.2 Palmer Drought Severity Index (PDSI)

The PDSI is a soil moisture algorithm developed by W.C. Palmer in 1965 and used extensively in the USA in decision making whether drought relief programmes should be applied (Palmer, 1965). It is based on a calculated index in the ranges shown in **Table 3** and indicates the physical severity of drought on soil. It is therefore primarily used in the agricultural sector.

Table 3: Palmer Drought Severity Indices descriptors

Index value	Description
4.0 or more	Extremely wet
3.0 to 3.99	Very wet
2.0 to 2.99	Moderately wet
1.0 to 1.99	Slightly wet
0.5 to 0.99	Incipient wet spell
0.49 to –0.49	Near normal
-0.5 to –0.99	Incipient dry spell
-1.0 to –1.99	Mild drought
-2.0 to –2.99	Moderate drought
-3.0 to –3.99	Severe drought
-4.0 or less	Extreme drought

Palmer based his index on the supply-and-demand concept of the water balance equation, taking into account more than just the precipitation deficit at specific locations. The objective of the Palmer Drought Severity Index (PDSI) was to provide measurements of moisture conditions that were standardised so that comparisons using the index could be made between locations and between months (Palmer, 1965). The PDSI is a meteorological drought index, and it responds to weather conditions that have been abnormally dry or abnormally wet. When conditions change from dry to normal or wet, for example, the drought measured by the PDSI ends without taking into account stream flow, lake and reservoir levels, and other longer-term hydrologic impacts (Karl and Knight, 1985). The PDSI is calculated based on precipitation and temperature data, as well as the local Available Water Content (AWC) of the soil. From the inputs, all the basic terms of the water balance equation can be determined, including evapotranspiration, soil recharge, runoff, and moisture loss from the surface layer. Human impacts on the water balance, such as irrigation, are not considered.

McKee *et al.* (1995) stated that since the PDSI is designed for the agriculture sector, it does not accurately represent the hydrological impacts resulting from longer or extended drought periods. Smith *et al.* (1993) and (Hayes, 2003) suggested that the PDSI is not well suited to regions with extremes in the variability of rainfall or runoff; and specifically referred to examples in Australia and South Africa. The natural lag between precipitation and the resulting run-off or recharge to groundwater is not considered, and therefore the index has little application to groundwater.

5.2.3 Standardized Precipitation Index (SPI)

The SPI was developed in 1993 by researchers from the Colorado Climate Center at the Colorado State University (McKee *et al.*, 1993). It is a single numeric index based on the probability of precipitation for any time scale and has the advantage that it can be calculated for different time scales. It thereby provides an early warning of drought. In contrast to the Palmer indices, which are based on a monthly water balance accounting scheme, the SPI was developed to quantify a precipitation deficit or increase for different time scales. SPI values cover a range of -3 to +3 in irregular steps (**Table 4**). Positive SPI values indicate greater than median precipitation, and negative values indicate less than median precipitation. Because the SPI is normalized, wetter and drier climates can be represented in the same way, and wet periods can also be monitored using the SPI. The SPI is the same as Standardized Rainfall Anomaly defined by Jones and Hulme (1996).

The understanding that a deficit of precipitation has different impacts on groundwater, reservoir storage, soil moisture and stream flow, led McKee, Doesken, and Kleist (1993) to develop the Standardized Precipitation Index (SPI) in 1993. The SPI was designed to quantify the precipitation deficit for multiple time scales. These time scales reflect the impact of drought on the availability of the different water resources. Soil moisture conditions respond to precipitation anomalies on a relatively short scale. Groundwater, stream flow, and reservoir storage reflect the longer-term precipitation anomalies. For these reasons, McKee *et al.* (1993) originally calculated the SPI for 3, 6, 12, 24 and 48-month time scales.

Because the SPI can be calculated for time scales, it can be adjusted to those time scales important to the water analyst. The SPI computation uses observer precipitation data and moving total time series are constructed from the precipitation data. For example, if precipitation data consists of monthly values, but the analyst is interested in three or six month events, a new time series can be calculated for these periods. This is done by summing the first 3 (or six) month rainfall values, then those of months 2, 3 and 4, etc and thereby constructing a new time series. This is then referred to as a 3-month SPI.

Table 4: The SPI indices and their description

SPI Index value	Description	Occurrence (%)*
>2.0	Extremely wet	2.3
1.5 – 1.99	Very wet	4.4
1.0 to 1.49	Moderately wet	9.2
-0.99 to 0.99	Near normal	68.2
-1.0 to –1.49	Moderately dry	9.2
-1.5 to –1.99	Severely dry	4.4
< -2.0	Extremely dry	2.3

*Hayes *et al* (1999), Rouault and Richard (2003)

Guttman (1999) provides the following explanation of the SPI calculation process. The first step in the calculation of the SPI is to determine the probability density function that describes the long-term series of observations. Once this distribution is determined, the cumulative probability of an observed precipitation amount is computed. The inverse normal (Gaussian) function is then applied to the probability and this results in the SPI. SPI values are positive (or negative) for greater (or less) than median precipitation. The departure from zero is a probability indication of the severity of the wetness (or aridity) that can be used for risk assessment. Drought monitoring and severity classification can be done by setting application specific thresholds of the SPI for defining beginning and ending times. It should be noted that he SPI is equally effective as a measure of both wetness and aridity.

Technically the SPI is the number of standard deviations that the observed value would deviate from the long-term mean for a normally distributed random variable. Since rainfall data is not normally distributed, a transformation is first applied to the data so that the transformed precipitation data follows a normal distribution. The SPI allows the determination of the probability of occurrence of dry or wet events at different time scales (from 3 monthly to 4 yearly mean rainfall) and can be calculated for all stations having a continuous rainfall record of 30 years or more. The climatological rainfall distribution at any station or ensemble of nearby stations, can be represented by a gamma distribution. The precipitation rate is fitted to a gamma distribution for different time scales (3, 6, 12, 24 months for example) for each month of the year. The resulting function can be used to find the cumulative probability of a rainfall event for a station for a given month of the dataset and at different time scales of interest (**Table 4**). The probability of occurrence of a climatic event is indicated by the percentage occurrence indicated in **Table 4.** For example, a SPI of –2 and less indicating a severe drought will occur approximately twice per century; a SPI of –1.5 to –1.99 about 4 times per century and a SPI between –1 and –1.9 about 9 times per century. By using the different time scales, drought indices for each time period can be calculated. The 3 month time period can be used to study seasonal events (i.e. start and end of rainy season), the total rainy season can be described using the 6 month time scale, while 12 month and longer time scales can be used to study the longer term impacts. The X-month SPI is used to compare the precipitation over a specific X-month period with the precipitation totals from the same period for all the years of the dataset.

The original classification or description by McKee *et al.* (1995) of the different indices is listed in **Table 4**. Several authors (Komuscu, 1999; Agnew, 2000) have suggested changes to this classification (**Table 5**), while a classification of SPI values proposed by Guttman (1999) and that by Hayes *et al.*, (1999) and McKee *et al.*, (1993) is listed in **Tables 6 and 7** respectively.

Table 5: Suggested modifications to the PDI classes.

SPI	Probability of occurrence	Komuscu (1999) and McKee et al. (1995) drought classes	Proposed new drought classes
Less than –2.00	0.023	Extreme drought	
Less than –1.65	0.050		Extreme drought
Less than –1.50	0.067	Severe drought	
Less than –1.28	0.100		Severe drought
Less than –1.00	0.159	Moderate drought	
Less than –0.84	0.201		Moderate drought
Less than –0.50	0.309		No drought
Less than 0.00	0.500	Mild drought	No drought.

Table 6. SPI Classes (From Guttman 1999)

Lower limit			Upper limit		Description
		SPI	≤	-2.0	Extremely Dry
-2.0	<	SPI	≤	-1.5	Moderately Dry
-1.5	<	SPI	≤	-1.0	Dry
-1.0	<	SPI	<	1.0	Neutral
1.0	≤	SPI	<	1.5	Wet
1.5	≤	SPI	<	2.0	Moderately Wet
2.0	≤	SPI			Extremely Wet

Pandey and Ramasatri (2002) proposed that when applying SPI to larger areas, that the concept of "climatic regions" be applied. Climatic regions were defined by Ponce *et al.* (2000) in terms of mean annual precipitation and mean annual evapotranspiration. This type of characterization is particularly useful for mid-latitudinal regions, where droughts are shown to be more intense (Karl, 1983). Specifically, Ponce *et al.* (2000) classified the climatic spectrum of mid-latitudinal regions using the ratio of local mean annual precipitation (P_a) to global terrestrial mean annual precipitation (P_g) and the ratio of mean annual potential evapotranspiration (E_p) to mean annual precipitation (P_a). The potential evapotranspiration of a terrestrial ecosystem is the amount of evapotranspiration that would take place under the assumption of ample supply of moisture at all times (Thornwaite, 1948). At the middle of the climatic spectrum, estimated global terrestrial mean annual precipitation is of the order of about 800 mm (Ponce *et al.*, 2000; Pandey and Ramasastri, 2001). The climatic spectrum can also be characterised by the ratio of mean annual potential evapotranspiration (E_p) to mean annual precipitation (WMO, 1975). The South African Weather Bureau (now SA Weather Services) have in 1972 divided the country into 93 rainfall districts based on more than 700 evenly distributed rainfall stations for which unbroken series of reliable data between 1921 and 1965 are available (SAWB, 1972). The distribution of these districts is shown in **Figure 5**.

Table 7: Classification scale of SPI values (From McKee *et al.* (1993) in Hayes *et al.* (1999)

SPI Values	Category
2.00 and above	Extremely wet
1.50 to 1.99	Very wet
1.00 to 1.49	Moderately wet
-0.99 to 0.99	Near normal
-1.00 to –1.49	Moderately dry
-1.50 to –1.99	Severely dry
-2.00 and less	Extremely dry

The SA Weather Bureau further also grouped southern Africa into 11 main rainfall regions (A-K) while each region was again further subdivided and denoted as A_1, A_2, A_3 and A_4 to K_1, K_2 and K_3 (SAWB, 1972) (**Figure 6**). Eight of these rainfall regions occur in South Africa and each of the 93 rainfall districts has been allocated to a rainfall region. For each of the regions the "annual march" of rainfall over the region has been plotted which indicated the rainfall distribution over the year. Examples of some of these "marches" are shown in **Figure 7**. The classification in terms of climatic regions may be appropriate in the case of the application of SPI to South African rainfall data and was successfully used by Rouault and Richard (2003) to investigate the intensity and spatial extension of drought in South Africa at different time scales. In this research a similar approach was used to correlate the SPI indicators for a specific rainfall district to geohydrological data. When comparing groundwater levels, it might be more conclusive if the borehole localities are grouped according to their different climatic classes as suggested by Pandey and Ramasastri (2002). Similarly, it might be more conclusive to group boreholes according to their catchment or recharge area (if this can be defined) when comparing it with rainfall or river flow records. Boreholes can also be grouped according to the seasonal rainfall area or geographical locality when being compared to the cumulative rainfall departure values as proposed by Bredenkamp (1995).

5.2.4 Advantages and limitations of SPI

Hayes (1999) has listed a number of advantages and limitations of SPI. The advantages are:

- Its simplicity – SPI only requires precipitation data.
- It is versatile – it can be calculated on different time scales which gives it the ability to observe the temporal dynamics of a drought including its development and decline. It can also be successfully applied to observing from agricultural scenarios (short term) to hydrological and geohydrological ones (longer term)
- Because of its normal distribution, the frequencies of the extreme and severe drought categories for any location and timescale are consistent; and
- As it is based only on precipitation and not soil moisture (as the Palmer Index for example), it can be applied to any season.

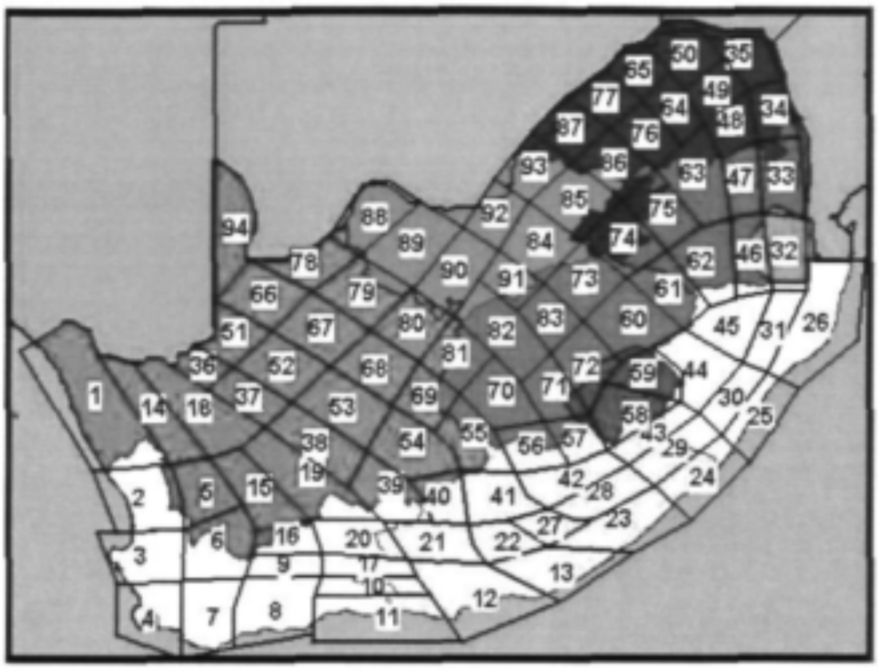


Figure 5: Distribution of the 93 rainfall districts across South Africa (SAWS, 2004, pers. comm.)

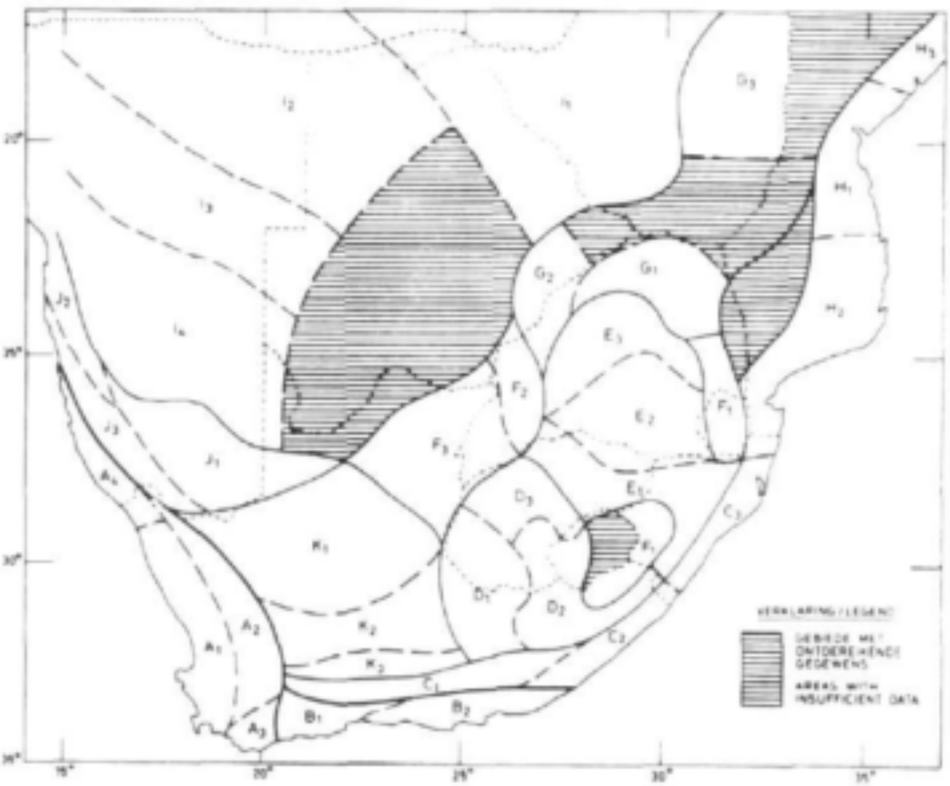
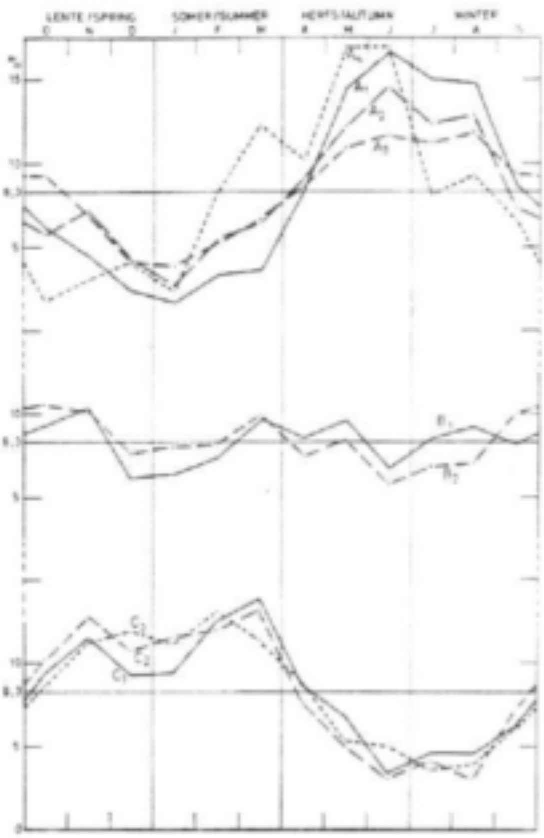
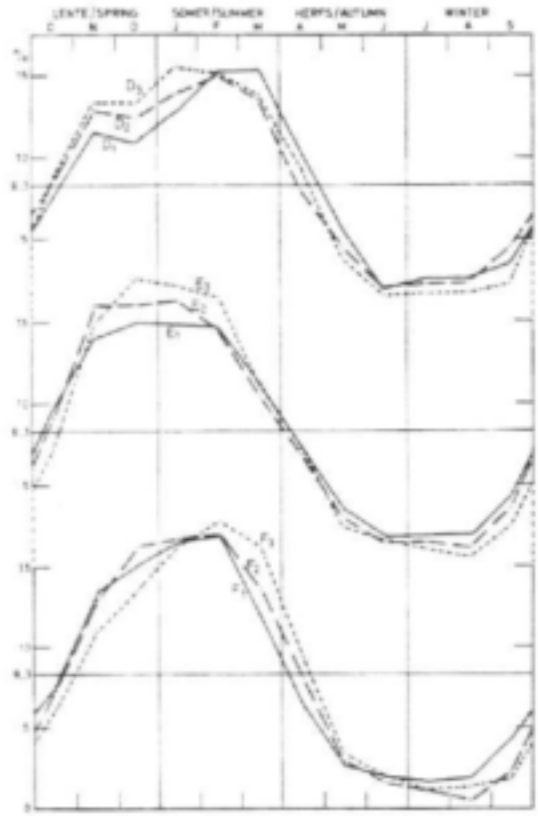
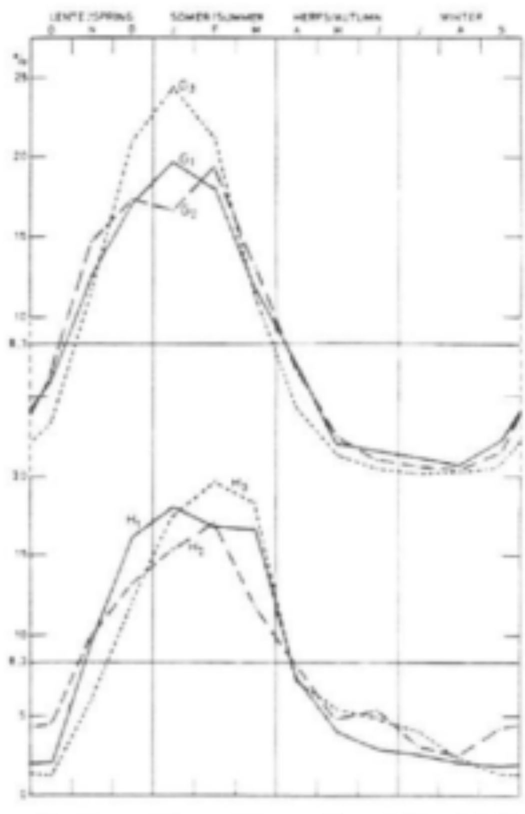


Figure 6: The eleven rainfall regions across southern Africa (from Weather Bureau, 1972)







(a): Rainfall regions A, B and C
(b) Rainfall regions D, E and F
(c) Rainfall regions G and H

Figure 7: Annual "march" over the eight rainfall regions of South Africa (from Weather Bureau, 1972)

Some limitations are:

- It requires reliable datasets over a period of at least 30 years.
- The calculations are complex and 68 terms are actually defined as part of the calculation procedure (Soule, 1992).
- To be used for short term predictions of dry conditions (especially in the case of agricultural applications), datasets have to be updated very regularly.
- The SPI cannot be used to identify regions that may be more "drought prone" than others. This is due to the characteristics associated with normal distributions where severe and extreme droughts as measured by SPI, occur with the same frequency.

The characteristics of the SPI as an indicator of drought conditions as described above, were seen as a possible new and innovative way of interpreting or correlating natural groundwater levels fluctuations with rainfall. There is no doubt that in southern Africa the natural groundwater level response is closely associated to rainfall (Bredenkamp *et al.*, 1995), and in particular the intensity and duration of rainfall events, and that lag in the response time is most probably also impacted upon by the physical characteristics of the aquifer and the overlying geological formations, as well as the recharge area relative to the position of the monitoring borehole. Due to the ability of the SPI technique to incorporate different time scales, it was proposed that this might be a way to study the impact of hydrological drought on the response time of natural groundwater level fluctuations. It should be noted that using the SPI values to establish possible correlations with groundwater level time series, has not been reported in the open literature before. The results described in this report is the first approach to establishing possible correlations between SPI and groundwater levels. Because of the preliminary nature of this investigation, correlations were only established through visual inspection and were not based on sound mathematical or statistical foundation.

6. LONG-TERM GROUNDWATER LEVEL DATA FROM SOUTH AFRICA

6.1 Availability and selection of data sets

The groundwater level data sets compiled by Zietsman and Nienaber (1994) were compiled in a format that is not accessible with currently and readily available software. The original data was made available to this project by DWAF and a considerable amount of effort went into finding software and methods that could read and translate all the information. This was eventually achieved and most of the data files referred to in the DWAF report GH3829 are now available in a format compatible with Microsoft Excel.

The DWAF GH3829 report (Zietsman and Nienaber, 1995) only contains water level and rainfall information up to 1994. In selecting data sets for analysis, preference was given to the longer data sets and those stating before 1970. A selection was made from the monitoring boreholes included in the DWAF report and updated water level and rainfall information (to at least December 2002) was supplied by the Department. A list of the station and relevant information originally selected and for which updated information was requested from DWAF is included as **Appendix B. Appendix C** contains more detailed information on each of the sites selected as well as a map showing the position of the borehole.

6.2 Some examples of declining groundwater levels over longer periods

The selection of monitoring boreholes for the initial phase of this study was done purely on the basis of the water level records published in the DWAF GH3829 report. Unfortunately there is no documented record at the Department that explains the original motivation for the selection of a specific borehole to be awarded the "status" of long term monitoring borehole, but it is assumed that the position was originally selected to record "natural" water level response, and that these were not influenced by external factors. Whether this still applies cannot be confirmed from existing records at the Department, and will require an on-site physical inspection of the present conditions in the vicinity of the borehole. Such a physical inspection of the current geohydrological conditions at each of the selected boreholes was outside the scope of this project. A request has, however, been submitted to the Department to assist in establishing the current conditions in the immediate vicinity of some of the selected monitoring boreholes. No effort was made to establish whether the water levels recorded at these selected boreholes had been affected by external factors such as large scale abstraction for irrigation purposes, domestic supply to towns or villages or the proximity to recharge sources (dams or rivers). Boreholes were selected purely on the basis of the graphical record. From a visual inspection of the records, it would appear that some water levels show short term fluctuations that could possibly be linked to nearby abstraction or recharge linked to river flow.

As mentioned before a number of different water level fluctuation patterns are recognizable in the records kept by the Department. These can broadly be classified as

- Short term (~1 year) cyclical fluctuations in the water level data;

- Sharp increases in water level usually associated with extreme climatic events;
- Relatively steep and short term declining trend presumably associated with external factors such as abstraction;
- Medium term (~5-10 years) declining trends in the water level data; and
- Longer term usually declining trend which may be of a cyclic nature, but due to the short time series, it is not clear whether it does reflect a specific cycle.

To illustrate different patterns of water level fluctuations with time, a number of examples are presented on the following pages (**Figures 8 to 16).** The graphs represent a continuous or almost continuous water level record of between 22 to 42 years. In general the boreholes included in the DWAF report GH3829 display a relatively shallow water level (<30m), but occasionally are of the order of 60m or more. At this stage it is not clear whether these levels represent unconfined or semi-confined to confined aquifer conditions.

The water level records have a number of features in common. In most records the water level "decline" phase occurs over a significantly longer period than the water level "rise" phase. The "decline" phase displays variable periods: from a few years to more than 20 years. In the case of borehole 2426DC00102 on the farm Parys (monitoring station A2N011) some 30 km north of Pilansberg on the Archaean granite (**Figure 8**) the "decline" phase represents a more than 30 year period (1967 to 2002) with only one major recharge event during this period. From the water level information presented in the accompanying graphs, no definite or constant periodicity in water levels is apparent. Increases in water level appear to be rather associated with either larger rainfall events, or long periods of excessive rainfall. The periodicity is, however, not in the form of a smooth sine curve, but is skewed due to the relatively rapid rise during periods of significant recharge. The recovery phase is often very sharp (**Figures 8, 12 and 13**) and happens over a very short period of time (a change of up to 30m over only a few days in the case of **Figure 13**), while the decline phase occurs over several years. In other cases, the almost 25 year record shows no sharp increases in water level despite a relatively shallow water level (**Figure 11**), while in some instances no appreciable water level change occurs at all for periods of up to 10 years (**Figures 11 and 15**). The water level depth does not appear to be a controlling factor, as the rapid rise in water level occurs in the case of both shallow and deep water levels (**Figures 9, 12 and13**). In almost all cases the decline phase displays a number of smaller amplitude water level rise anomalies, but these a generally superimposed on the declining trend. In some cases it would appear that and even longer period is present in the data, with shorter periods superimposed on the long-term downward trend (**Figures 8 and 9**). Increases in water levels over long periods are also observed, as is the case in **Figure 14** (8 years) and **Figure 16** (20 years). Such cases have to be investigated individually, as special circumstances may be present. For example, in the case of **Figure 16**, representing the water level fluctuations of a borehole in the Uitenhage artesian aquifer, may be linked to the declaration of the Uitenhage Groundwater Control area during the 1960's. It is however, unfortunate that the groundwater level records in South Africa are in most cases not long enough to show trends of periods in excess of 30 years.

From these few graphs it would appear that each aquifer (or even borehole) has a unique water level response curve and that it would not be possible to make any general statements about aquifer response to rainfall patterns or events. Bredenkamp and co-workers (1995) have reported reasonable correlations between the water level and "Cumulative Rainfall Departure" datasets. They have also reported many cases where no correlations could be established. Two examples where the CRD technique has been applied are shown in **Figures 17 and 18**. In both cases a reasonable correlation (r=0.6 to 0.7) has been achieved. However, in many of the datasets reported in the DWAF Report GH3829, no or at least a very low correlation could be found between the water level and the CRD curve.

The SPI technique evaluated during this project may be another way to establish correlations between rainfall and water level response. A few examples are presented in the next section.

Figure 8: Water level graph for borehole 2426DC00102, Groundwater level monitoring station A2N011, some 30km north of Pilanesberg on the farm Parys.

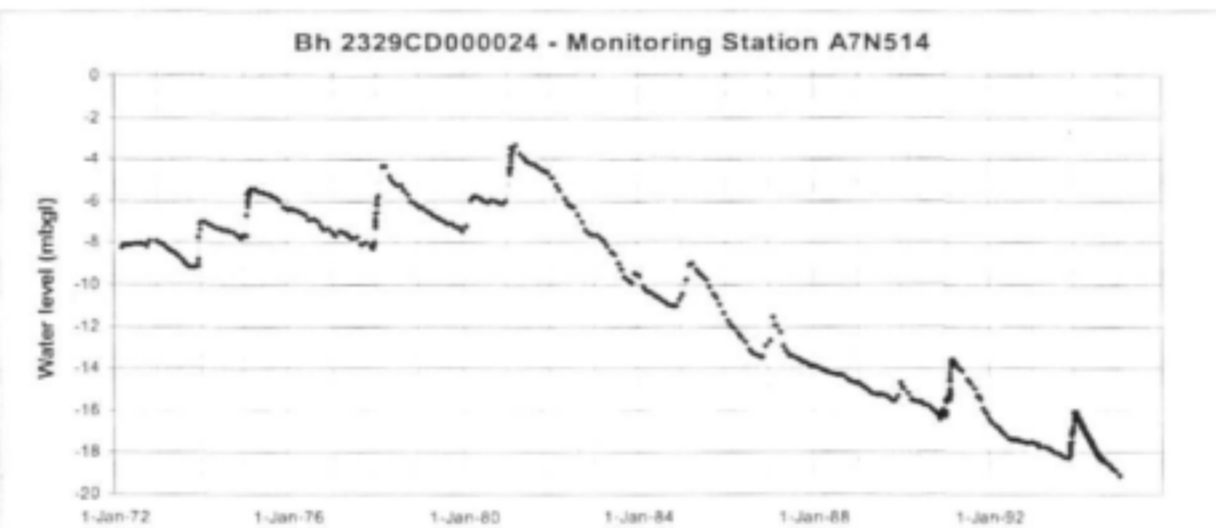


Figure 9: Water level graph for borehole 2328CD00024, Groundwater level monitoring station A7N514, south of Pietersburg on the farm Weltevreden.

Figure 10: Water level graph for borehole 3018CC00056, groundwater level monitoring station F5N001, approximately 100km northwest of Van Rhynsdorp on the farm Moordenaarskraal.

Figure 11: Water level graph for borehole 3222BA00112, groundwater level monitoring station L1N136 approximately 80 km northeast of Beaufort West on the farm De Hoop.

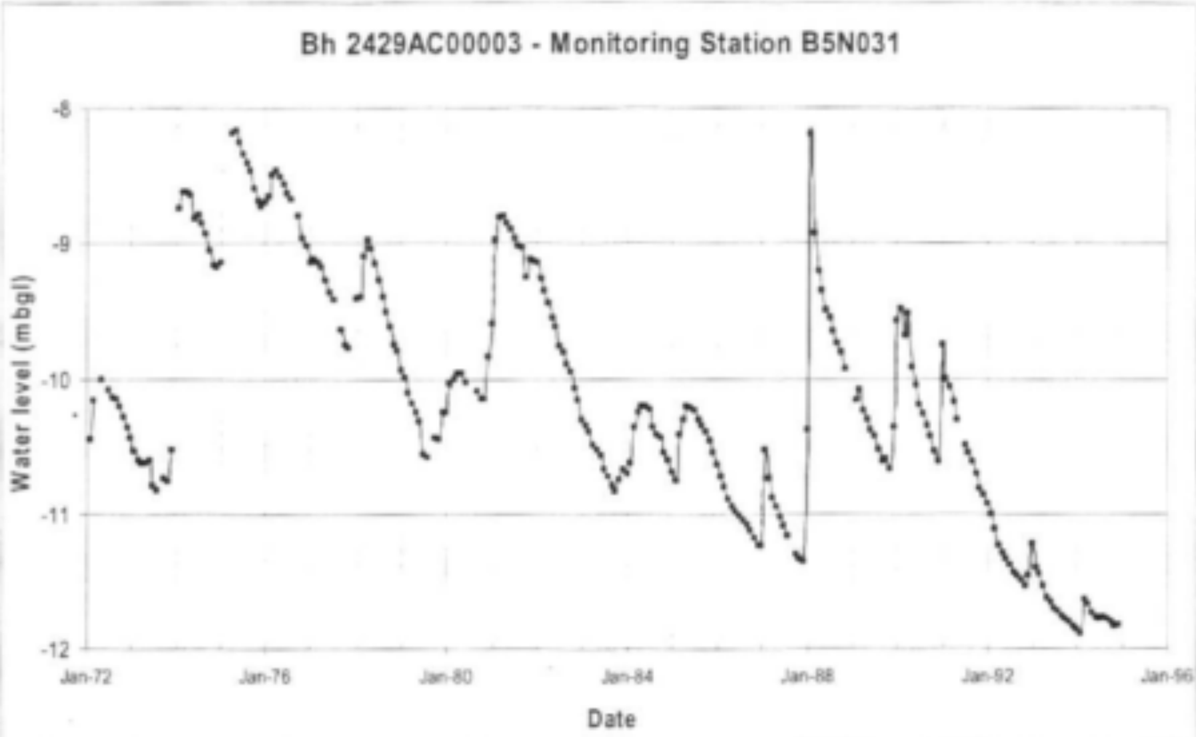


Figure 12: Water level graph for borehole 2429AC00003, groundwater level monitoring station B5N031, approximately 25 km south of Potgietersrus on the farm Doelen.

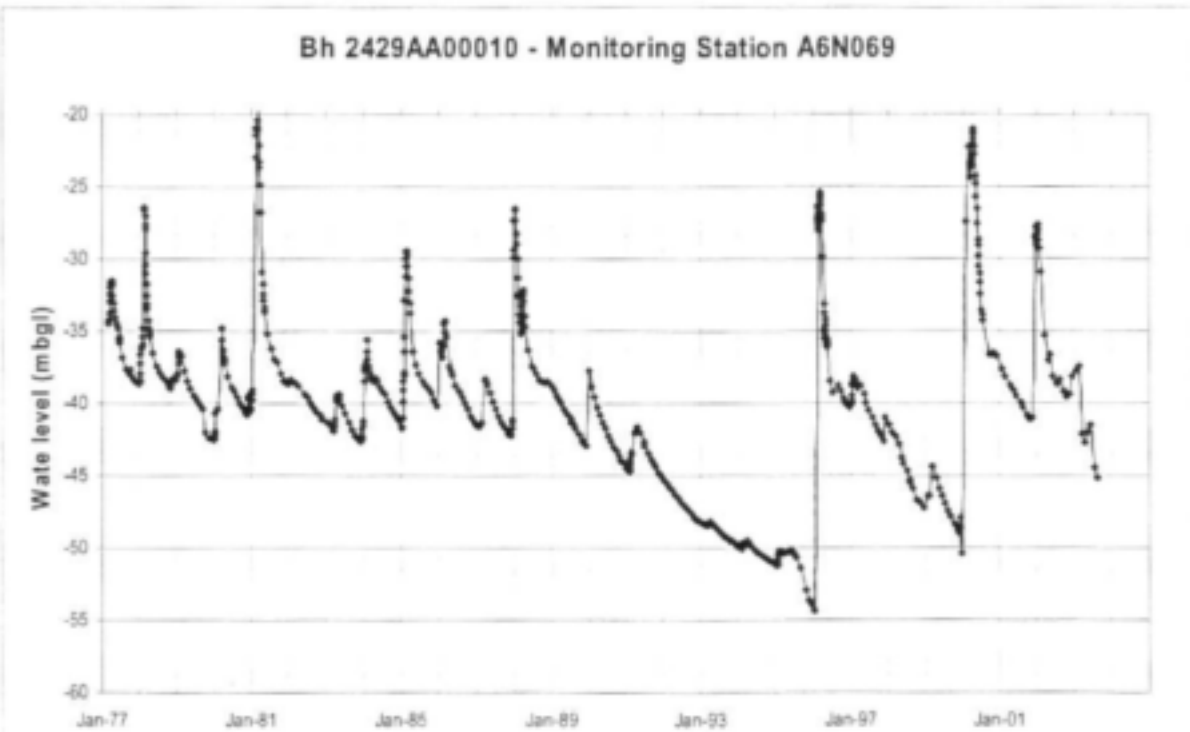


Figure 13: Water level graph for borehole 2429AA00010, groundwater level monitoring station A6N069, approximately 15km east of Potgietersrus on the farm De Hoop.

Figure 14: Water level graph for borehole 2429AA00011, groundwater level monitoring station B5N011 approximately 15km east of Potgietersrus on the farm Portugal.

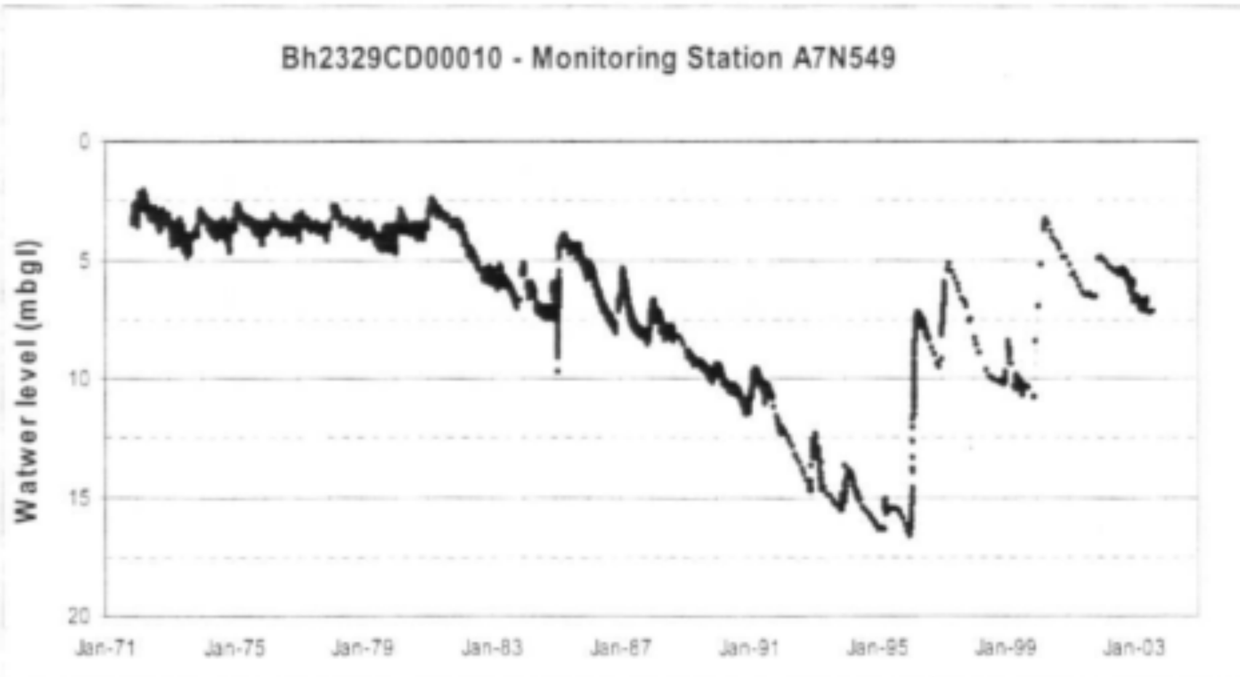
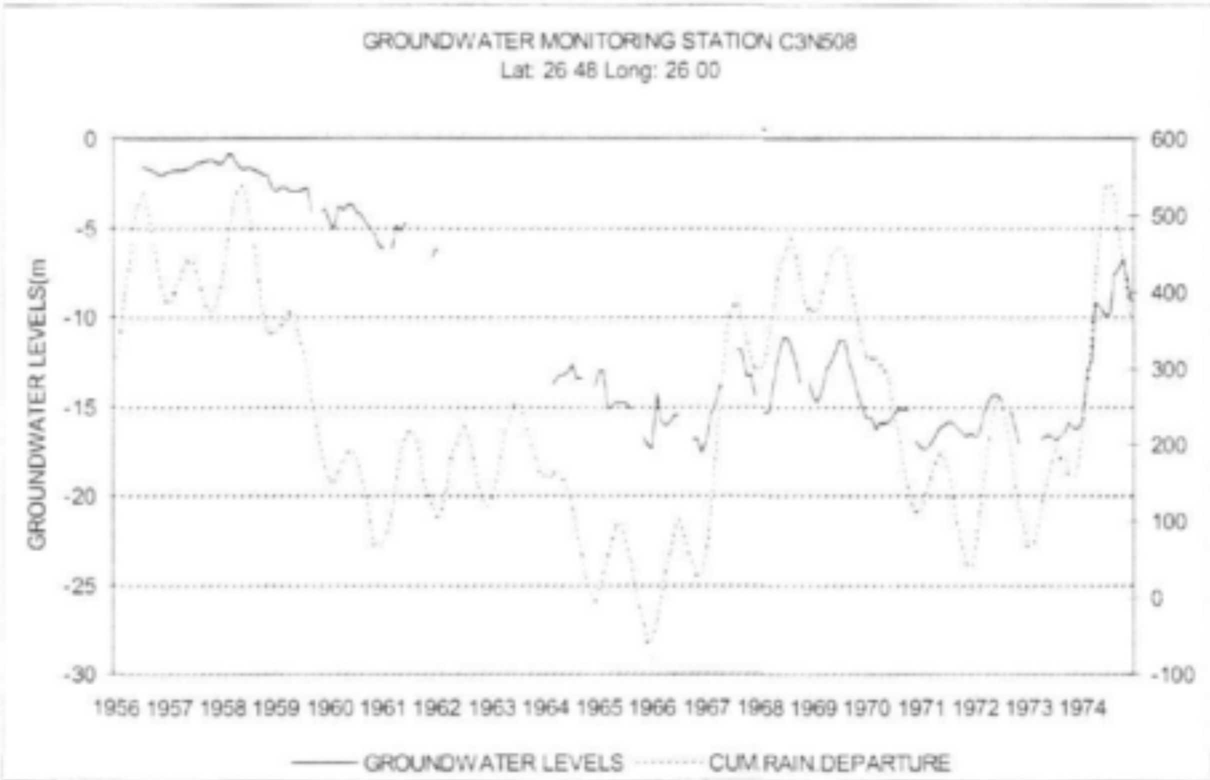


Figure 15: Water level graph for borehole 2329CD00010, groundwater level monitoring station A7N549, on the farm Sterkloop in the Pietersburg District.

Figure 16: Water level graph for borehole 3325CB00002,Groundwater level monitoring station M1N005, approximately 15 km north of Uitenhage on the farm Prentice Kraal.



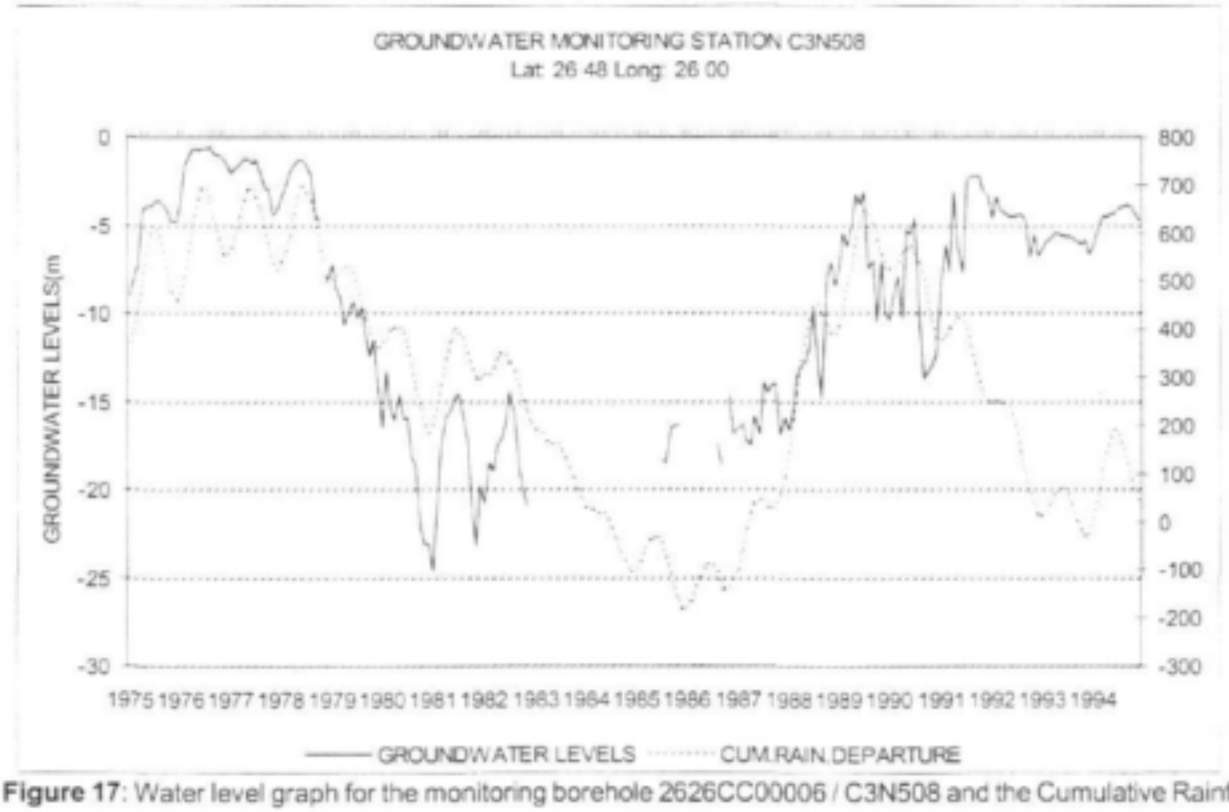
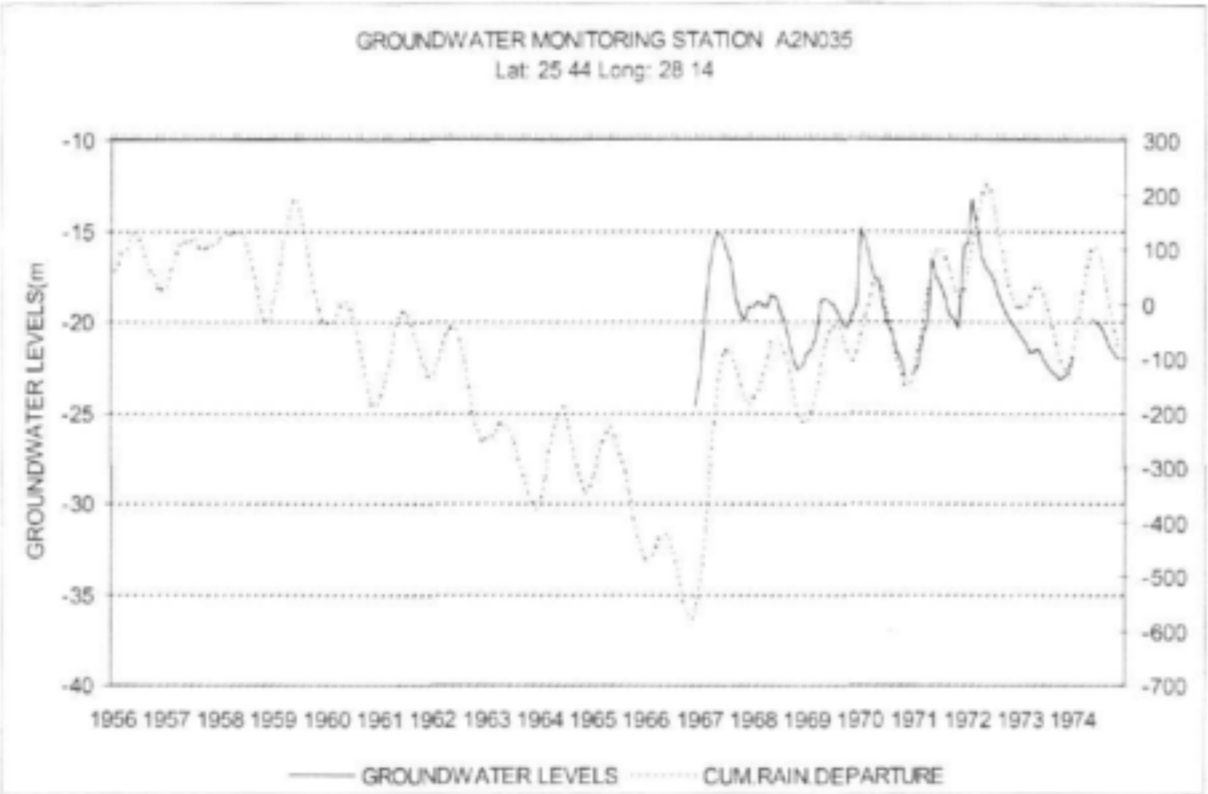


Figure 17: Water level graph for the monitoring borehole 2626CC00006 / C3N508 and the Cumulative Rainfall Departure (CRD) curve as published in the DWAF report Gh 3829.



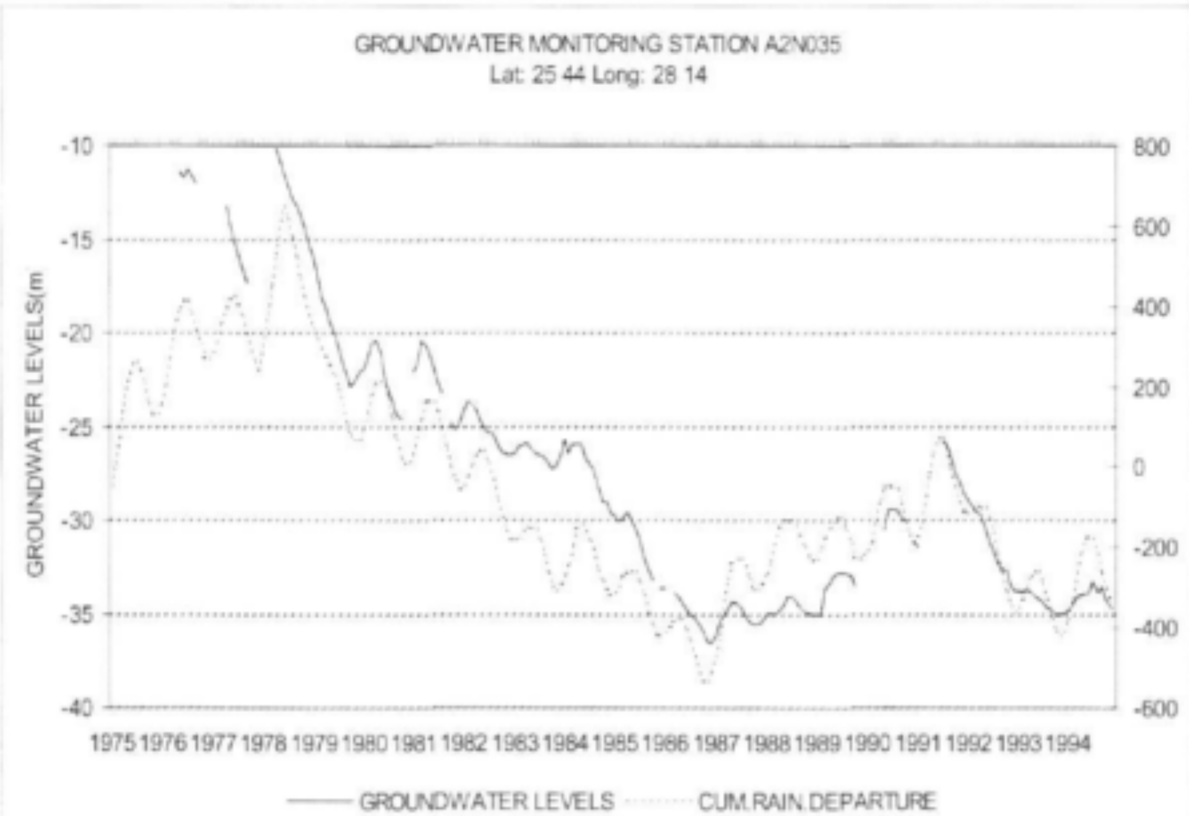


Figure 18: Water level graph for the monitoring borehole 2528CA00014 / A2N035 and the Cumulative Rainfall Departure (CRD) curve as published in the DWAF report Gh 3829.

7. APPLICATION OF THE STANDARISED PRECIPITATION INDEX (SPI) TECHNIQUE TO LONG-TERM GROUNDWATER LEVEL DATASETS

7.1 Presentation of SPI values

The calculated SPI values for a specific rainfall dataset can be displayed in different ways. The original motivation for the development of the index was to be able to monitor drought conditions on a regional scale. For this application regional maps of the SPI were constructed to identify drought conditions. An example of this approach using South African datasets was reported on and in published in Water SA (Rouault and Richard, 2003). They prepared maps of the spatial distribution of SPI values across the country for the 20 worst dry years since 1922. These maps are shown in **Figure 19**.

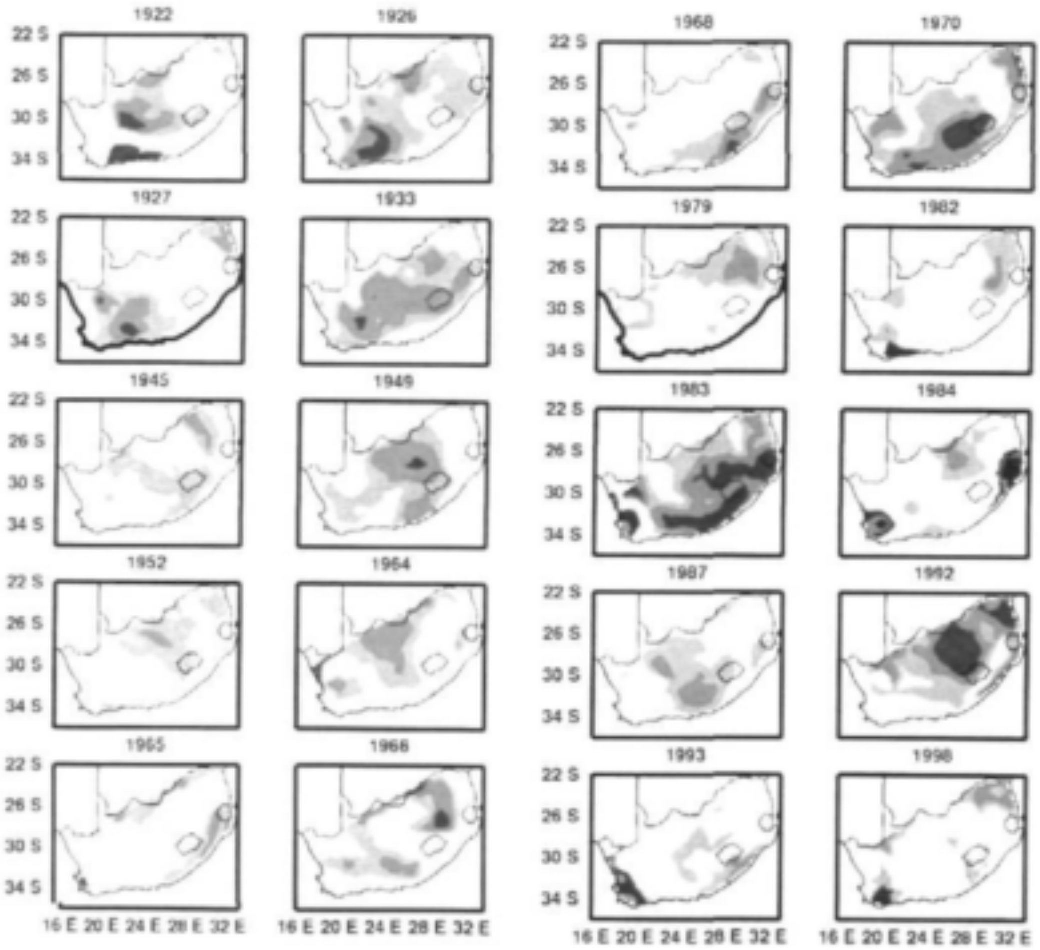


Figure 19: Spatial extension of the 6-month SPI at the end of April for the 20 driest years since 1922. Colour code: brown (SPI=-3 to -2; extremely dry period) to green representing an SPI=1 to 0.5 (Near normal to moderately wet) (Copied from Rouault and Richard, 2003)

Another way to display the SPI values is in a bar chart format. This display method is shown in

Figure 20, again using South African data presented by Rouault and Richard (2003). With the longer time scales (say 24 month; lower graph in **Figure 20**) a periodicity becomes apparent in the data.

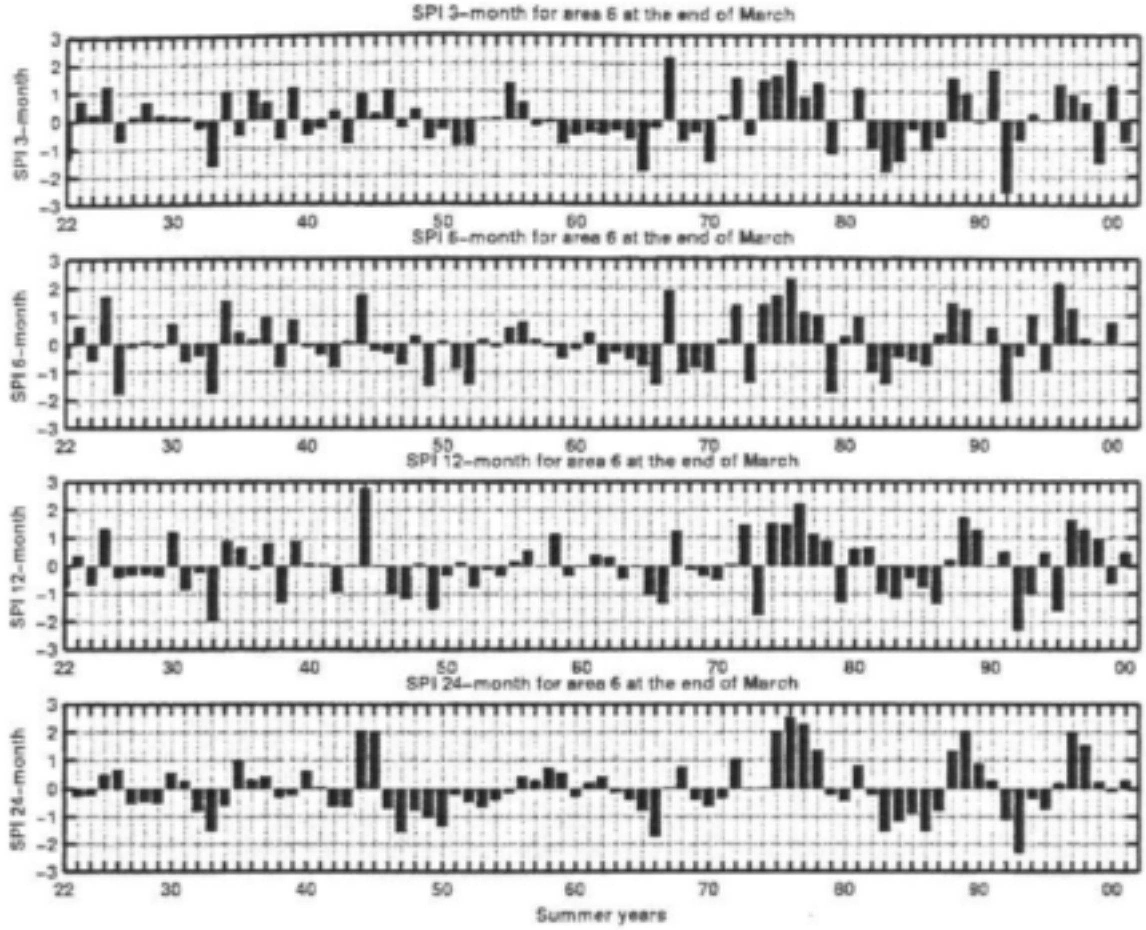


Figure 20: Bar chart representation of SPI for the Central interior of South Africa for different time scales (Rouault and Richard, 2003).

A third way of presenting SPI values, and the one most often used, is in the form of time series graphs. The South African National Disaster Management Centre housed in the Department of Local and Provincial Government (DPLG) have used the SPI approach as a way of early warning for imminent drought conditions. Their SPI values are calculated for individual quaternary catchments in time steps of 3, 6, 12, 24 or 48 months. They used the WR90 rainfall dataset and therefore their SPI values extended over the period 1920 to 1990. Examples of the way they have presented their SPI calculated values are given in **Figures 21 and 22**. This way of presenting the data is more applicable for geohydrological applications. However, because they used the WR90 rainfall dataset, the last about 15 years of rainfall information is not used in the SPI calculations. In view of the relatively short time periods for which groundwater level information is available, it is advisable to use the longest rainfall record that correlates to the groundwater dataset as possible.

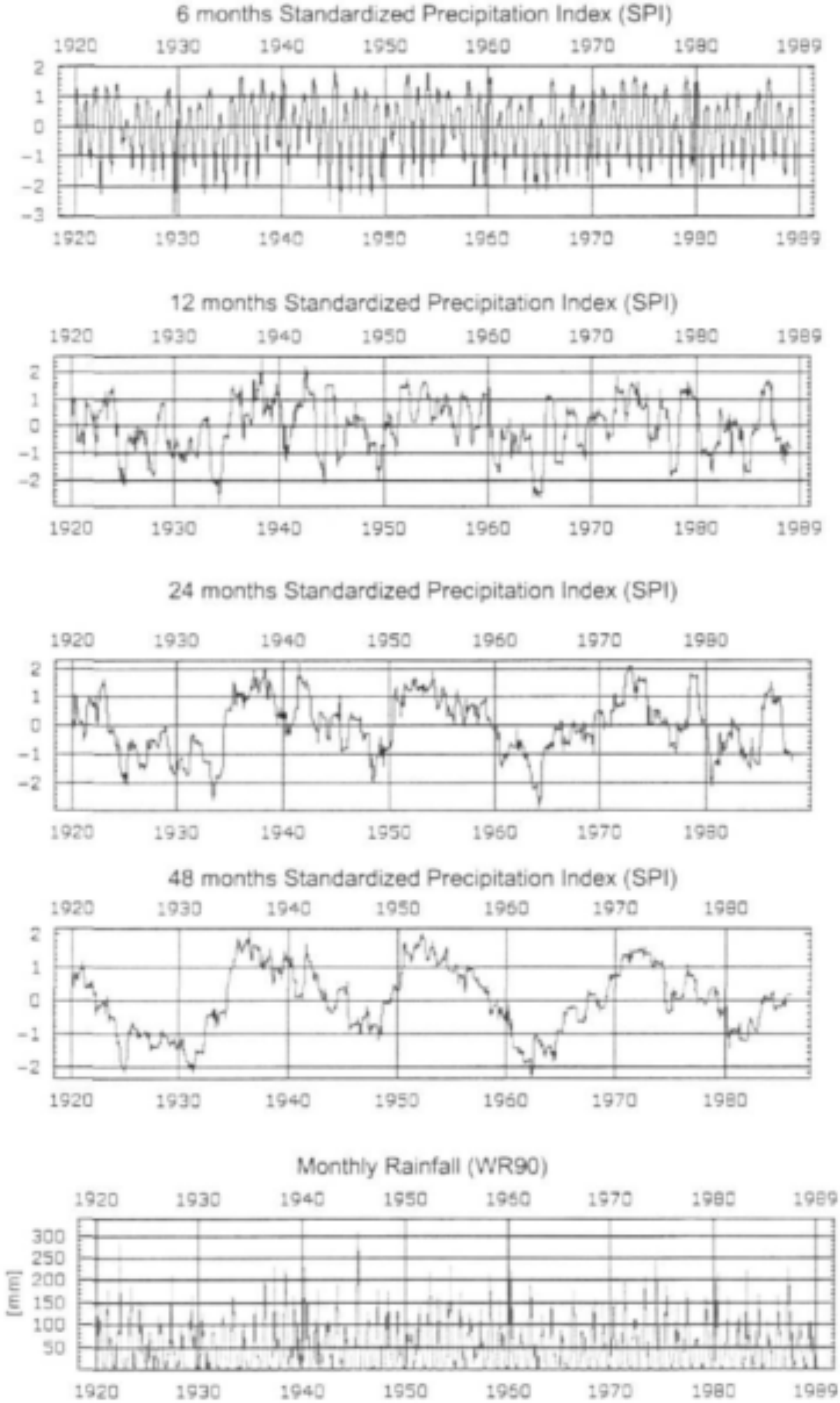


Figure 21: SPI graphs for different time scales and monthly rainfall graph for the Quaternary Catchment A61F in the Lichtenburg area.

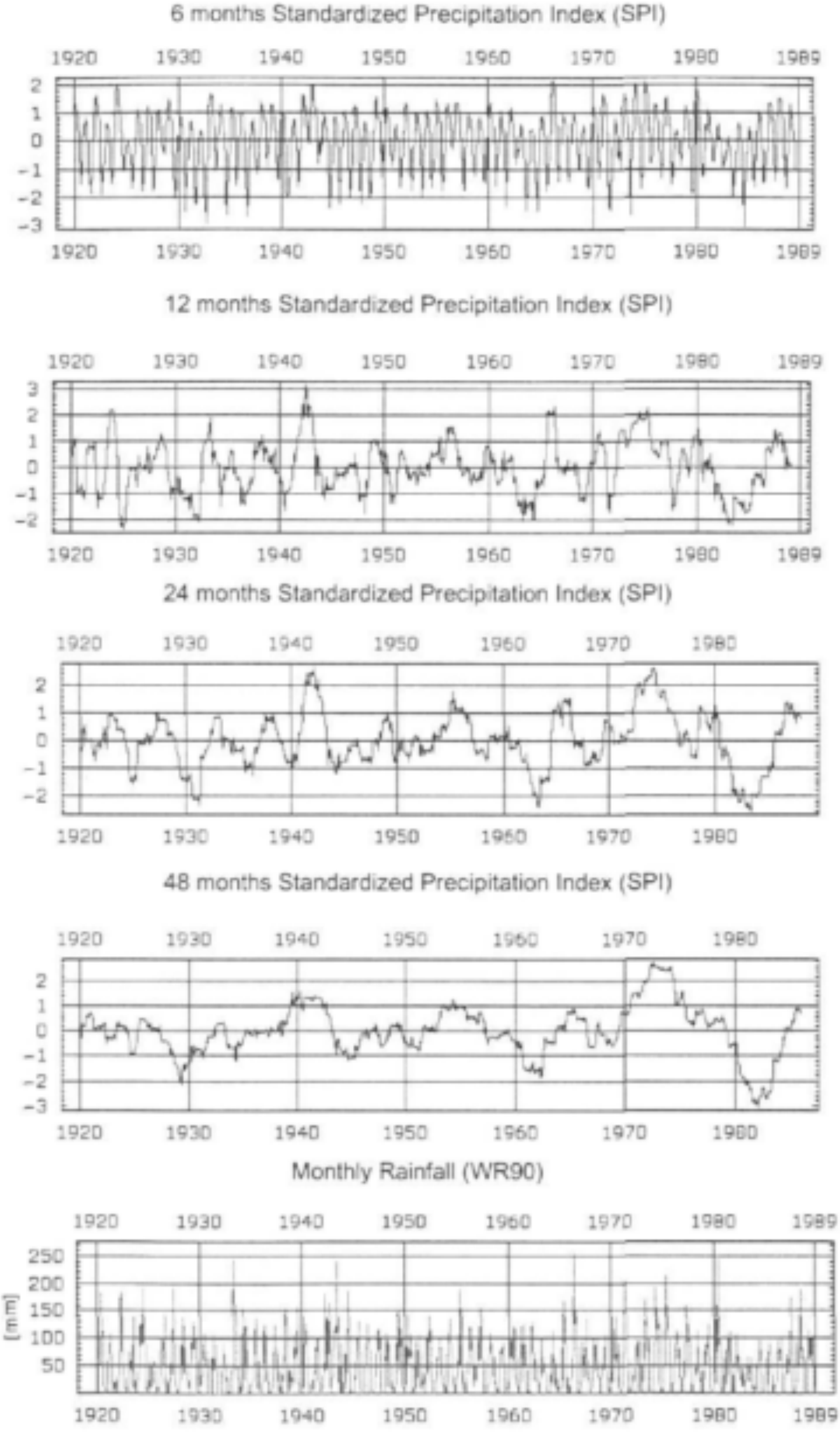


Figure 22: SPI graphs for different time scales and monthly rainfall graph for the Quaternary Catchment C31C in the Potgietersrus area.

On the recommendation of Dr Rouault of the Oceanography Department of the University of Cape Town, SPI datasets calculated according to the Weather Bureau's climatic districts and regions were used in this study. Dr Rouault kindly made his SPI dataset, based on an 80 year rainfall record covering the period 1921 to 2001 available to this project. This dataset contains the SPI values for each of the 93 rainfall districts at time scales of 3, 6, 12 and 24 months. Examples to illustrate the difference in SPI values of the different time scales for two rainfall districts: one with winter rainfall (rainfall district 3, rainfall region A_2) and one with summer (rainfall district 86, rainfall region E_2) are presented in **Figures 23 and 24**. In each of these datasets, some periodicity is displayed by the monthly rainfall data. By applying the SPI technique to the rainfall data, the periodicity in the data becomes much clearer, especially with the longer time periods of 24 months (**Figures 23 and 24**) and 48 months (**Figures 21 and 22**).

These graphs are to be compared to major wet and dry cycles in Southern Africa presented in **Table 2**. In broad terms there is a good correlation, but when comparing the graphs in more detail, the value of the SPI graphs become apparent. Using the SPI technique, the spatial extent, the duration as well as the intensity of dry and wet cycles can now be determined with much better accuracy for specific regions in the country. Using the SPI classification (**Table 7**) it can be confidently stated that the dry period in Rainfall District 3 extended from about 1965 to 1975 (**Figure 23**) while the latter part of this period was the worst on record with SPI values below –2 (Extremely dry). Similarly, the wet period during the mid 1950s again was the wettest period on record for this rainfall district (Extremely wet; SPI>3). On the other hand, the mid 1950s was a transition zone between a dry and wet period in Rainfall District 86 (**Figure 24**), while the late 1950s can be described only as a "near normal" period (**Table 7**). For this rainfall district the wettest periods on record were the years 1975-1978 and 1997 (SPI>2).

7.2 Correlation between SPI values and groundwater level information

In the following section a number of water level time series from selected areas across South Africa are compared to the calculated SPI values for the specific rainfall district in which the water level monitoring borehole is located. Water level response at eleven boreholes across South Africa have been selected for this correlation. These were selected on the basis of the length and quality of the water level record, and that the water level record represents a background type response unaffected by external factors such as pumping and recharge directly linked to river or stream flow. A specific example to illustrate this is presented in **Figure 25**. Here the SPI values calculated by the DPLG (National Disaster Management Centre) and are based on the WR90 rainfall records.

Information relating to the original motivation for the identification of boreholes for long-term water level monitoring is sparse. This applies especially to those boreholes with 25 or more years of monitoring data. To ensure that the groundwater levels of the selected dataset used in the correlations had not been affected by external factors such as groundwater abstraction from nearby boreholes, the water level responses were analysed using the computer program EARTH (Xu and Beekman, 2003) kindly supplied by Prof Van Tonder of the IGS, University of the Free State (van Tonder, pers. comm., 2004).

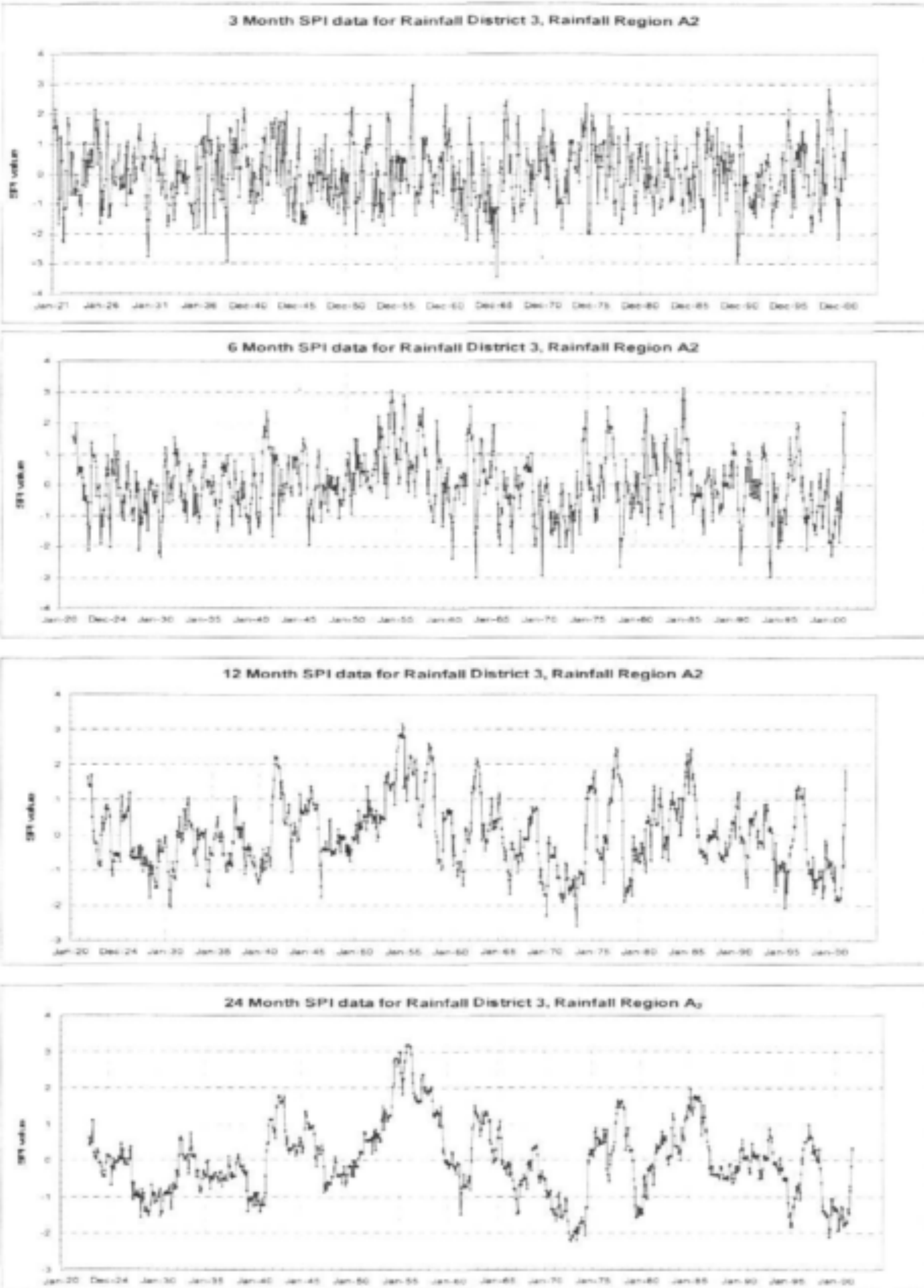


Figure 23: SPI values representing rainfall District 3 in the Western Cape for the period 1921 to 2001 for 3,6, 12 and 24 months time scales. Calculated SPI values are plotted at monthly intervals.

Figure 24: SPI values representing Rainfall District 86 in the Limpopo Province for the period 1921 to 2001 for 3,6, 12 and 24 months time scales. Calculated SPI values are plotted at monthly intervals.

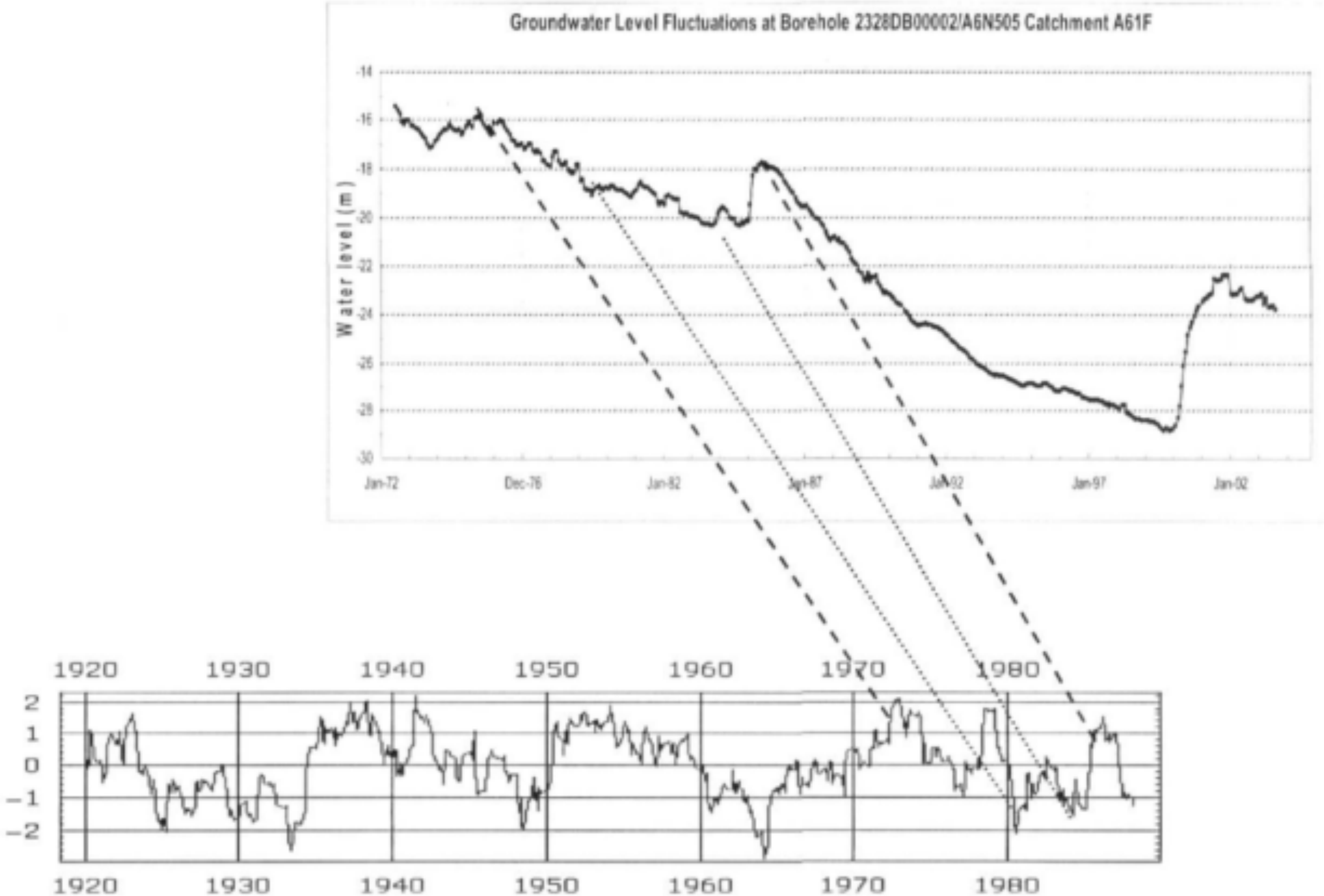


Figure 25: Visual correlation between the 48 month SPI values for the Quaternary Catchment A61F (Potgietersrus area) and borehole 2328DB0002 in the same catchment.

With this program, influences of nearby abstraction on the water level record of a monitoring borehole can be studied. With this technique, and by changing the percentage recharge of MAP and S_y of the aquifer, the best fit is obtained between level response as a result of a given rainfall record, and the observed water level response. An example of subjecting a dataset to this programme, using the water level record of borehole 2328DB00002 near Gilead northwest of Potgietersrus and the rainfall station 0676/523, is presented in **Figure 26**.

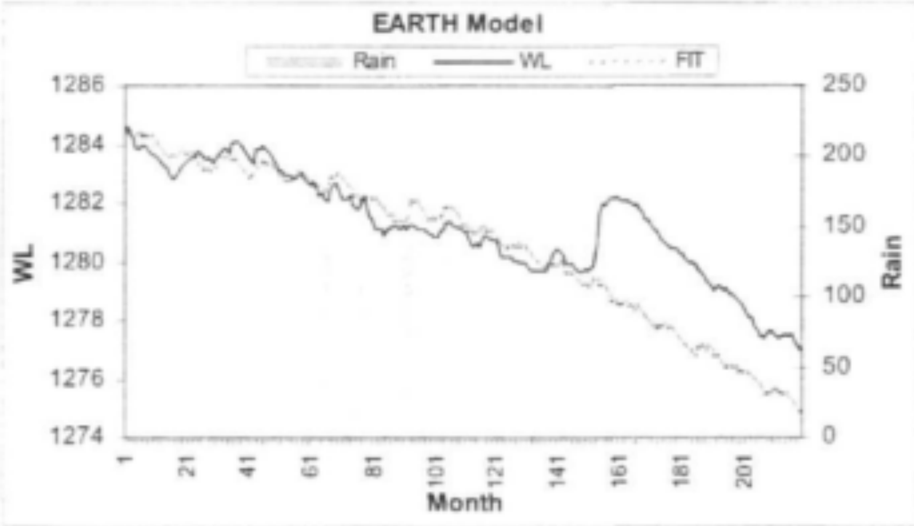


Figure 26: Application of the EARTH model to water level data from borehole 2328DB00002

The model indicates that the decline in water level up to month 150 is probably the result of abstraction in the vicinity of the monitoring borehole and that the sudden increase in water level after month 150 can be attributed to a period of no pumping that lasted for only a few months. It would however, be advisable to investigate the specific conditions at this borehole to confirm the interpretation made from the model.

Another example to illustrate the correlation between water level and SPI values using the DPLG 48-month SPI values is given in **Figure 27**. The almost 50 year long water level record for borehole 2626CC00006 situated in quaternary catchment C31C around Lichtenburg, shows relatively large amplitude oscillations. The 48-month SPI values appear to correlate best with the major water level oscillations. Individual maxima and minima on the two curves were visually correlated as shown in **Figure 27**. From this provisional analysis it appears that an approximate 3-year lag between rainfall and water level response exists. The relatively long lag time in water level response, together with the shallow water level, would indicate that the water level record represents that of a confined system. Recharge of this confined system may occur a large distance away from where the water level is recorded and therefore the rainfall record used may not be the most appropriate one for this borehole. This example suggests that the selection of the time period for which SPI values should be calculated for a specific correlation, may be critical and may be influenced by the prevailing aquifer type. The interaction between SPI times and response time of an aquifer to rainfall and recharge events is not well understood and it is recommended that this aspect should be studied in more detail.

Figure 27: Visual correlation between the SPI values for the Quaternary Catchment C31C (near Lichtenburg) and borehole 2626CC00006 in the same catchment.

7.3 Examples using SPI values calculated for SAWB Rainfall Districts

On the following pages 10 examples of water level datasets from across South Africa are compared to the SPI of the rainfall district in which they are located. In all cases the upper diagram displays the SPI time series, annual rainfall and the annual deviation from the average annual rainfall. In the lower diagram the SPI is compared to the water level record. Specific detail of each of the selected areas is given in Appendix C together with a map of the area. First some general comments on the correlations are made, followed by a description of each of the specific examples presented. These examples are followed by a section in which a first attempt at designing a generic "Recharge index" based on correlations between groundwater level and SPI values for South or Southern African conditions is proposed (Section 7.4).

7.3.1 General comments on SPI and water level correlations

The first eight examples **Figures 28 to 35** show a remarkable good visual correlation between SPI and water level. It must be remembered that these examples were primarily chosen for the length of the water level record and the assumption that the records have not been affected by external factors. In most cases the broad features of both record types correlate well. Good examples are longer periods of above average rainfall (SPI>~1.5) correlate well with increases in water levels (**Figures 28, 29, 35**), while periods of average rainfall (-1<SPI<1) correlate with constant or slightly declining water levels (**Figures 28, 31, 35**). Rapid and significant increases in water level (for example **Figures 30, 31 and 33**) are usually associated with SPI values above 2 and in some cases even as high as 3. An SPI of 2 and higher is defined as "Extremely wet" (**Table 7**). Longer periods of SPI<0.5 are generally associated with declining water levels (**Figure 28, 29, 33**). In some cases the short term (2-3 years) changes in SPI are also reflected in the water level record (for example **Figures 28 and 31**).

In two of the chosen examples no obvious good correlations between SPI and water level are evident. These are displayed in **Figures 36 and 37**. The water level record displayed in **Figure 36** represents the water level in the Uitenhage artesian aquifer. Despite large variations in the SPI value over the first almost 20 years (SPI>2 to SPI<-2 in less than 5 years), the water level record does not show similar changes. The decline in water level only starts during the mid 1980s when the SPI remained below 0 for a period of almost 10 years. During the approximately 5-year period of increase in SPI (SPI>1), the water level remained virtually constant. This behaviour cannot be explained satisfactorily at the moment but it is expected that it is linked to the artesian nature of the Uitenhage aquifer and possibly also to the proclamation of this aquifer as an Underground Water Control Area during the mid-1960s. In the case of **Figure 37** the long-term decline in water level is not reflected in the SPI values. This may be due to the impact of possible abstraction from nearby boreholes on the water levels as explained earlier. However, the significant increase in SPI during the mid 1990s (from <-2 to >+2) had no impact on the water levels whereas a much smaller increase in SPI a few years later, is associated with more than 5m increase in water level.

7.3.2 Description of specific examples

***Figure 28**: Groundwater level recorder D6N5000 Caroluspoort, De Aar*

The correlation between the two datasets is remarkable over the entire period. Both the larger and smaller anomalies (amplitude and duration) correlate well, especially for the first section of the record. Water levels respond to small changes in SPI which gives the impression that at least some groundwater recharge occurs during almost every year. Water level response is also almost immediately after rainfall events, perhaps reflecting high permeabilities and/or shallow water levels.

***Figure 29:** Groundwater level recorder D4N522, Boschkoppie, Delareyville*

Good correlation between water level and both macro and micro changes in SPI. The 5 year period of high SPI values (1974-1979 and SPI>+2) in reflected in the continuously high water levels, whereas in the case of shorter periods of moderate SPI values (1981-1983), a water level decline period sets in shortly after the end of the somewhat higher SPI period. It also appears that in order to raise water levels significantly, high SPI values have to be maintained for quite some time. This is illustrated by the water level response around 1989 when water levels rapidly declined again after a short period of high SPI values.

***Figure 30**: Groundwater level recorder F5N001, Moordenaarskraal, Van Rhynsdorp District*

For a period of 15 years (1981-1996) the SPI remained between –1 and +1. Over this period the water level shows a steady decline. Water levels start to respond about a year after the SPI values start to increase and remain high for the next 3 years. As soon as the SPI values start to decline the water level response is similar. It is concluded that under the specific geohydrologiocal conditions prevailing at this site, an SPI value in excess of +2 is required before recharge occurs.

***Figure 31**: Groundwater level recorder A6N069 De Hoop, Potgietersrus district*

The water level record shows a number of rapid water level increases which are not reflected in the SPI values. The fact that the water level does not respond to the significant increase in SPI values during the period 1992-1996 suggests that the water level record may be impacted upon by nearby groundwater abstraction. Water levels keep on declining during periods of relatively high SPI values (1997-1999) possibly for the same reasons. The rapid increase in water levels appears to be in response to exceptional rainfall periods or events.

***Figures 32, 33 and 35**: Groundwater level recorders C3N508 Korannafontein, Lichtenburg District, C3N511 Commonage, Vryburg District, and D6N501 at Zevenfontein, De Aar District*

Most of the SPI anomalies can be correlated with the water level response indicating a rapid response of recharge to rainfall events. Unexplainable deviation occurs in the case of Figure 32 during the period after 1991 and in the case of Figure 32 the periods 1993-94 and 1996-2000.

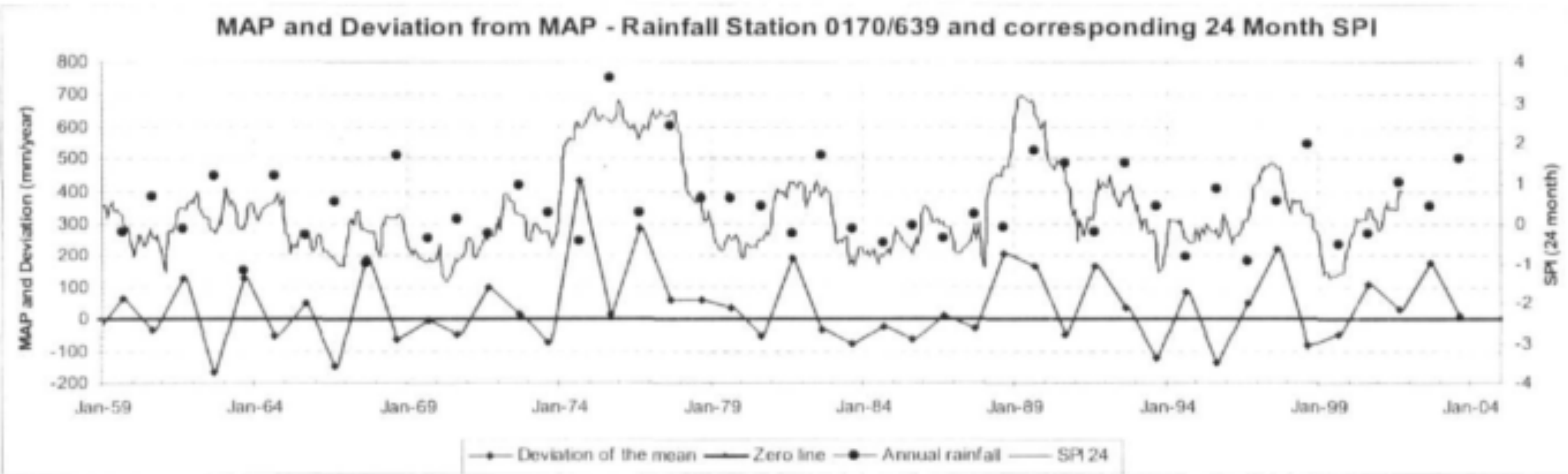


Figure 28: Groundwater level response at recording station D6N500 (borehole 3024CA00328) on the farm Caroluspoort, De Aar district using the rainfall record of Rainfall District 54.

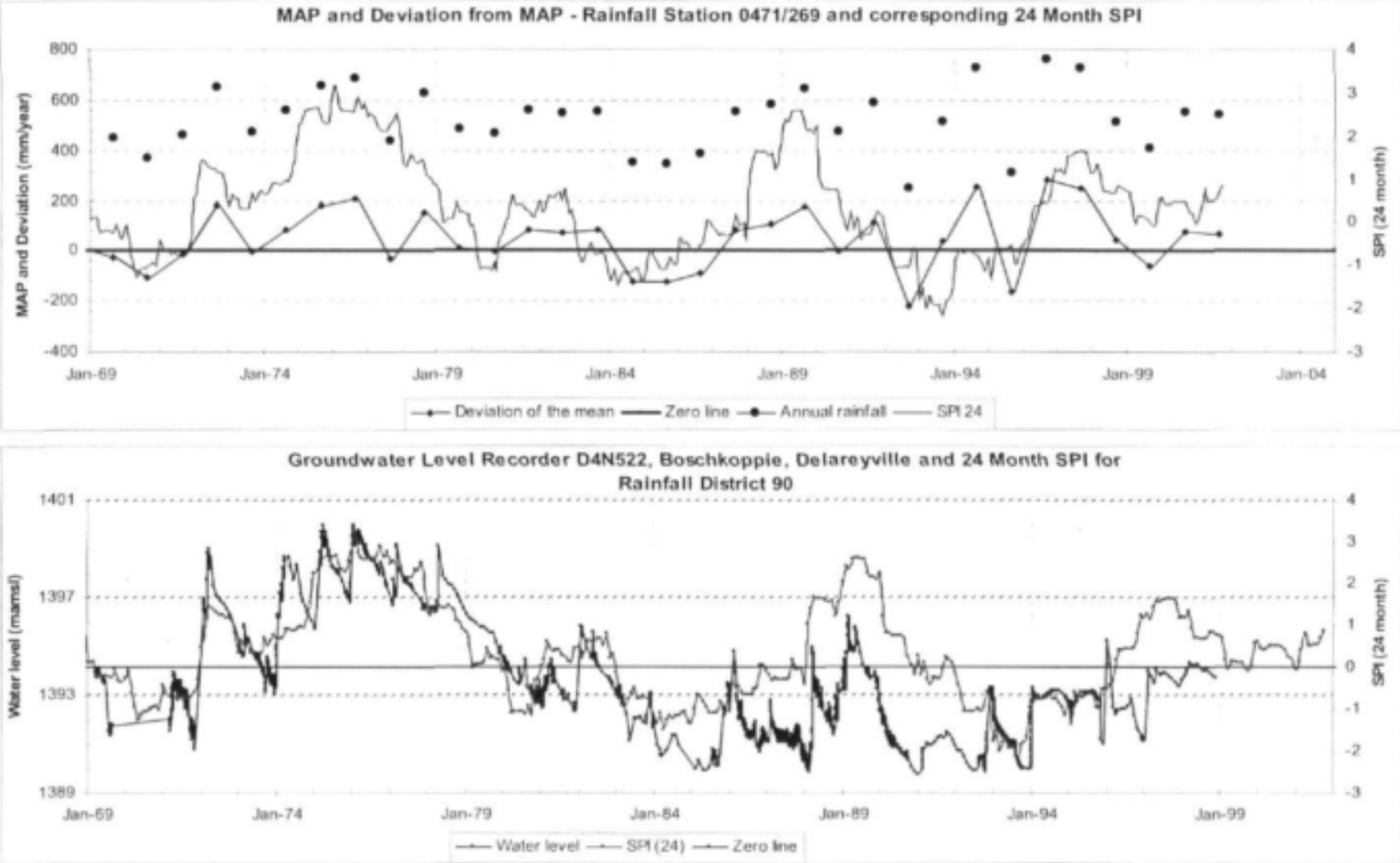


Figure 29: Groundwater level response at recording station D4N522 (borehole 2625AD00001) on the farm Boschkoppie, Delareyville district using the rainfall record of Rainfall District 90.

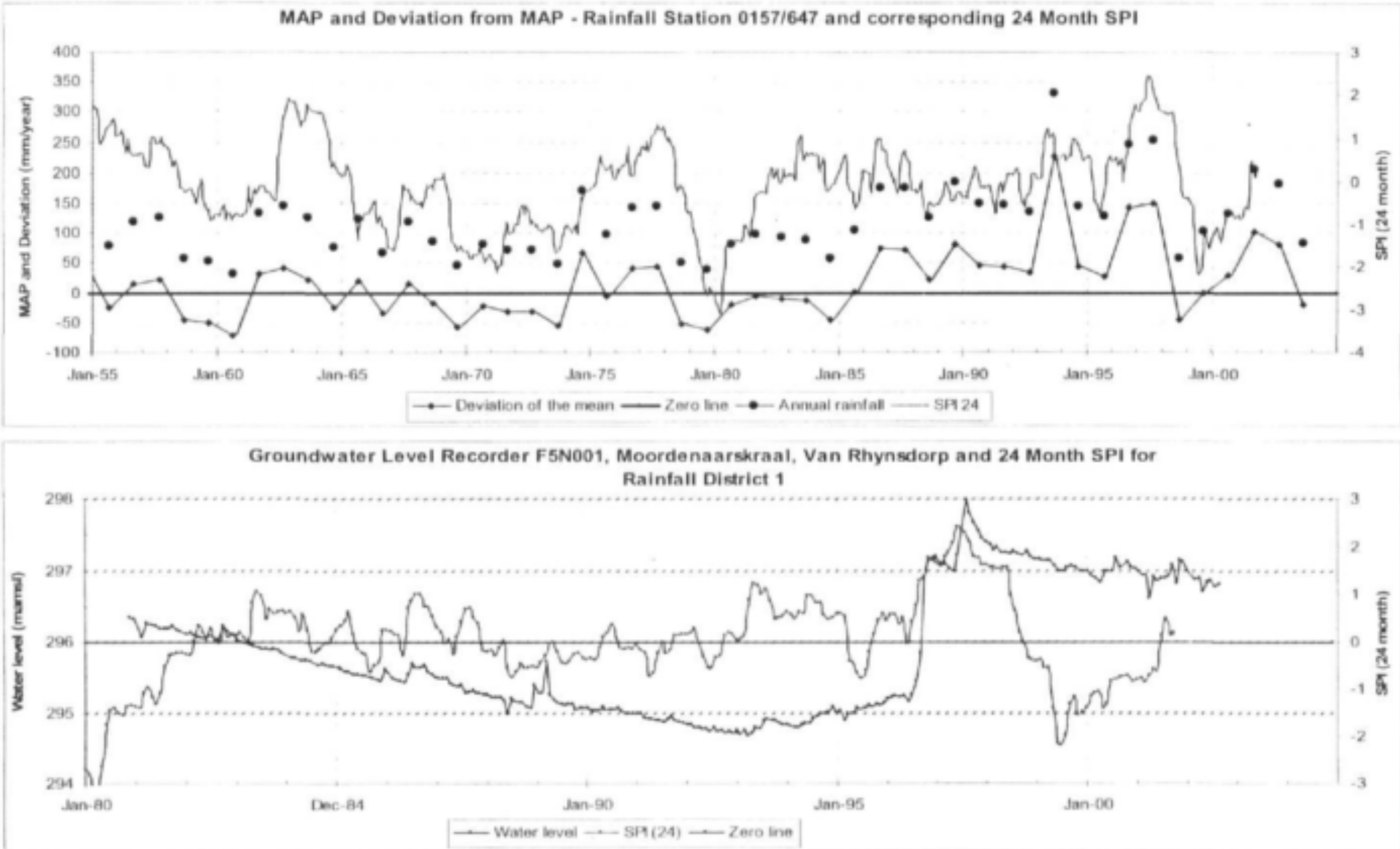


Figure 30: Groundwater level response at recording station F5N001 (borehole 3018CC00056) on the farm Moordenaarskraal, Van Rhynsdorp district using the rainfall record of Rainfall District 1.

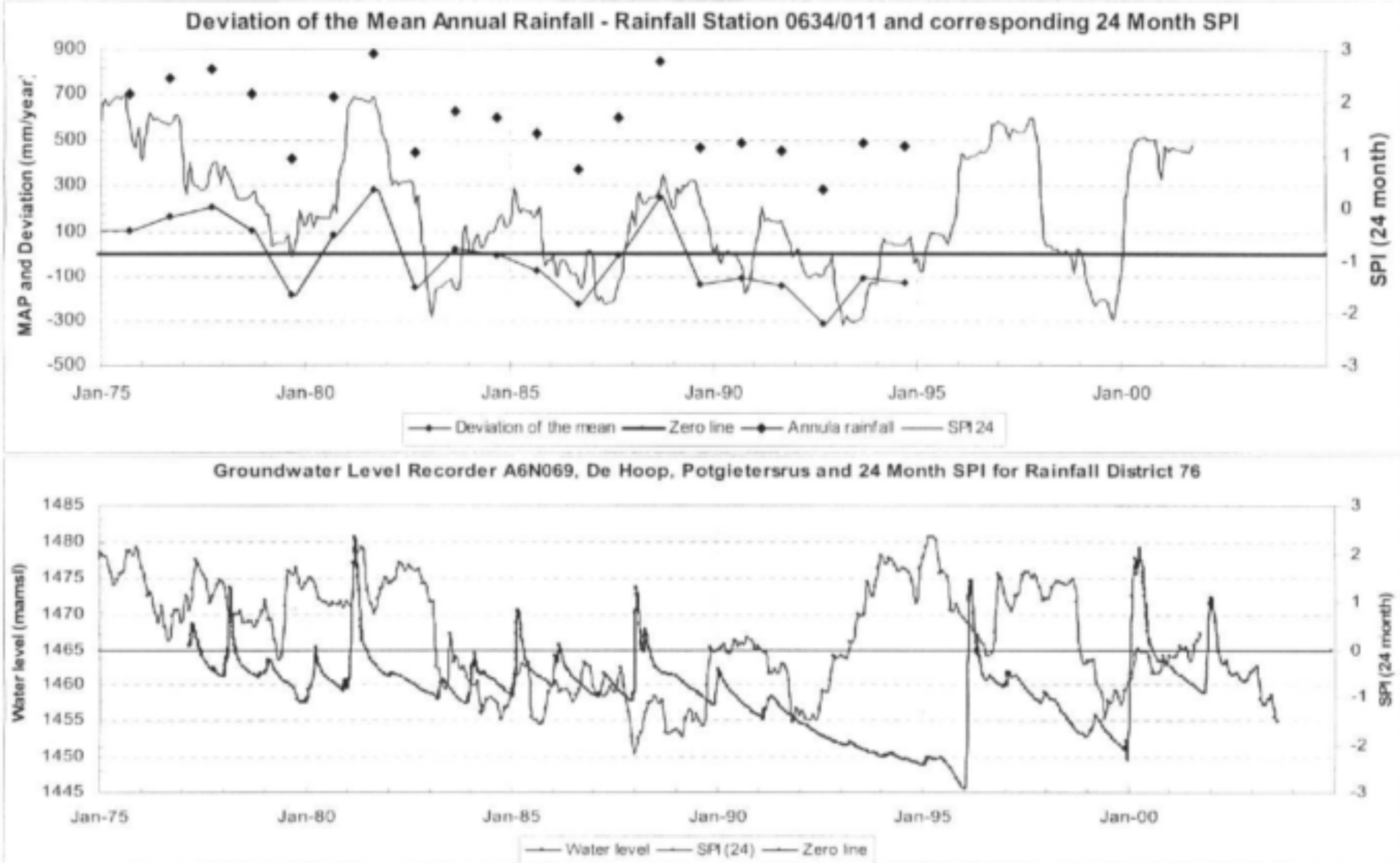


Figure 31: Groundwater level response at recording station A6N069 (borehole 2429AA00010) on the farm De Hoop, Potgietersrus district using the rainfall record of Rainfall District 76.

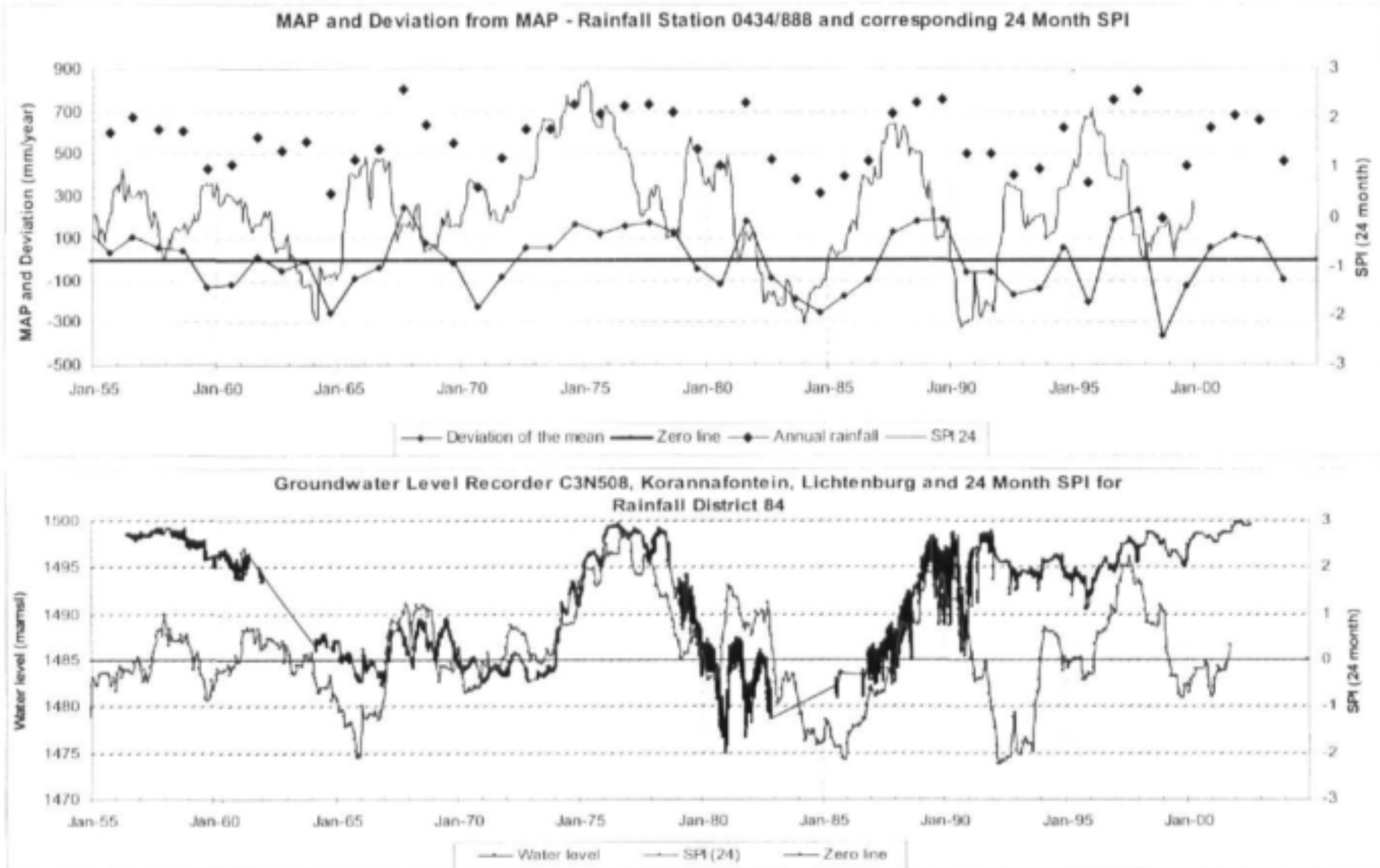
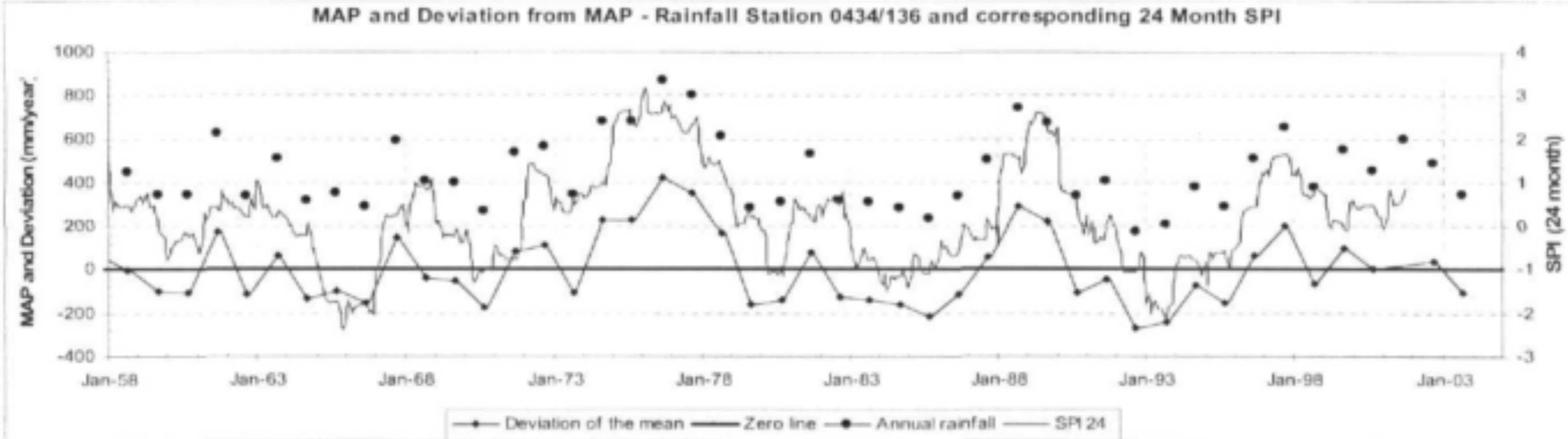


Figure 32: Groundwater level response at recording station C3N508 (borehole 2626CC00006) on the farm Korannafontein, Lichtenburg district using the rainfall record of Rainfall District 84.



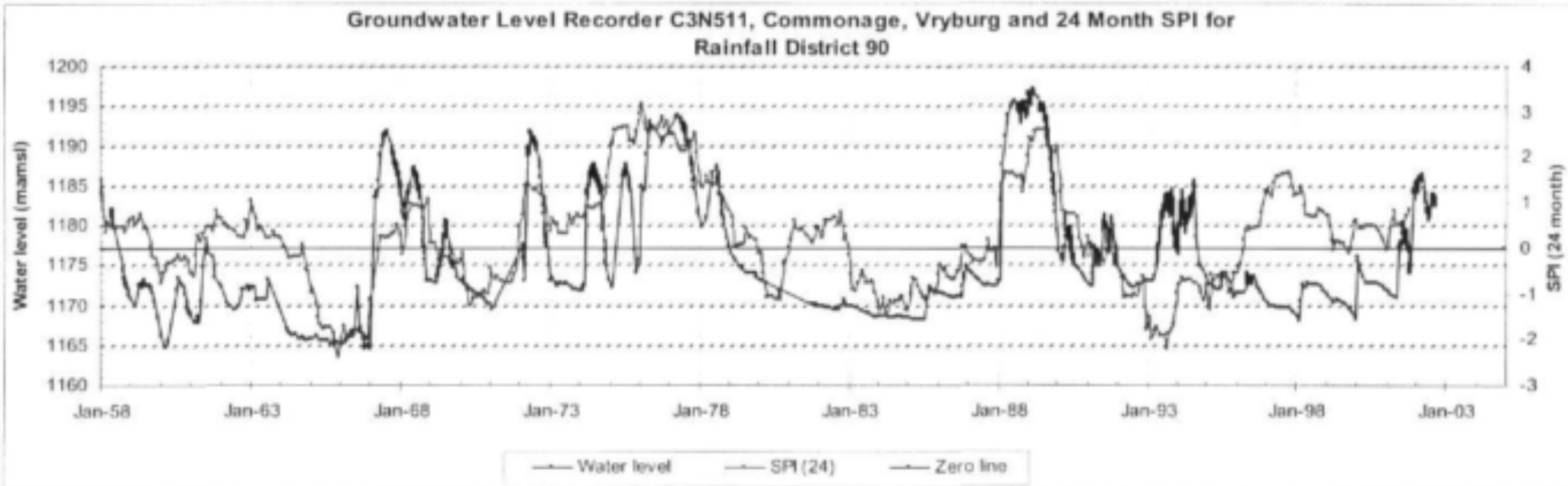


Figure 33: Groundwater level response at recording station C3N511 (borehole 2624DC00032) on the farm Commonage, Vryburg district using the rainfall record of Rainfall District 90.

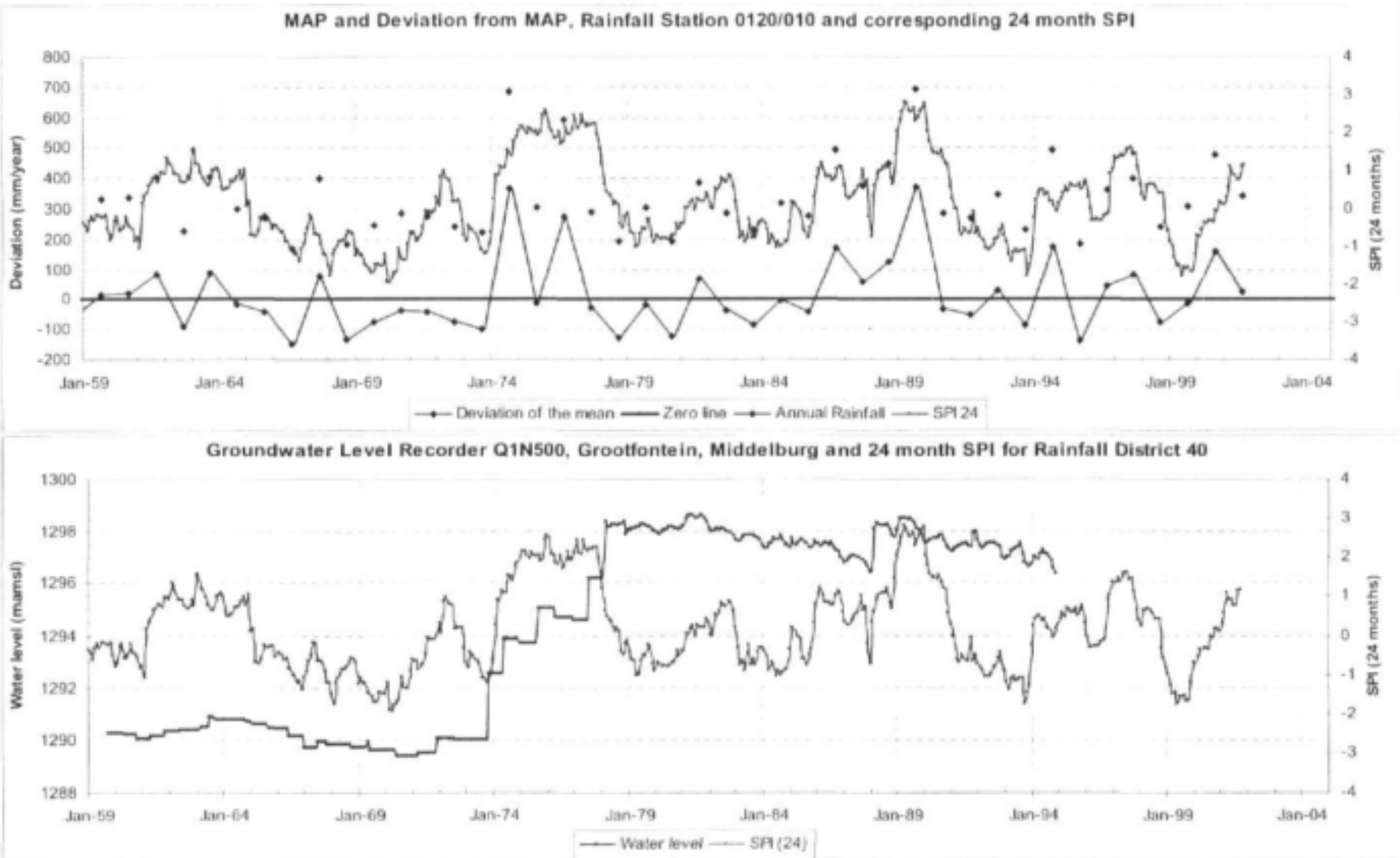
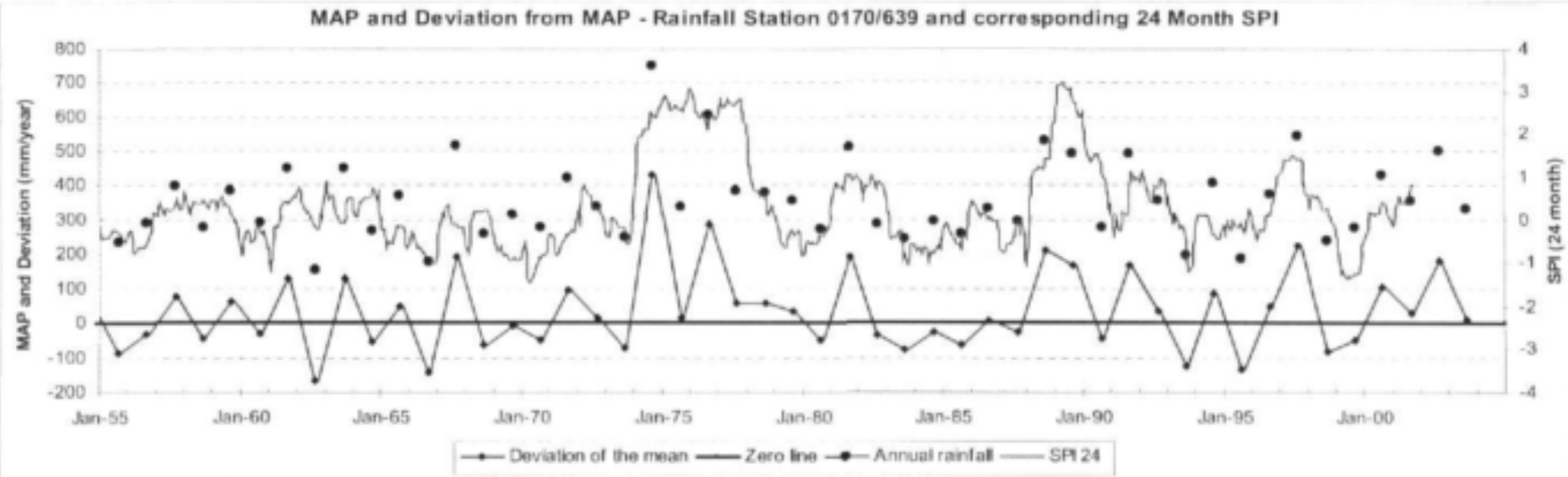


Figure 34: Groundwater level response at recording station Q1N500 (borehole 3125CA00057) on the farm Grootfontein, Middelburg district using the rainfall record of Rainfall District 40.



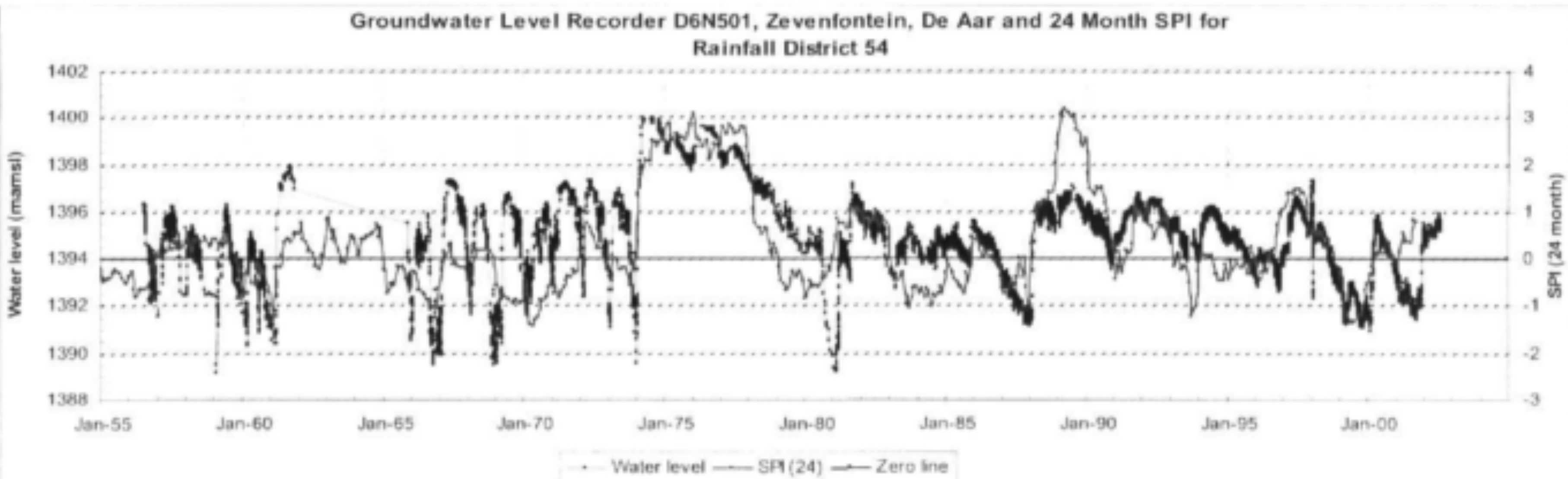


Figure 35: Groundwater level response at recording station D6N501 (borehole 3024CB00067) on the farm Zevenfontein, De Aar district using the rainfall record of Rainfall District 54.

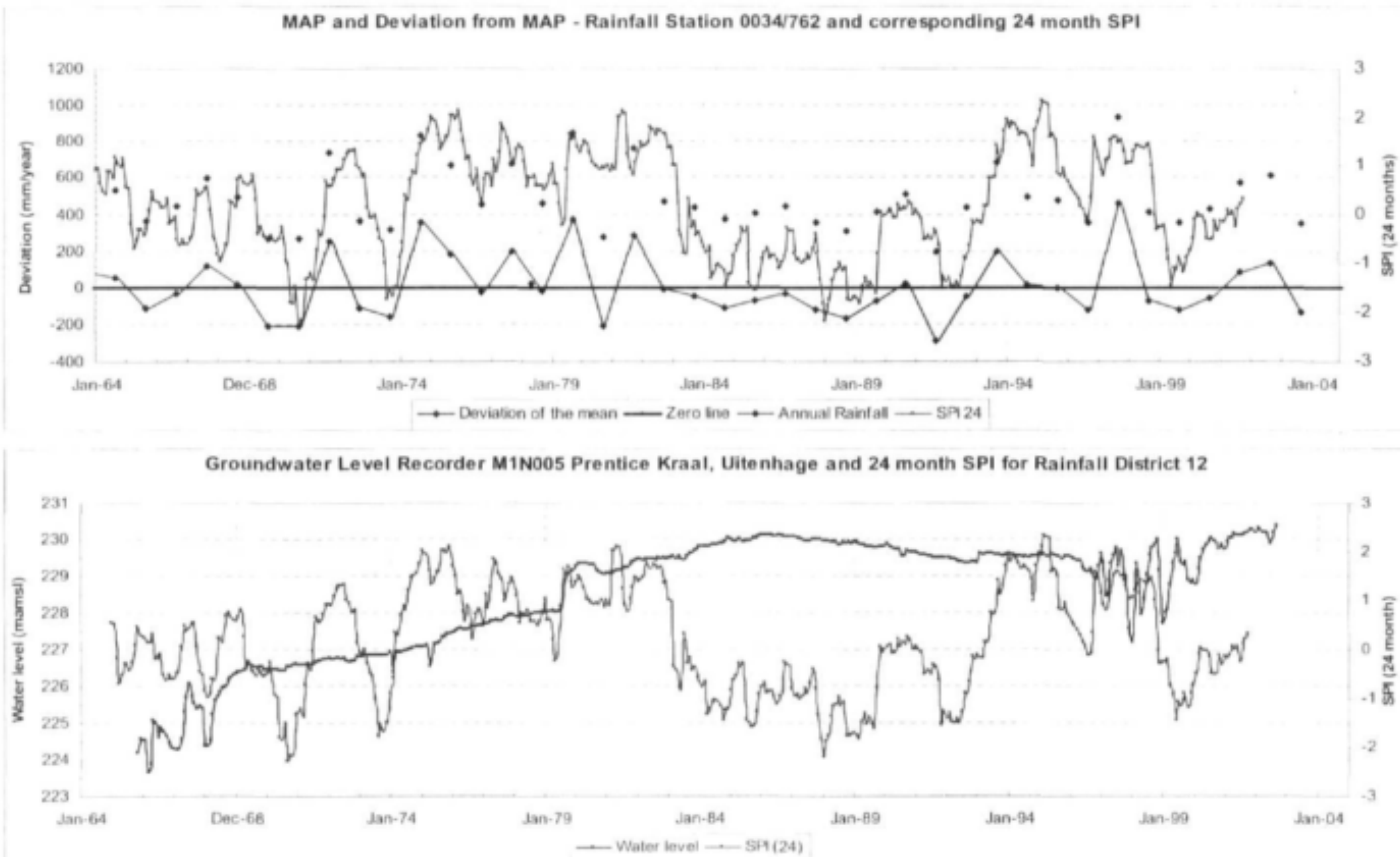


Figure 36: Groundwater level response at recording station M1N005 (borehole 3325CB00002) on the farm Prentice Kraal, Uitenhage district using the rainfall record of Rainfall District 12.

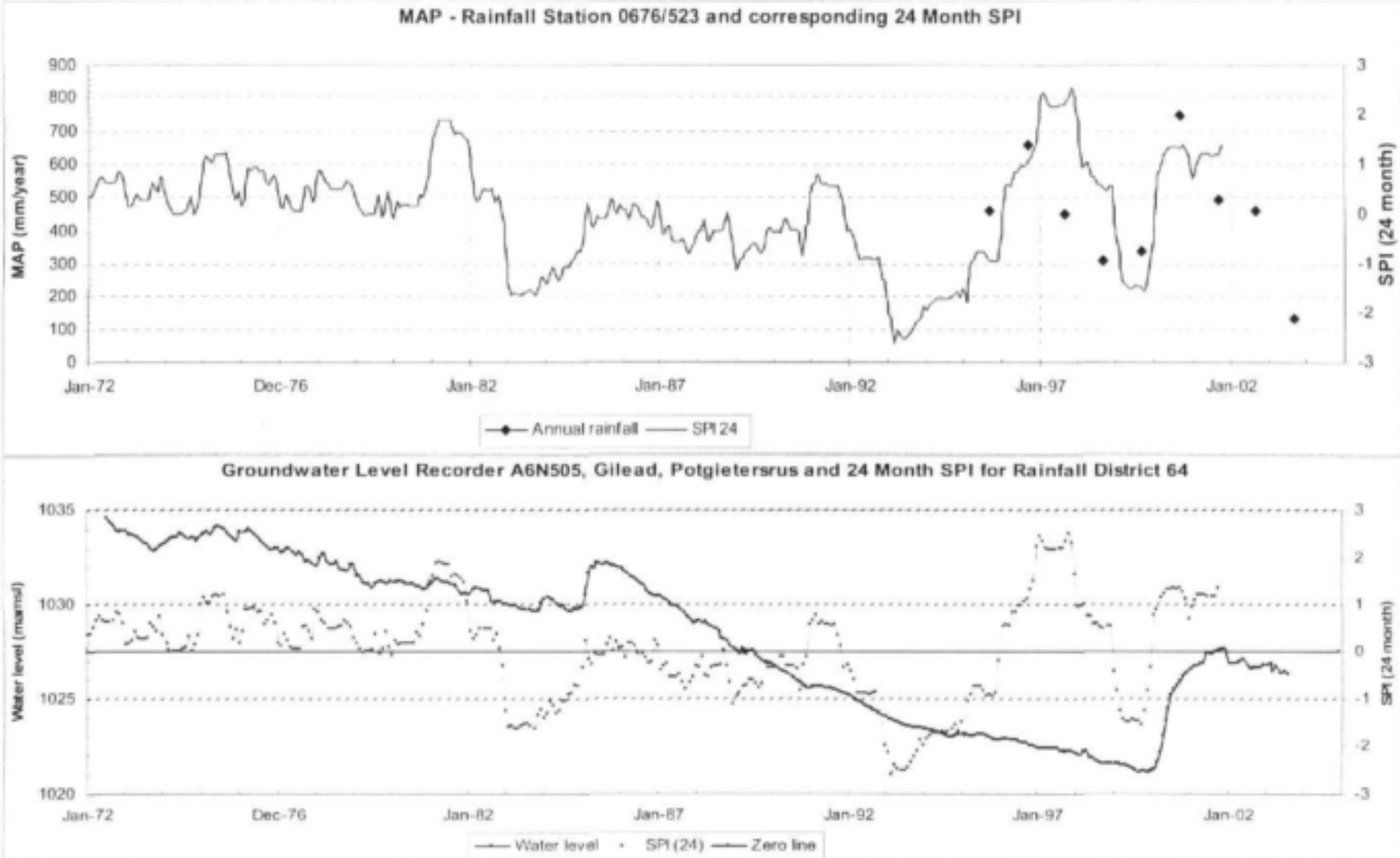


Figure 37: Groundwater level response at recording station A6N505 (borehole 2328DB00002) on the farm at Gilead, Potgietersrus District using the rainfall record of Rainfall District 64.

***Figures 34, 36 and 37**: Groundwater level recorders Q1N500 Grootfontein, Middelburg District; M1N005 Prentice Kraal, Uitenhage District, and A6N505 Gilead, Potgietersrus District*

In all three these records there is some correlation, but generally it is poor. The reason for the poor correlation is not apparent. In the case of recorder M1N500 (**Figure 36**), the water level response represents that of the Uitenhage Artesian aquifer. In this particular case the recharge area may be outside that represented by the rainfall recording station and resulting in a poor correlation. Another possible reason for the constant increase in water level from about 1966 to 1988 may be the linked to the fact that the area has been declared an Underground Water Control Area during the early 1960s.

In the case of recorder A6N505 (**Figure 37**) some correlation can be seen until the mid 1980s, but the high rainfall period during the mid 1990s, and shown by the high SPI values for this period (at times the SPI>2), are not at all reflected in the water level record.

7.4 Recharge index

Although not specified as a specific aim of this research, some thoughts on whether the correlation of water level information with climatic data can assist in determining the amount or degree of recharge to groundwater, are included. The original title of the project implies that the relation between long-term water level response and recharge will also be addressed. A first attempt is therefore made here to design a "recharge index" similar to that of the SPI, and derived from the SPI values, water level response and climatic indicators. No attempt was made at this stage to do this in a quantitative manner as this is beyond the scope of the project, but at least a qualitative index or guideline how to derive such an index is presented for discussion.

During the design of the proposed "Recharge Index" it became apparent that only a generic index can be developed that specifies the "rules" or conditions that apply while developing a more definitive index for a particular region or district. Recharge depends on the complex interaction between a number of factors: geological and hydrogeological conditions, rainfall (type, intensity, duration), other climatic conditions (wind, evaporation), soil and ground surface conditions, vegetation (density and moisture demand), etc. Using water level fluctuations as in indication of recharge, could result in a measure of the "effective recharge". It is an accepted fact that groundwater recharge varies across the country due to spatial variation in the above-mentioned factors. Hopefully the development of a "Recharge Index" using the SPI approach will combine the effect of a number of these variables and reduce the uncertainty in recharge estimates. In the descriptions that follow, recharge is defined as equivalent to an increase in water level. It is realized that this is an over simplified view of recharge, but it is seen to be an appropriate definition for this purpose.

Some of the factors to be taken into account in developing the SPI based "Recharge Index"

- The value and duration of an SPI anomaly. Based on the information presented it appears that the SPI value has to be at least positive in order to result in groundwater recharge. In many cases it would appear that the SPI value has to be in excess of +2 to cause recharge.
- Together with a period of positive SPI values, water levels have to show and increasing trend for a period generally at least equivalent in duration to that of the SPI anomaly.

- The rate, duration and intensity of water level increase.
- The ratio between the SPI anomaly and the relative rise in water level.
- Annual rainfall above the long term MAP.

A suggested way of rating the groundwater recharge is presented below. It is acknowledged that the proposed methodology is very subjective and that a considerable amount of additional work needs to be done on this, especially to make it more quantitative. It also needs to be transformed into a computer routine to calculate a continuous recharge index.

Each of these factors has been allocated a weight and a matrix was then drawn up to assign a relative rate of recharge based on the water level and SPI records. The proposed methodology to follow is presented in **Table 8** and in the text following the table.

Table 8: Criteria for calculating a SPI based "Recharge Index".

Rating Criteria	Weight allocated
1. SPI value	
2. Duration of anomalous SPI value	
3. Water level response	
4. Duration of WL increase	
5. Ratio of increase relative to total (maximum) fluctuations	
6. Excess (over long term average) annual rainfall	
Cumulative weight	
Recharge rating	

Weighting criteria:

1. SPI value

SPI Value:	>2	Weight = 5
SPI Value:	>1 but <2	Weight = 4
SPI Value:	>-1 to <1	Weight = 3
SPI Value:	>-2> but <-1	Weight = 2
SPI Value:	<-2	Weight = 1

2. Duration of SPI value

Duration > 5 years	Weight = 3
Duration 2-5 years	Weight = 2
Duration < 2 years	Weight = 1

3. Water level response:

	Increasing WL
Increasing	Weight = 3
Constant	Weight = 2
Decreasing	Weight = 1

4. Duration of WL increase:

	Increasing WL	*Decreasing WL*
More than 5 years	Weight = 5	Weight = -5
Between 3 and 5 years	Weight = 3	Weight = -3
One year or less	Weight = 1	Weight = -1

5.	Ratio of WL increase as a % of total fluctuation	*Decreasing WL*	*Increasing WL*
	More than 50%	Weight = 5	Weight = -5
	Between 25% and 50%	Weight = 3	Weight = -3
	Less than 25%	Weight = 1	Weight = -1
6.	Excess rainfall as a % of MAP	*Above MAP*	*Below MAP*
	More than 50%	Weight = 5	Weight = -5
	Between 25% and 50%	Weight = 5	Weight = -3
	Below 25%	Weight = 5	Weight = -1

Maximum possible weight: 26
Minimum possible weight: -4

Recharge categories:	High recharge rate:	Cumulative weight	> 18
	Moderate recharge rate	Cumulative weight:	12-18
	Low recharge rate:	Cumulative weight:	5-12
	No recharge:	Cumulative weigh:	<5

To test the proposed routine the time period between 1970 and 1992 of the SPI and water level time series for groundwater level monitoring station at Carolusberg, De Aar has been selected (Figure 27).
This period was divided into three sections: 1970-1978; 1978-1986 and 1986-1992 (**Table 9**) and the methodology proposed in **Table 8** was then followed. The results are shown in **Table 9**.

Table 9: Recharge index calculations for sections of the water level record of D6N500

Rating Criteria	**Weight allocated**		
	1973-1978	1978-1986	1986-1992
1. SPI value	5	3	4
2. Duration of anomalous SPI value	2	3	1
3. Water level response	3	2	3
4. Duration of WL increase/decrease	2	-5	3
5. Ratio of increase/decrease relative to total (maximum) WL fluctuations	5	-5	5
6. Max. Excess/Shortfall (over long term average) annual rainfall	5	3	5
Cumulative weight	22	1	21
Recharge rating	High recharge	No recharge	High recharge

8. CONCLUSIONS

The literature survey to study the climatic conditions since 200 000 years BP revealed that significant changes in temperature and rainfall have prevailed over long periods and that these were of a cyclic nature and of variable duration. These periods of alternating wet and dry cycles range from approximately 23 000 years to the well studied and documented 11 year cycle. These alternating cycles of wet and dry conditions can be summarised as:

- an approximately 23 000 year cycle of major wet and dry periods during the last approximate 200 000 years (Partridge, 1999);
- a possible 400 – 500 year "cold/warm" or "wet/dry" cycle (this report);
- an ~120 years cycle;
- an ~18 year cycle (Schumann and Thompson,1934; Hofmeyr and Schulze, 1963; Tyson, 1980; Ngara *et al.*, 1983; Dyer, 1976, Currie, 1993; Alexander, 1995, 2002);
- an 11 year cycle (Tyson, 1980; Currie, 1993);
- a 3.5 year cycle (Tyson, 1980); and
- a 2.3 year cycle (Tyson, 1980).

In terms of drought cycles and the potential impact on groundwater levels, the 18 and 11-year cycles are perhaps of most significance.

Predictions made on future world climatic conditions using complex modeling techniques with a resolution of about 250km x 250 km (IPCC, 2001), suggest a changing climate over the next centuries that is, when compared to what is documented in the geological history, relatively minor. The available documented records (geological and others) indicate that much larger variations in climate have occurred and that these have not been influenced by human activity. A similar viewpoint was also expressed by Prof W R J Alexander in an article in The Water Wheel (Alexander, 2004). Kokot (1948) came to a similar conclusion after an extensive investigation in the mid 1940s. In his report he formulated one of his conclusions very diplomatically by saying "... *the climate of any region is by no means stable. Even if we do not know why it changes all the evidence points to the fact that it has in the past revealed many changes and there is no reason to believe that such changes can no longer take place. Some changes may be so slow that no appreciable effect can be observed in the course of a few hundred years, other changes may be relatively rapid, particularly those caused by changes in the sun; but of this we have at present very little knowledge.*"

A large number of groundwater level records covering lengths of time and kept by the Department of Water Affairs and Forestry, were studied. Although the present study has not investigated this issue in any great detail, it has to be concluded that when viewed from a geological perspective, our relatively short documented record of climatic conditions in general, and rainfall and especially groundwater level in particular, no conclusive statement can be made regarding changing geohydrological conditions as a result of changing climatic or hydrological conditions. The South African groundwater level records cover a too short time period to make any conclusive statements whether a steady and long term decline in our groundwater levels is present or not.

One of the aims of the project was to determine whether the apparently long-term declining trends observed in some of the South African water level datasets is indicative of a current and or longer drought cycle(s), or whether other factors are contributing to this observed trend. It is generally accepted that there is a relation between water level fluctuations and recharge. The numerous techniques developed in the past in this field are a proof of this. No evidence was, however, found of continuous declining trends in the studied datasets; at least for the approximately 40 year period for which information on water levels is available in South Africa. Periods of up to 20 years of declining groundwater levels are not uncommon in South African datasets, and the declining trends in all cases investigated are terminated by recharge events from either a single large recharge event as a result of a period of high rainfall, or a series of recharge events over a relatively short period of time. In all cases studied these recharge events result in groundwater levels to return to the original reference level, or in some instances, even higher levels. Smaller recharge events superimposed on the longer term declining trend can be seen on most of the water level records studied.

A further aim of the project was to investigate methods that can be used to correlate groundwater level time series with rainfall and climatic cycles. The possible correlation between a relatively new development in drought prediction technology, referred to as the Standardized Precipitation Index or SPI in short (McKee *et al.*, 1993) was investigated during this project. The SPI has been proven in the United States and elsewhere in the world to be a reliable tool for the analysis of drought, regional drought patterns and for monitoring drought conditions. The application of the SPI technique in the study of the impact of drought on groundwater resources as was done in this project, is as far as could be ascertained from the literature, unique. As such there are no proven methodologies developed yet according to which geohydrological information should be handled when correlated with SPI values in order to obtain the most benefit from the analysis.

What this limited study has shown is that correlations between SPI values and groundwater level fluctuations are present in South African data sets. Correlations were restricted to visual inspection of the degree of correlation and no further statistical analysis of any of the datasets and the correlations observed, was done. The quality or degree of correlation varies. Examples are presented where excellent correlations exist, but some examples of poor correlations have also been recorded. It is clear that the reasons for correlation, whether these are good or poor, is not yet well understood and warrants further investigation. It was shown that only groundwater level data that are not impacted upon by external forces should be used when correlating SPI values and water level fluctuations. A further uncertainty that could further impact on this correlation is the position of the rainfall recording station relative to the position of the monitoring borehole. The approach adopted in this study was to use rainfall information averaged over the SAWS rainfall district in which the monitoring borehole is located. The rational for this approach was to exclude the site-specific rainfall events recorded by a specific rainfall recording station, usually the one closest to the monitoring borehole. As very little information on the boreholes and aquifers (water strike depths, construction, confined or unconfined, etc.) is available, it could not be accepted that the recharge to the aquifer necessarily is caused by rainfall in close proximity to the monitoring borehole and therefore, at least as a first attempt in the correlation study, this approach is believed to be warranted.

A first attempt in developing a "Recharge Index" derived from SPI data is presented here. Although the concepts that have been formulated and included in the methodology are subjective and may seem to be simplistic, it is believed that the development of such an index has merit and should be investigated further. The method on its own may not provide the required quantitative assessment of groundwater recharge, but together with other methods available for the estimation of aquifer recharge may add the required information to provide more quantitative answers that can be to the benefit of the water resource planners in future. It is generally accepted that there is a relation between water level fluctuations and recharge. The numerous techniques developed in the past in this field are a proof of this. The results obtained during this project, have confirmed that the SPI methodology can also make a valuable contribution to this still challenging field.

There are however, still many aspects that may impact on the quality of the correlations and these need further analysis. It may also be used for groundwater drought prediction especially in areas where low yielding aquifers are used as the only source of water, for example in the case of rural communities in the lower rainfall areas of the country (sometimes referred to as sole source aquifers).

9. RECOMMENDATIONS AND PROPOSED FUTURE RESEARCH

It is recommended that a detailed analysis of the nature of groundwater level time series should be done to categorize and explain the wide variety of response patterns to climatic conditions and other aspects that impact on the different responses observed in the currently available records. The possible impact of non-climatic conditions on the water level record is regarded as very important should be removed from water level datasets or at least accommodated prior to the formulation of correlations between water levels and climatic conditions.

The regional office of the Department of Water Affairs and Forestry in Limpopo Province is considering the closing down of selected groundwater level monitoring stations following an investigation aimed at the optimization of the monitoring programme (del Rosario *et al.*, 2005). Some of those boreholes selected include ones with a very long (30+ years) record. An appeal is made that monitoring stations only be closed down after careful consideration of all aspects and taking into account the benefit of having real long-term groundwater level records. Although it is acknowledged that the costs involved to monitor water levels in remote areas are high, modern technology is currently available to reduce this cost substantially, despite a relatively high initial capital investment. In the past these records were often kept without a specific purpose and that little has in the past been done with these records. However, it remains a valuable data set that will definitely benefit future research and contribute to the understanding of aquifer behaviour.

It is therefore recommended that the Department reconsider any recommendations made to close down any of the existing monitoring programmes. On the contrary, in view of the expected increased importance of the role of groundwater as a water resource in selected areas, the monitoring network should rather be expanded.

The fundamental theory behind the SPI analysis should also be thoroughly investigated and its possible application to geohydrological datasets should be given a theoretical basis. Some aspects that need further attention include for example

- What rainfall dataset is to be used:
  - One that is the closest to the monitoring borehole;
  - a dataset based on some average of the rainfall in the immediate vicinity;
  - rainfall data for based on the SAWS rainfall districts approach as was used in this study; or
  - another, as yet undefined way of handling the rainfall data.
    - What is the appropriate time period to be used in SPI calculations and how is this to be determined.
    - The impact of unconfined, semi-confined and confined aquifers on water level correlations with SPI values;
    - The impact on the reaction time of different aquifer types and geohydrological variables to rainfall and or recharge events.

It is anticipated that the identification between groundwater level and the SPI can be developed into groundwater recharge estimation technique. It is therefore recommended that the development of a groundwater recharge estimation methodology using groundwater levels, rainfall data and SPI as the basis for the technique be further investigated. This method can initially take the form of a "Recharge Index", where recharge is indicated on a relative scale similar to the Standardized

Precipitation Index. Once a sound calculation methodology for the Recharge Index has been developed, it should be calibrated in order to produce meaningful figures representing the actual recharge that contributes to the groundwater resources, provisionally termed "Quantitative Recharge Index" for particular aquifers. Thereafter the process of calculating the "Quantitative Recharge Index" should be automated and the derived values could be given a reliability rating. Once a reliable methodology has been developed to calculate recharge, a groundwater recharge map of the country should be compiled based on for example the rainfall districts as defined by the Weather Bureau. It is possible that this proposed recharge calculation technique may on its own not provide the required quantitative assessment of groundwater recharge, but when used together with other methods available for recharge estimation (Xu and Beekman, 2003), it may add the required information to provide more quantitative answers that can be to the benefit of the water resource planners in future.

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APPENDIX A

LITERATURE REVIEW ON CLIMATIC CYCLES DURING THE PLEISTOCENE AND HOLOCENE IN SOUTHERN AFRICA

LITERATURE REVIEW

Climatic periods in southern Africa during the Pleistocene and Holocene

There is overwhelming evidence that significant climatic changes occurred throughout the geological history of the earth and more specifically also southern Africa. Dingle *et al.* (1983) published a sea level curve graph showing sea level changes during the Upper Cretaceous and Tertiary (last approximately 100 Ma; **Figure A-1**). Based on geological evidence, these authors concluded that fluctuations from –300m to +200 m relative to the present day sea level occurred. More detailed information on sea level fluctuations during the last 200 000 years is provided by WR Miller in a report on a study of Lake Sibaya in Northern Kwazulu Natal (Miller, 2001). What is interesting is that sea level dropped by more than 130m during a period of approximately 80 ka, starting around 100 ka ago to 18 ka (Last Glacial Maximum) **(Figure A-2)**. What is even more remarkable is that sea level recovered to its present level within about 10 000 years. Since that recovery (8 000 years to present) fluctuations were of the order of 5 m maximum (**Figure A-3**). The oscillations between glacial and interglacial climate conditions over the last three million years have been characterised by a transfer of immense amounts of water between two of the largest reservoirs on Earth – the ice sheets and the oceans. Since the most recent of these oscillations, referred to as the Last Glacial Maximum (LGM) that occurred between 30 000 and 19 000 years ago, approximately 50 million cubic kilometres of ice has melted, causing a rise in sea level of ~130m (Lambeck *et al.*, 2002). Evidence for this rise in sea level is present in the geological record in several places along the Southern African coastline (Dingle *et al.*, 1983; Vogel, 1989; Tyson, 1999; Wright, 2002). The Cenozoic climates of Southern Africa have been subject to global influences; these include orbitally controlled cycles of change as well as a number of stepwise coolings that characterised the last 65 Ma. The evolution of ocean current systems that dictated the distribution of sea surface temperatures around the southern African coastline, coupled with differential uplift of the landmass in the interior, have modified patterns of atmospheric circulation to create the unique climate system of today (Tyson and Partridge, 2000).

According to a recent publication on climate change and its effect on plant diversity in South Africa (NBI, 2001), the earth has experienced at least 20 warm and cool periods over the last half million years resulting in glaciers retreating and advancing and sea levels rising and falling. These changes have been rapid and extreme with mean temperatures fluctuating by more than 2^0C in 50-100 years. According to recently developed computer models for the prediction of climate known as General Circulation Models or GCMs, climatic changes will not occur uniformly across the globe. In general it is predicted that land areas will warm faster than the oceans and polar latitudes faster than temperate latitudes. Over the next 50 years temperatures are predicted to increase over the whole of South Africa with January temperatures increasing most in the central interior and Northern Cape (2.5-4.5^0C) and least at the coast (0.5-1.0^0C) (**Figure A-4**). It is further predicted by these models that summer rainfall will decrease by between 5% in the northern regions and 25% in the Eastern and Southern Cape while parts of the Western Cape may lose a significant portion of its winter rainfall.

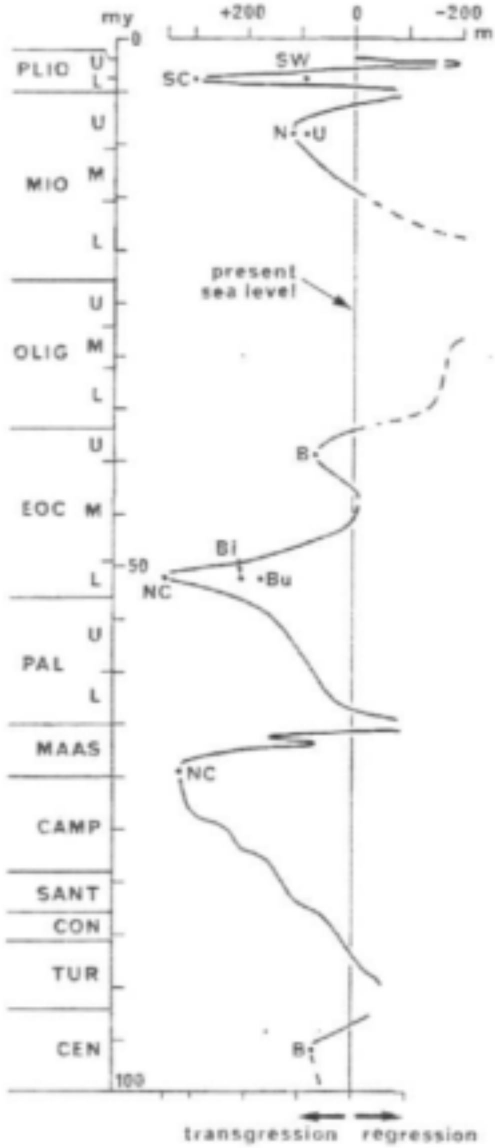

Figure A-1: Upper Cretaceous and Tertiary sea level movements along the southern African coast relative to present day sea level (from: Dingle *et al.*, 1983).

The current worldwide changes in climatic patterns should not be viewed in isolation, but in the context of our existing and increasing knowledge of climatic patterns and cycles during modern geological times observed in southern Africa. One of the greatest impacts on climate during the Cenozoic has been the regional uplift of the landmass that occurred during the Miocene (23Ma – 5 Ma) and most notably also during the Pliocene (5Ma – 1.6 Ma), on the east coast of South Africa (of the order of 900m to 600m) coupled with subsidence in the Pliocene (in the order of 400m) in the Northern Cape (**Figure A-5**; Partridge (1997). Another independent influence on climate was "*... a significant period of global oceanic warming, which began late in the Oligocene (35 Ma – 23 Ma) and persisted through much of the Lower Miocene*" (Tyson and Partridge, 2000).

Partridge (1997; 1999) calculated a relationship between soil texture on granitic bedrock and mean annual rainfall and used this to establish the palaeo-rainfall record of the last 200 000 years at the Pretoria Saltpan (Tswaing Crater). This 200 ka rainfall record is characterised by well defined variations with a period of about 23 000 years (**Figure A-6**). According to this analysis the rainfall varied between about 450mm/a and 900mm/a compared to the current annual average of 630mm/a.

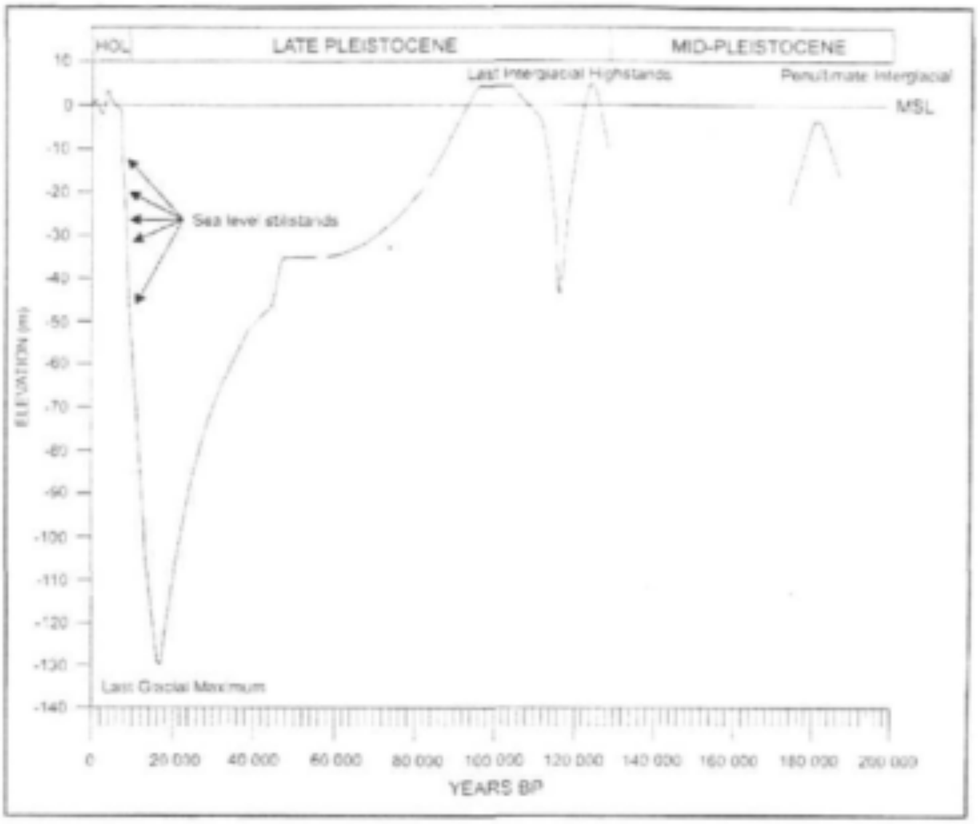

Figure A-2: Quaternary sea level curve for southern Africa (After Ramsay 1995; copied from Miller, 2001)

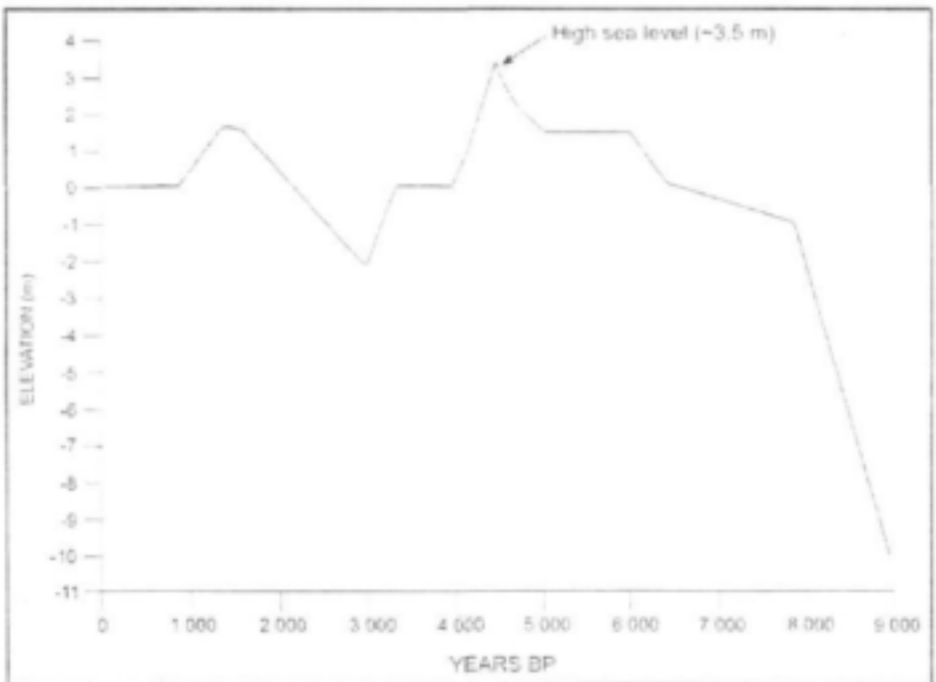

Figure A-3: Holocene sea level curve for southern Africa based on dating of beachrocks (after Ramsay, 1995; copied from Miller, 2001)

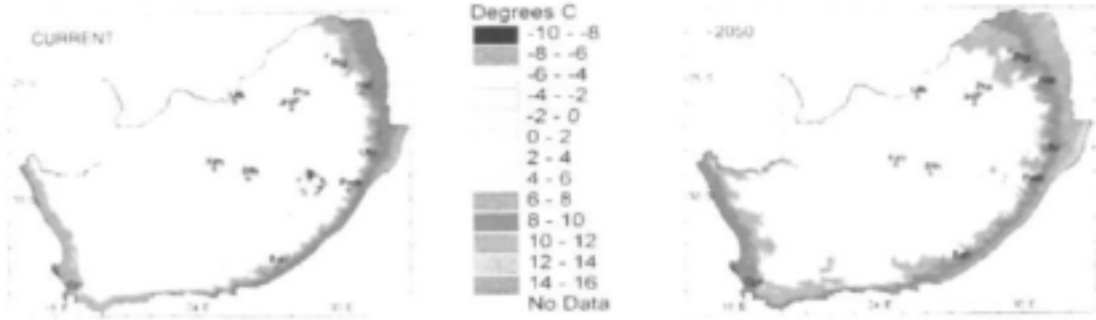

Figure A-4: The current and predicted (2050) impact on minimum July temperatures across South Africa (from National Botanical Institute, 2001).

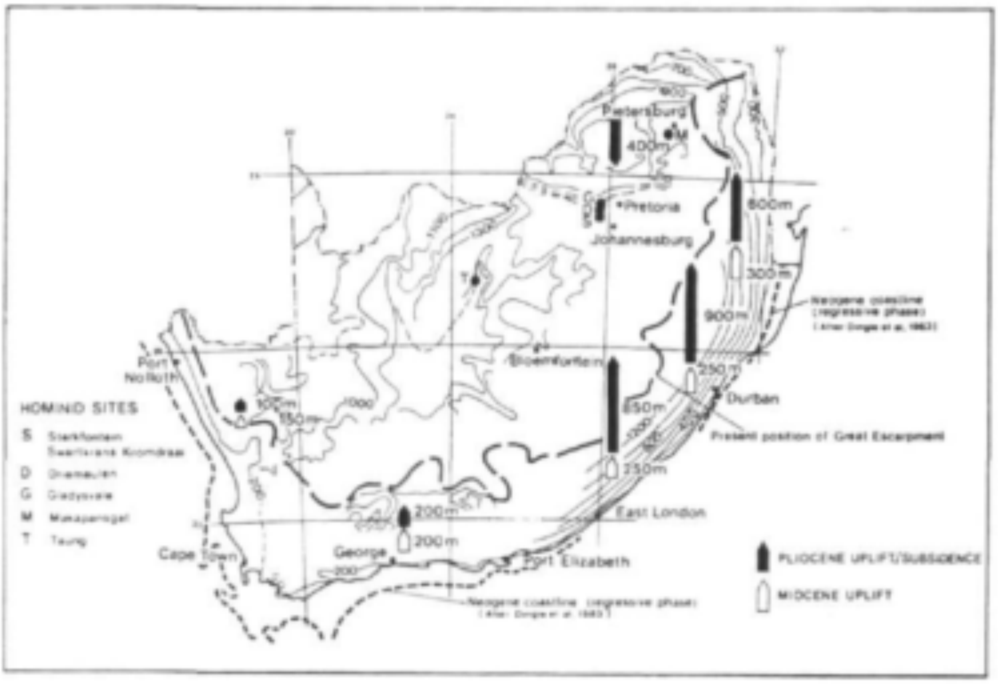

Figure A-5: General contours on the Post-African Miocene erosion surface. Open arrows indicate the uplift during the early Miocene, while solid arrows show the uplift or subsidence during the Pliocene (Partridge, 1997).

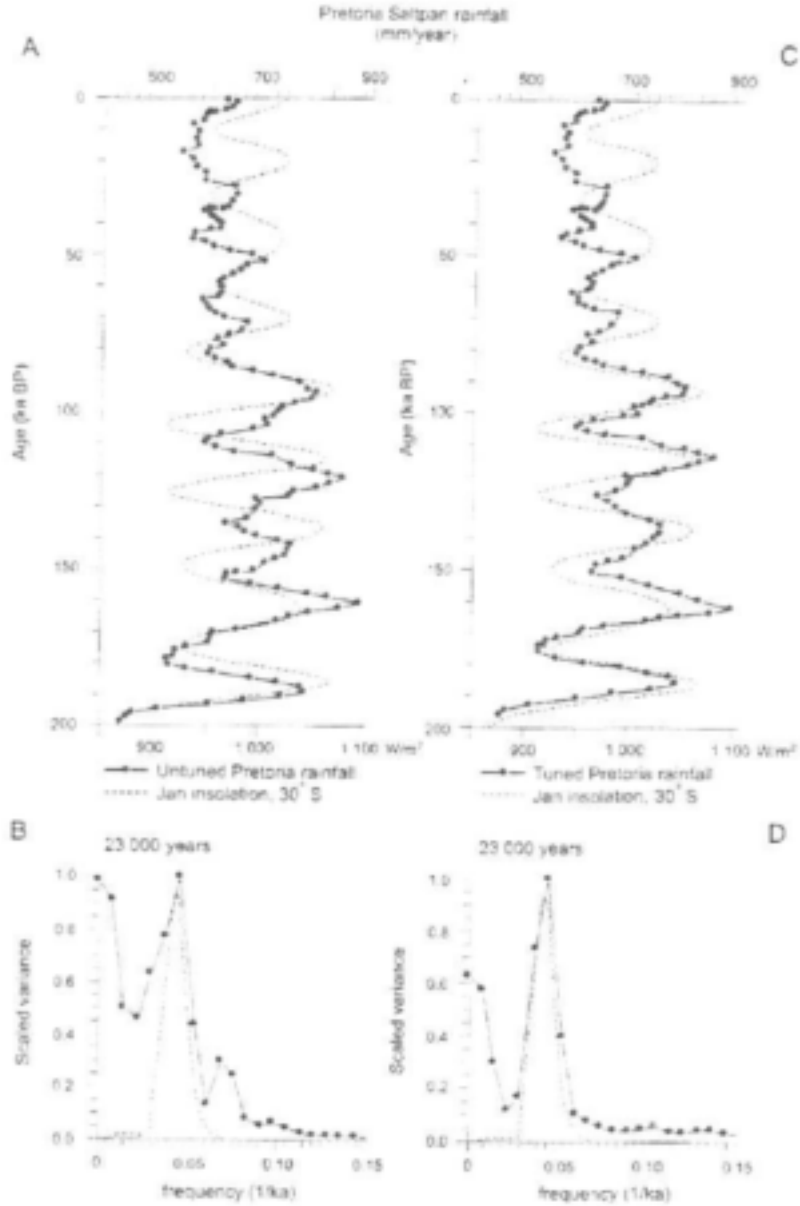

Figure A-6: The Tswaing rainfall time series derived by Partridge (1997, 1999) from soil sediment texture and precipitation relation and Pretoria Saltpan textural and compositional data (from Partridge, 1999).

Partridge *et al.* (1990) summarized the climate for the late Pleistocene and Holocene as follows:

- "**40-30 ka ago:** Temperatures during this interval were apparently low, although not as cold as during the Last Glacial Maximum. All regions, with the possible exception of D (the Eastern region), appear on both biological and geological evidence to have been wetter than today during at least part of this period.
- **30-25 ka ago:** Temperatures evidently remained low in all regions; isotopic measurements at Cango and Uitenhage indicate mean temperatures around 4-5°C lower than present. Except in Namib and Kalahari, which seem to have been almost uniformly wetter than now, drier conditions indicated throughout the sub-continent.
- **25-21 ka ago:** During this interval, all evidence continues to reflect cool conditions, with isotropic temperatures in the southern Cape marginally lower than in the preceding period.

In the southern and eastern parts of the subcontinent the climate apparently remained dry, but there is some evidence for a modest increase in wetness in the Karoo (region B). In the Kalahari the evidence for humid conditions is universal, but the Namib seems to have become significantly drier during this period.

- **21-17 ka ago:** This interval includes the Last Glacial Maximum and, except in the Kalahari, is characterized by widespread dryness. Isotropic temperatures reached their lowest values of about 5° - 6°C lower than present, and the evidence everywhere indicates the presence of cold conditions.
- **17-12 ka ago:** On isotopic evidence from the Vostok core, warming became quite rapid after 16 ka ago; this is not as clearly reflected in the biological evidence from some individual sites, although it is evident at both Wonderkrater and Boomplaas. Warming was everywhere accompanied by a significant increase in wetness to around, or slightly above, the present levels. In the Kalahari the wetter trend of earlier periods was maintained and temperatures were between 5° and 6° lower than present Partridge *et al.* (1990).
- **12-10 ka ago:** The terminal Pleistocene saw continued warming on the evidence of isotopes from both the Uitenhage aquifer and the Vostok ice core. This upward trend is reflected also in the biological indices, which further suggest the occurrence of a discrete warm phase in the Kalahari. Over the eastern and southern parts of the subcontinent humidity appears to have been much as present, but clear drying trends are evident in both the Namib and the Kalahari.
- **The Holocene:** Warming apparently continued in some areas during the earliest part of the Holocene, although there is some evidence for a brief cooling between 8 and 9 ka ago. This trend culminated in a period during which temperatures rose above the present mean (the Holocene Maximum). Biological evidence suggests that, in both the southern and western Cape and Eastern regions (Region A and D respectively), maximum warming occurred between 5 and 8 ka ago. In both these regions, the preceding interval of the earliest Holocene was apparently significantly wetter than at present; at that time drier conditions seem to have prevailed in both the Kalahari and the Namib. During the 5-8 ka ago temperature maximum the southern Cape and Karoo were, for the most part, drier than at present, but the Kalahari and Eastern region were decidedly wetter during at least the latter part of this period. The Namib seems, however, to have remained dry throughout this interval.

The latter part of the Holocene was evidently characterized by several fluctuations of relatively small amplitude in both temperature and wetness. Isotopic evidence suggests that, over the last 5000 years, temperatures did not depart by more than 2°C from the present mean. Similar small-scale variations in wetness are indicated in all regions, although in the Eastern region conditions between 1 and 2 ka ago seem to have been decidedly wetter than now. In the Namib the climate was generally dry, except for a wetter interval between 3 and 4 ka."

Distinctive spatial palaeoclimatic gradients were present over southern Africa towards the end of the LGM period (Partridge, 1997). Compared to the present day mean, the annual total rainfall over the Kalahari appears to have been approximately 40% lower during the period 21 000 – 18 000 BP, while temperatures were also 5-6°C during this period (Heaton *et al.*, 1986; Talma and Vogel, 1992, Stute and Talma, 1998). This was followed by rapid warming after 15 000 BP, cooling around 11 000 BP, and then again a general rise in temperatures over most of the subcontinent (Tyson and Partridge, 2000). Between 7 000 and 4 500 BP temperatures were 2°C higher than present.

Considerable regional variation in rainfall occurred over the subcontinent during these times. Silt deposits from the Kuiseb Valley in Namibia indicate a dry period that lasted from about 8 300 to 4 200 BP (Vogel, 1989). While the northeastern part of South Africa and southern Zimbabwe experienced lower rainfall, wetter conditions were experienced in the Kalahari. Isotope studies on stalagmites from the Cold Air Cave at Makapansgat Valley, provided a detailed climatic record of the last 6 000 BP (**Figure A-7**). Increasing ‰ $\delta^{18}O$ and $\delta^{13}C$ values represent warmer, wetter conditions, while lower values indicate cooler and drier environments. During the Little Ice Age (~1 300 – 1 850 AD) an increase in the frequency of flood events is evident from tree ring analyses from widely separated sites, and from palaeoflood hydrology of the Orange River (Zawada, 1996), borehole temperature profiles (Jones *et al.*, 1999). Evidence is mounting for a general warmer and wetter period in southern Africa between 1 320 and 880 BP. There is evidence in the palynological, palaeoflood, Cango Cave and Namibian offshore sediment records of a dry spell during the mid fifth century, a cooler period between 0 and 300 BC followed by a warm and wet period during 0-200 AD.

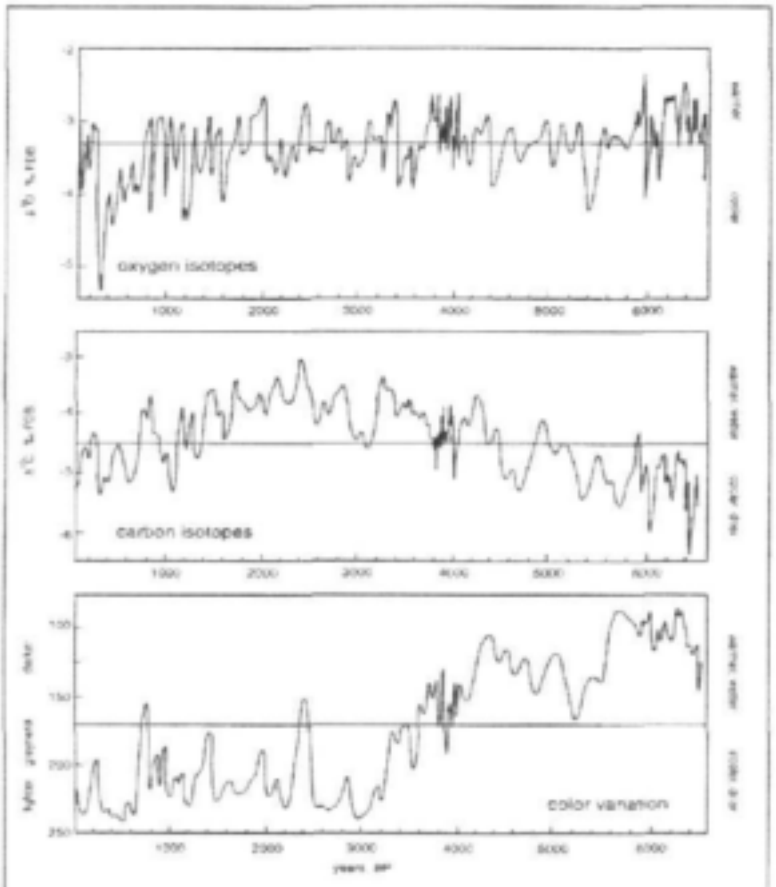

Figure A-7: A 6 600 year record $\delta^{18}O$, $\delta^{13}C$ and color density changes in a stalagmite from the Cold Air Cave in the Makapansgat Valley south west of Pietersburg (after Holmgren *et al.*, 1999, in Partridge and Maud, 2000).

In his 1997 paper Partridge (1997) concluded that precipitation patterns during the Holocene are of considerable interest in the context of responses to possible future global warming as a result of the anthropogenic increase in concentrations of greenhouse gases. Assuming the existence of similar boundary conditions today to those prevailing at around 7 000 yr ago may well be similar to those which could be generated by the ~2°C rise in global mean temperatures, considered probable by some modellers over the next 50-60 years (NBI, 2001). This would have serious implications for maize production in the sub-humid northeastern interior of South Africa and parts of Zimbabwe. The evidence to date suggests that a rise in temperature in the winter rainfall region tends to bring with it an increase in summer rainfall. Thus, while the mountains of the Western Cape may enjoy some increase in orographic precipitation, warming could conceivably result in a partial loss of the winter rainfall belt with negative impacts on the production of wheat, wine and deciduous fruits of this agriculturally important region.

The climatic history over the last 200 ka as described and recorded by various authors is summarised in **Table A-1**. For the period between 200 ka and 40 ka the model developed by Partridge indicating a 23 ka oscillation period between wet and dry cycles has been used. It would also appear, although speculative, that another long-term "wet/dry or "cold/warm" cycle of around 400-500 years may have been present in the Holocene (**Table A-2**).

Climatic variations during the last approximately 200 years

Several authors have published information relating to the climatic conditions in southern Africa over the last two centuries. These include Tyson *et al.*, 2002; Muller and Tyson, 1988; Tyson, 1980; Currie, 1993; Richard *et al.*, 2001; Tyson and Lindsay, 1992; Vogel, J.C., 1989, 1995; Huffman, 1996; Vogel and Fuls, 1999; Tyson and Partridge (2000); Cockcroft *et al.*, 1987; Nash and Endfield (2002) and others.

Vogel, C.H. (1989) used missionary diaries, letters, newspapers, official documents and bank archival material to obtain information of the climatic conditions in the Cape Province since the early 1800s. He came to the following conclusions:

- Notably wet periods span the years 1822-1823, 1831-1832, 1844-1848 1869-1871 and 1885-1900;
- notably dry of periods of below-normal rainfall include the years 1820-1822, 1824-1929, 1860, 1865, 1877-1885 and 1894-1896;
- areas of the eastern Cape were particularly affected by drought in 1862, 1865, 1877 and in the mid-1890s;
- the documentary derived-chronologies have been corroborated by using available dendrochronological data and meteorological instrumental data; and
- the 1890s were not as consistently wet as had been previously proposed, but rather, good rains were experienced at the outset and close of the decade, offset by sever drought conditions during the middle 1890s.

Vogel, J.C. (1989) also observed that there appeared to be particular associations between phases of the Southern Oscillation and periods of drought and below-normal rainfall in the I19th century. In addition there are indications of an inverse relationship when wet conditions are experienced in the southwestern Cape, the eastern areas are characterised by dry and drought conditions. No distinct periodicity of below- and above-normal rainfall years is discernable from the information presented by Vogel (1989). The information rather indicates that the frequency and type of rainfall event, including below- or above-normal events that prevailed at the Cape during the last century were essentially similar to those prevailing in the area at the present time. Periods of extreme drought were and are often followed by periods of abundant rains.

Table A-1: Climatic conditions and variations over the last 200 ka in southern Africa compiled from various published sources.

Age (kyr)		Region A	Region B	Region C	Region D
		Southern & Western Cape (Current winter rainfall region)	Karoo	Kalahari (incl. Namib sub-region)	Eastern region
PLEISTOCENE	-190 000				Below average annual rainfall
	-190 000 to -180 000				Above average annual rainfall
	-180 000 to -166 000				Below average annual rainfall
	-166 000 to -153 000				Above average annual rainfall
	-153 000 to -140 000				Below average annual rainfall
	-140 000 to -130 000				Above average annual rainfall
	-130 000 to -119 000				Below average annual rainfall
	-119 000 to -108 000				Above average annual rainfall
	-108 000 to -97 000				Below average annual rainfall
	-97 000 to -86 000				Above average annual rainfall
	-86 000 to -75 000				Below average annual rainfall
	-75 000 to -65 000				Above average annual rainfall
	-65 000 to -52 000				Below average annual rainfall
	-52 000 to -40 000				Above average annual rainfall
	-40 000 to -30 000	Temp. low but above that of LGM	Temp. low but above that of LGM	Temp. low but above that of LGM	Temp. low but above that of LGM
		Wet	Wet	Wet	Wet, but less than in Regions A, B and C
	-30 000 to -25 000	Temp low, 4-5°C than present	Temp low, 4-5°C than present	Temp low, 4-5°C than present	Temp low, 4-5°C than present
		Drier period	Drier period	Wet	Drier period
	-25 000 to -21 000	Cool conditions; marginally lower than preceeding period	Cool	Cool	Cool
		Dry	Increase in wetness	Becoming significantly drier	Dry
	-21 000 to -17 000 (includes LGM)	Temp 5-6°C lower than present; evidence of cold conditions			
		Dry	Dry	Wet	Dry
	-17 000 to -12 000	Rapid warming, especially after 16kyrr	Rapid warming, especially after 16kyr	Rapid warming, especially after 16kyr	Rapid warming, especially after 16kyr
		Significant increase in wetness; ~same, or slightly above, present conditions	Significant increase in wetness; ~same, or slightly above, present conditions	Previous wetter trend maintained	Significant increase in wetness; ~same, or slightly above, present conditions
	-12 000 to -10 000	Warming	Warming	Warming, with distinct warm phase in Kalahari	Warming
		Humidity similar to present conditions		Becoming drier	Humidity similar to present conditions

Table A-1 (continued): Climatic conditions and variations over the last 200 ka in southern Africa compiled from various published sources.

	Age	Region A Southern & Western Cape (Current winter rainfall region)	Region B Karoo	Region C Kalahari (incl. Namib sub-region)	Region D Eastern region
HOLOCENE	-10 000 to -8 000	General warming; temps. increased to levels above present mean towards end of period, with a brief cool period between 9-8 kyr	General warming; temps. increased to levels above present mean towards end of period, with a brief cool period between 9-8 kyr	General warming; temps. increased to levels above present mean towards end of period, with a brief cool period between 9-8 kyr	General warming; temps. increased to levels above present mean towards end of period, with a brief cool period between 9-8 kyr
		Significantly wetter than present		Drier conditions prevailed	Significantly wetter than present
	-8 000 to -5 000	Maximum warming between 5 and 8 kyr (Holocene Maximum)	Maximum warming between 5 and 8 kyr (Holocene Maximum)		
		Drier conditions set in	Dryer conditions set in	Wetter conditions, at least in the latter part of the period in Kalahari; Namib remained dry	Significantly wetter than present
	-5 000 to -900	Temperatures fluctuated ~2°C around the present mean	Temperatures fluctuated ~2°C around the present mean	Temperatures fluctuated ~2°C around the present mean	Temperatures fluctuated ~2°C around the present mean
		Small scale fluctuations in wetness	Small scale fluctuations in wetness	Generally dry in the Namib, with wet period between 3-4 kyr	Small scale fluctuations in wetness; wetter interval between 3-4 kyr
	~ -900	Major warm period			
	-800 to -200	Coolest periods within the last three millennia			
	-250 to +600	Warmer period with major warm episodes around 100 years; between 100 and 200 years cooler periods experienced			
	+600 to +900	Generally a variable period of cooling with wet conditions in the Kalahari between 850 and 900 yrs during which cattle farmers established themselves on the fringes of the Kalahari			
	+900 to +1 300				Warming ("Medieval Warm Epoch" of Tyson) in Central Limpopo Valley. By 1290 drier conditions set in as Little Ice Age (LIA) starts. Wetter conditions prevail
	~1300 - 1800 (Little Ice Age)	The Little Ice Age was associated with aridification and increase in the frequency of major flood events. Two major cooler periods during this period: (i) 1300 - 1500, and (ii) 1675 - 1850. Sudden warming between 1500 and 1675. Drier conditions around 1290, especially in the Central Limpopo Valley that contributed to the decline of the Mapungubwe population. Wet conditions in Zimbabwe between 1250 and 1450. Drier conditions in the Kuiseb Valley in Namibia during 1460 to 1640.			

Table A-1 (continued): Climatic conditions and variations over the last 200 ka in southern Africa compiled from various published sources.

Age		Region A	Region B	Region C	Region D
		Southern & Western Cape (Current winter rainfall region)	Karoo	Kalahari (incl. Namib sub-region)	Eastern region
HOLOCENE	1816/17			Major wet period	
	1820-1822	Dry periods of below-normal rainfall			
	1820-1827			Major drought period	Major drought in parts of Eastern Cape
	1822-23	Notably wet periods			
	1824-1829	Dry periods of below-normal rainfall			
	1829-1830		Major wet period areas adjacent to Kalahari	Major wet period	
	1831-1832	Notably wet periods			
	1831-1835			Dry conditions in southern Kalahari	Dry in parts of Eastern cape
	1844-1848	Notably wet periods			
	1844-1851			Drought conditions in entire Kalahari plus adjacent parts of Angola and Zambia	
	1851/1852	Major wet periods in entire Kalahari plus large areas of South Africa			
	1857-1865	Middle and Southern Kalahari plus much of South Africa with wet period at 1863/64			
	1860	Dry periods of below-normal rainfall			
	1863/64			Major wet period in southern Kalahari and parts of Eastern Cape	
	1865	Dry periods of below-normal rainfall			
	1869-1871	Notably wet periods			
	1874/75	Major wet periods in Middle and Southern Kalahari and large parts of southern Africa			
	1876-1878	Dry spell			
	1877-1885	Dry periods of below-normal rainfall in entire Kalahari amd parts of South Africa			
	1885-1900	Notably wet periods			
	1889-1891	Major wet periods in Middle and Southern Kalahari plus large areas of South Africa			
	1894-1896				Dry period of below normal rainfall in Eastern Cape
	1894-1899			Dry periods of below-normal rainfall in entire Kalahari and adjacent parts of South Africa	
	1899/1900			Major wet periods in Middle and Southern nKalahari and adjacent parts of South Africa	
	1974/75	Extremely wet year witin the wet spell of the 1970s			
	1982/83	Extremely dry year witin the dry spell of the 1980s			

Table A-2: Postulated climatic cycles during the Holocene

Period (years)	Length (years)	Climatic condition
-800 to –200	600	Cold (Wet)
-200 to 100	300	Warm (Dry)
100 to 200	100	Cold (Wet)
200 to 600	400	Warm (Dry)
600 to 900	300	Cold (Wet)
900 to 1300	400	Warm (Dry)
1300 to 1800	500	Cold (Wet)
1800 to present	300?	Warm (Dry)?

Archival material from the Council for World Mission (CWM) have been used by Vogel, C.H. (1989) and Nash and Endfield (2002) to reconstruct climate patterns for the Kalahari region of Botswana and South Africa during the nineteenth century. Their findings are summarised in **Table A-3**. Formal meteorological observations and records are available from around the start of the 20h Century. Tyson (1986) analysed the rainfall records and his conclusions for the 20th century information is incorporated into **Table A-3**.

A comparison between the information presented by Vogel, C.H. (1989) and Nash and Endfield (2002) it appears that the major drought periods (most notably in the 1820s, mid- to late-1840s, 1877 to 1875/6 and mid 1890s) occurred over the whole of Botswana and the Cape whilst major wet periods tend to be more restricted to smaller areas.

Extreme weather conditions

Several authors refer to extreme weather, and especially rainfall seasons. From a groundwater perspective these are important, as it is known that during these periods increased recharge occurs. From an analysis done by Cockcroft *et al.*, (1987) and Muller and Tyson, 1986) it appears that when the summer rainfall region becomes drier, the winter region becomes wetter and, most importantly, the winter rainfall over the summer rainfall region tends to increase. Examples from our meteorological records of these phenomena are the following:

- The year 1982/83 was an extremely dry year in the extended dry spell of the 1980s. During 1982/83 the Mediterranean south-west was wetter during the year as a whole than the summer rainfall region of the north-east of South Africa.
- 1974/75 was an extremely wet year in the wet spell of the 1970s. During this season the reverse situation to that of 1982/83 occurred. The winter months (July and August) in the great drought year of 1982/83 were wetter over the north-eastern parts of South Africa than in the extreme wet year. Not only was more cloud recorded, but also a higher number of rain days, more rain per station and more rain per rain day were observed in the area defined by the stations used in the analysis.
- Extreme years from the wet spells of the 1950s and the dry spell of the 1960s yield similar results. An inverse relationship between rainfall over the summer rainfall region and rainfall over the winter rainfall region was again evident from annual rainfall deviation maps. In most cases analyses of cloud and rainfall data showed similar patterns.
- Between 1905 and 1981 the highest space-mean rainfall in any one year was experienced

in 1924/25 (143 per cent of normal); the lowest in 1932/22 (66 per cent of normal). In comparison, during the great drought of 1982/83 the space mean rainfall was 68 per cent of normal. The most persistently wet spell has been that of 1971/72-1980/81 with six consecutive years experiencing above-normal rainfall. Zimbabwe experienced five successive good seasons (Ngara *et al.*, 1983). In general the dry spells have been more persistently dry than the wet spells have been wet. Not only is this relative variability of rainfall greater during above-normal years, but also so is the spatial homogeneity of wet spells. Corresponding data for wet and dry spells defined by calendar year rainfall are presented by Tyson and Dyer (1978) and Tyson (1980).

Table A-3: Major wet and dry phases in the Kalahari during the nineteenth century identified from documentary sources (from Vogel, C.H. (1989) and Nash and Endfield, 2002), and for South Africa in general for the 20th century.

Major wet periods	Major drought periods	Probable regional extent
1816/17		Southern Kalahari*
	1820-1822	Cape. Dry period of below normal rainfall.
	1820-27	Southern Kalahari plus parts of the former Eastern Cape*
1829/1830		Southern Kalahari plus adjacent parts of South Africa*
	1831-35	Southern Kalahari plus parts of the former Eastern Cape*
	1844-51	Entire Kalahari plus adjacent parts of Angola and Zambia*
1851/1852		Entire Kalahari plus large areas of South Africa
	1857-65	Middle and Southern Kalahari plus much of South Africa, with drought punctuated by widespread wetter conditions in 1863/64*
1863/64		Southern Kalahari plus areas of former Eastern Cape
1874/75		Middle and Southern Kalahari plus large areas of South Africa*
	1877-86	Entire Kalahari plus parts of South Africa
1889-91		Middle and Southern Kalahari plus large areas of South Africa*
	1894-99	Entire Kalahari plus large areas of neighbouring South Africa
1899/1900		Middle and Southern Kalahari plus adjacent parts of South Africa*
	1905/06-1915/16	Southern Africa
1916/17-1924/25		Southern Africa
	1925/26-1932/33	Southern Africa
1933/34-1943/44		Southern Africa
	1944/45-1952/53	Southern Africa
1953/54-1961/62		Southern Africa
	1962/63-1970/71	Southern Africa
1971/72-1980/81		Southern Africa
	1982/83-1992/93	Southern Africa
1993/94-2002/3 *		Southern Africa *

Note: * Last part of 2000 was, however, a dry period.

Climatic cycles

Cycles, periodicity or oscillations in the rainfall patterns of southern Africa have over the years have attracted the attention of many researchers and institutions from the early 1900s. These include Nevill (1908), South African Parliament (1914; 1923; 1951), South African Agricultural Union (1912-1914), Barber (1910), Cox (1925), Schumann and Thompson (1934), Kokot (1948), Vorster (1957), Hofmeyr and Schulze (1963); Tyson and Dyer (1975, 1978), Tyson (1980), Currie (1993) and Richard *et al.*, 2001). Articles with titles such as "Is South Africa drying up?" (Barber, 1910), "Periodicity in rainfall" (Cox, 1925), and the more recent ones such as "20th Century droughts in

Southern Africa: Spatial and temporal variability, teleconnections with oceanic and atmospheric conditions" (Richard *et al.*, 2001) it is evident that the subject has been and still is of great interest and importance to the country.

The climate of subtropical southern Africa has been characterised by a high degree of both temporal and spatial variation. Despite much of the variability being random, there are also clearly identifiable real and significant non-random components (Preston Whyte and Tyson 1988). A number of quasi-periodic rainfall oscillations have been reported of which the 18 year period is the most noteworthy (**Figure A-8**, Preston-Whyte and Tyson, 1988; Currie, 1993). A secondary frequency is at 10.5 years (**Figure A-9**) with other smaller amplitudes at 3.5 and 2.3 years (Tyson, 1980). The 10-12 year oscillation is seldom a strong component of the rainfall and its regional effect is confined to the southern Cape. Tyson concludes that the association of the regions affected predominantly, but not exclusively, by specific oscillations and the core areas of the various rainfall regimes of the subcontinent, is close. The 18-year oscillation is the predominant temporal variation ion the summer rainfall region, the 10-12 year oscillation is confined mainly to the all season region and the quasi-biennial oscillation is most clearly observed in the area in which the semi-annual rainfall cycle is most evident. Zucchini and Adamson (1984) concluded from their study of rainfall data that although the 18-year cycle is present in the data, its significance could not be established beyond doubt. Vines (1980) used selective mathematical filters and confirmed the existence and spatial dependence of both 18 and 11-year cycles in South African rainfall data. Oscillations around 18 years have also been confirmed from statistical analysis of data from Zimbabwe (Ngara, 1983;) and Mozambique (Reddy, 1986). Currie (1993) performed spectrum analysis on 59 rain-gauge records and found evidence for two peaks with periods of 18.2 ± 1.4 years and 10.3 ± 0.5 years which confirmed the work done by Tyson and his co-workers in the 1970s.

Alexander (2002) reports that Hutchins already in 1889 reported the presence of an 11-year periodicity in South African rainfall and noted its linkage with the sunspot cycle. He noted that the periodicity rose steeply to a maximum and then fell gradually to a minimum. This observation by Hutchins is also reflected in the observation that long droughts are often broken by the sudden occurrence of a series of exceptionally high river flows. These sudden reversals occurred during the hydrological years beginning October 1912, 1932, 1953, 1972 and 1994. The number of years between these reversals is 20, 21, 19 and 22 years respectively." This concept is schematically shown in **Figure A-10**.

Related evidence for a 18-20 year cycle includes:

- A strong spectral peak at 20-years shown by Hall (1976) in his spectral analysis of a *Popdocarpus* tree ring series for the period 1790 to 1910.
- Analysis of a 376 year tree ring series from a *Widdringtonia cederbergensis* from the Western Cape gave spectral peaks of 18 and 120 years in growth rate (Visagie, 1985). The 18-year period was shown to be stable over a 376-year period.
- An inverse relation between temperature and rainfall with a 16-20 year cycle was demonstrated by Keen (1971).

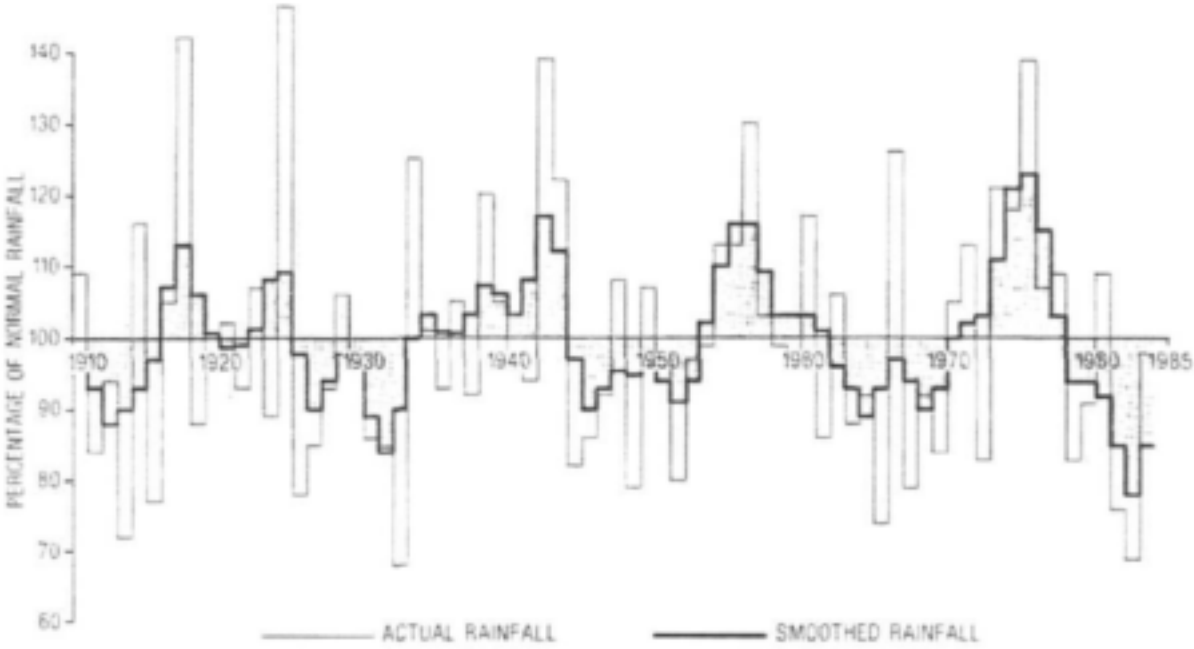

Figure A-8: Averaged rainfall series for the hydrological year in the summer rainfall region of South Africa for the period 1910/11 to 1983/84 (from Preston-Whyte and Tyson, 1988).

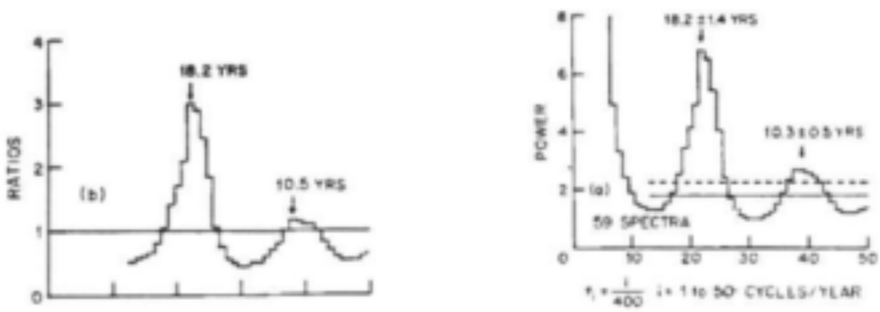

Figure A-9: Maximum entropy power spectrum based on 59 rain-gauge records (from Currie, 1993)

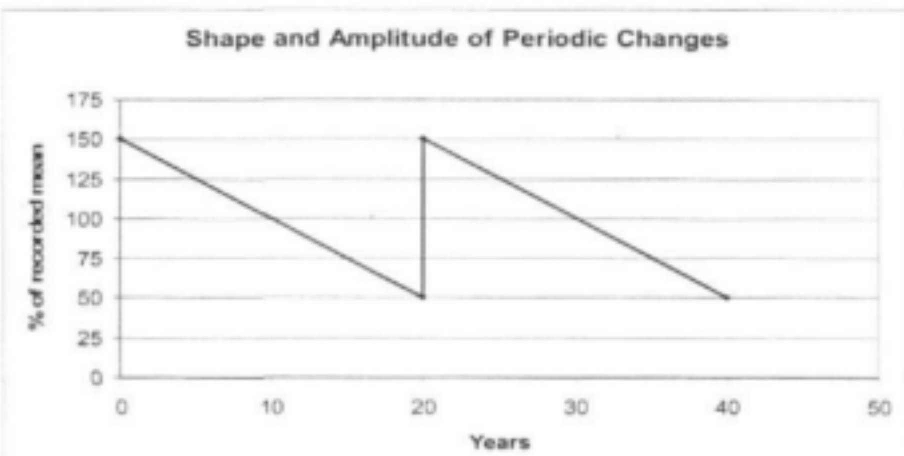

Figure A-10: Schematic representation of the 20-year rainfall cycle with gradual decrease to a minimum, followed by a sudden increase in rainfall intensity.

- A 20-year variation in run-off of certain rivers, particularly in the summer rainfall area (Abbott and Dyer (1976). Vaal River has a clear peak at 18.4 years (Dyer, 1978). In 1995 Alexander confirmed the 20-year periodicity in river flow based on graphical analyses "which has now reached a 95% level of significance" (Alexander 1995; 2002). He confidently states that there can be no doubt about the presence of the 20-year periodicity in the rainfall and river flow records and its link to solar activity. The analyses show that 91% of the rainfall and river flow sites have a discernable 19 to 21-year periodicity. At 20% of the sites the periodicity has reached a 95% level of significance; and only 9% of the sites show no discernible periodicity in this range.

Tyson (1986) prepared a table which depicts the mean deviation for wet and dry spells as a whole, wettest and driest years within wet and dry spells and the number of years during spells for which rainfall of the opposite sign occurred. In this analysis the hydrological year (October to September) was used.

Whatever doubts may be attached to the statistical significance of the 18-year peak in the spectrum for the spatially-averaged data for the summer rainfall region, the sequence of alternating spells since 1906 in which preponderances of wetter and drier than normal years have occurred shows the physical reality of the oscillation during the twentieth century. Around the turn of the century the rhythm of change faltered (Tyson, 1980). Instead of being wet, as backward extrapolation suggests, the period 1897-1905 (based on calendar year analysis) was dry and the oscillation underwent a phase shift. Since 1900 the oscillation has been stable for over 80 years (Tyson, 1980).

Table A-4: Recorded dry and wet spells during the 20th century (from Tyson, 1986)

Spell	Period	Number of years	Space-mean rainfall deviation (%)	Wettest or driest year	Max. or min. deviation (%)	Number of years with opposite sign
Dry	1905/06-1915/16	10	-4.3	1913/14	-30.0	5
Wet	1916/17-1924/25	9	+5.4	1924/25	+42.5	4
Dry	1925/26-1932/33	8	-14.7	1932/33	-33.5	1
Wet	1933/34-1943/44	11	+6.0	1942/43	+34.5	5
Dry	1944/45-1952/53	9	-9.4	1949/50	-23.0	2
Wet	1953/54-1961/62	9	+7.0	1956/57	+30.0	3
Dry	1962/63-1970/71	9	-6.0	1965/66	-24.5	3
Wet	1971/72-1980/81	10	+10.6	1975/76	+39.0	2

Tyson (1987) reiterates, "No evidence exists to show that southern Africa is becoming progressively drier. Some evidence is available to indicate that the quasi 18-year oscillation was present during the nineteenth century and earlier. However the evidence is based on proxy data and is somewhat tenuous. A phase shift occurred at the turn of the century." Others who support his view are Schumann and Thomson (1934). They stated that there was no evidence to support the idea that South African rainfall is undergoing a general long-period decline. This view was subsequently confirmed by the work of Hofmeyr and Schulze (1963).

Over the years, and before the detailed analyses made by Tyson and his co-workers since the 1980s, the southern African rainfall record has been analysed by many researchers, especially with regard to cyclic patterns or a steady diminution of the rainfall (Hutchins, 1889; Nevill, 1908; Barber, 1910; Agric. J of the Union of South Africa, 1913; Union of South Africa, 1914; Schwartz, 1919; union of South Africa, 1923; Cox 1925; Van Reenen, 1925; Peres, 1930). At the end of the extended drought period of the late 1920s and early 1930s, Schumann and Thompson (1934) concluded that there was no evidence to support the theory that South African rainfall was undergoing a general long-period decline. Hofmeyr and Schulze (1963) came to a similar conclusion. Work by Tyson *et al.* 1975) and Dyer (1976a) also indicated that there is no statistical evidence to support the notion that South Africa has experienced or is experiencing a progressive decline in rainfall.

Using a model developed by Dyer and Tyson (1977), Tyson (1980) extrapolated the fitted curve backwards in time and postulated spells of about 9 years during which runs of dry and wet years have occurred during the nineteenth century. Documented evidence shows that the period 1897-1905 was dry over South Africa (instead of being wet as backward extrapolation suggests). However, for the period before 1880, there are suggestions that extended wet and dry spells of about nine years duration also occurred in the nineteenth century. Thus 1886-96 was widely experienced above normal rainfall period, in fact the wettest complete wet spell on record. The period 1880-87 was dry over much of South Africa south of about 29°. One can do little more than speculate about conditions prior to 1880. Of eleven stations with records going back to 1871, ten recorded above-average rainfalls over the period 1871-1879. Of the six stations with series beginning before 1862, all showed negative deviations during the supposed dry spell of 1862; of three stations for the possible wet period of 1853-61 all showed positive deviations.

Provisional backwards extrapolation, based on information from Vogel (1989), and Nash and Endfield (2002), would result in some changes to the dates of the dry and wet spells and proposed by Tyson (1980). By linking these dates to those of Tyson's table presented earlier (**Table A-4**) results in the extended **Table A-5** for the approximate period of 1800 to 2000, with some predicted extrapolation into the 21st century.

Alexander (1995, 2002) analysed South African river flow data. He confirmed a 19 to 21 year periodicity in both rainfall and river flow records. This cyclicity in river flow data in schematically shown in **Figure A-11**. In the postscript of the 1995 article he concluded that (i) there is clear evidence of cyclicity in river flow data for most of the large river catchments in South Africa, (ii) that this cyclicity is closely associated with sunspot activity, (iii) that this cyclicity is much more apparent in annual river flow than in annual rainfall, or the annual Southern Oscillation index, and (iv) that time series analyses cannot be used with confidence where the data are lower bounded, highly skewed, not identically distributed, and with appreciably cyclicity or non-random grouping as is the case with annual river flows in most South African rivers. Consequently it will not be possible to detect changes in the statistical properties of climatological data sets within a period of several decades after the postulated changes have occurred.

The periodicity in the historic rainfall data for southern Africa presented in Table A-4 is schematically represented in **Figure A-13.**

Table A-5: Wet and Dry cycles over the last 200 years

Spell	Period	Number of years	Space-mean rainfall deviation (%)	Wettest or driest year	Max. or min. deviation (%)	Number of years with opposite sign
Wet	1807/08-1817/18	10				
Dry	1818/19-1826/27	8				
Wet	1827/28-1933/34	6				
Dry	1934/35-1943/44	9				
Wet	1844/45-1855/56	11				
Dry	1856/57-1865/66	9		1862/65		
Wet	1866/67-1876/77	10				
Dry	1877/78-1885/86	8		1877		
Wet	1886/87-1893/94	7				
Dry	1894/95-1904/05	10				
Dry	1905/06-1915/16	10	-4.3	1913/14	-30.0	5
Wet	1916/17-1924/25	9	+5.4	1924/25	+42.5	4
Dry	1925/26-1932/33	8	-14.7	1932/33	-33.5	1
Wet	1933/34-1943/44	11	+6.0	1942/43	+34.5	5
Dry	1944/45-1952/53	9	-9.4	1949/50	-23.0	2
Wet	1953/54-1961/62	9	+7.0	1956/57	+30.0	3
Dry	1962/63-1970/71	9	-6.0	1965/66	-24.5	3
Wet	1971/72-1980/81	10	+10.6	1975/76	+39.0	2
Dry	1982/83-1992/93	10				
Wet	1993/94-2002/3	9				
Dry	2003/4-2012/13	9				

Conclusion

From the information presented in the previous sections, a number of different climatic cycles of different duration appear to have been present or are postulated to have been present during the last 200 000 years. These can be summarised as:

- An approximately 23 000 year cycle of major wet and dry periods during the last approximate 200 000 years (Partridge, 1999)
- A possible 400 – 500 year "cold/warm" or "wet/dry" cycle (this report);
- An ~120 years cycle
- An ~18 year cycle (Schumann and Thompson,1934; Hofmeyr and Schulze, 1963; Tyson, 1980; Ngara, 1983; Dyer, 1976, Currie, 1993; Alexander, 1995, 2002)
- An 11 year cycle (Tyson, 1980; Currie, 1993);
- A 3.5 year cycle (Tyson, 1980), and
- A 2.3 year cycle (Tyson, 1980).

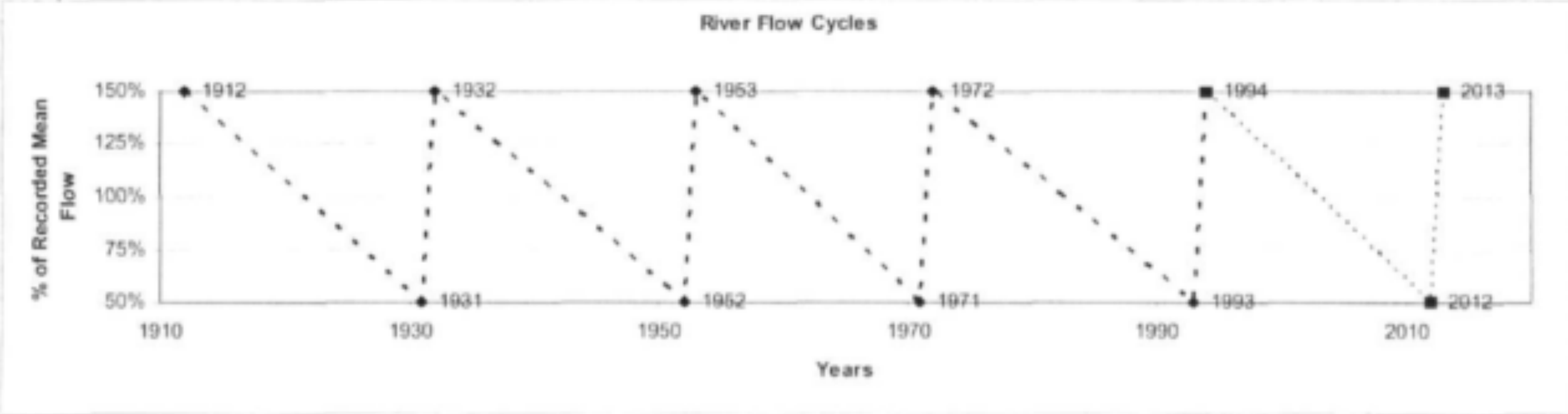

Figure A-11: Schematic representation of river flow periodicity according to Alexander (1995) (1994-2012 projected)

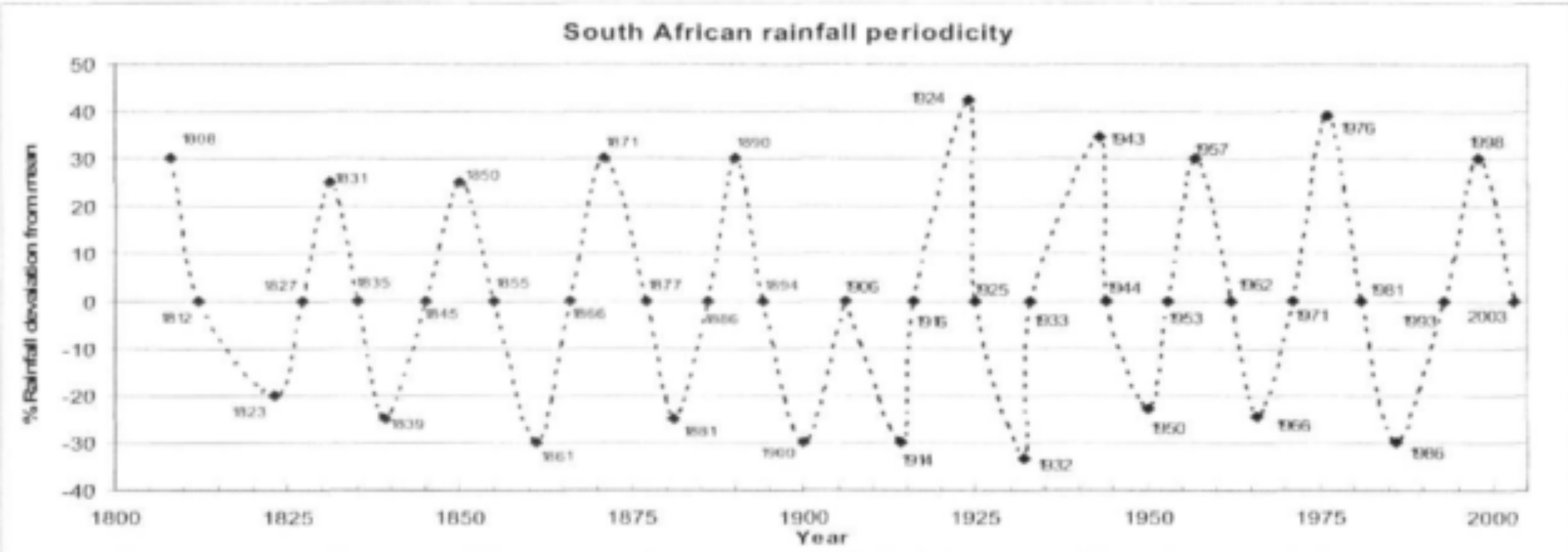

Figure A-12: Schematic representation of major wet and dry periods in southern Africa over approximately the last 200 years.

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APPENDIX B

ADDITIONAL WATER LEVEL INFORMATION SUPPLIED BY THE DEPARTMENT OF WATER AFFAIRS AND FORESTRY

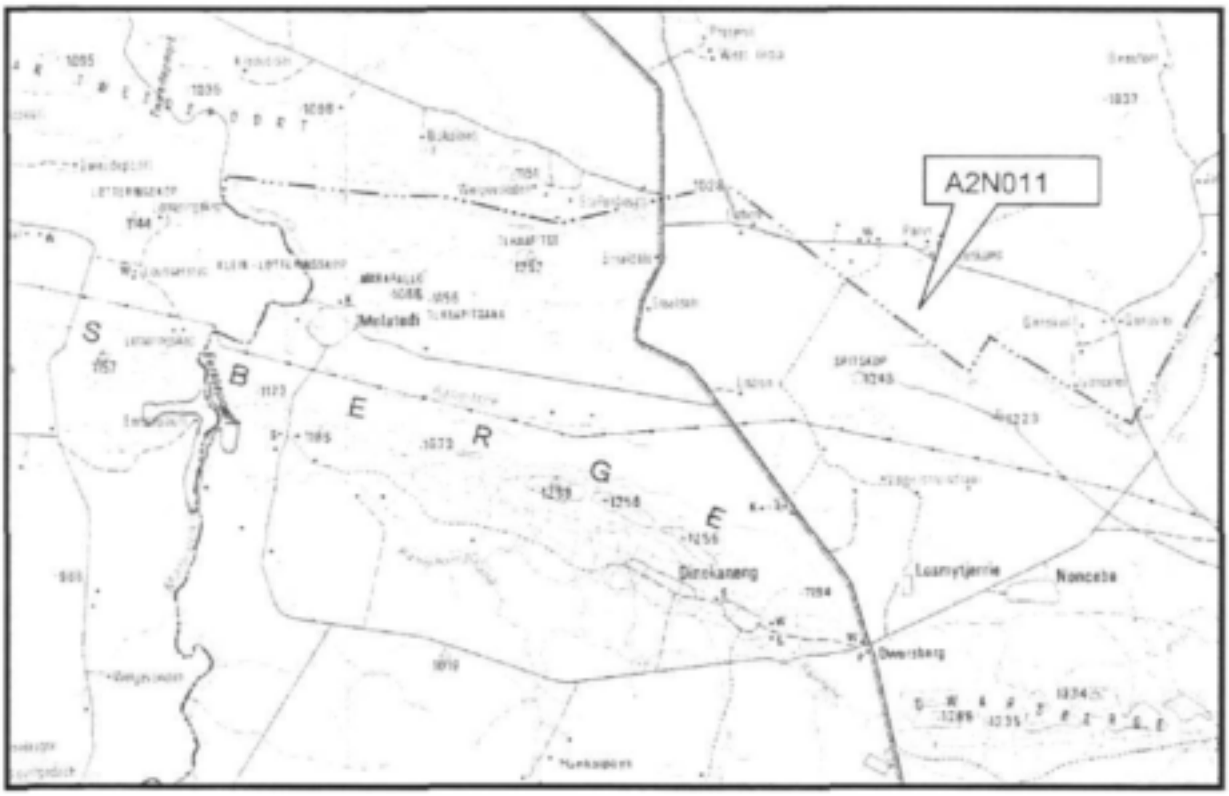
Station name	District	Station #	ID	Record from	Page number	Rainfall station
Buffelshoek Thabazimbi	Thabazimbi	A2N003	2427CB00001	1967	2	0587/697
	Thabazimbi	A2N005	2427DC00007	1967	4	0588/230
Merino Walk Thabazimbi	Thabazimbi	A2N010	2426DA00094	1960	6	0586/006
	Thabazimbi	A2N011	2426DC00102	1960	8	0586/523
Rietondale Pretoria	Pretoria	A2N034	2528CA00015	1967	10	0513/404A
	Pretoria	A2N035	2528CA00014	1967	12	0513/404A
Olifantskop	Thabazimbi	A2N068	2427CB00006	1967	15	0588/230
Commonnage	Pretoria	A2N535	2528CD00066	1975	30	0513/437
Commonnage	Pretoria	A2N543	2528CD00065	1975	32	0513/437
Strydfontein	Marico	A3N007	2526CC00012	1977	35	0508/825
Rietpoort	Marico	a3n012	2525DB00008	1977	36	0508/825
Du Toitskraal	Potgietersrus	A6N017	2428DB00002	1967	44	0590/361
Makapansgat	Potgietersrus	A6N019	2429AA00025	1969	46	0634/011
Du Toitskraal	Potgietersrus	A6N023	2428DB00001	1971	48	0590/361
Commonnage	Potgietersrus	A6N044	2429AA00001	1981	50	0634/011
Zandfontein	Potgietersrus	A6N048	2428DA00003	1975	51	0590/307
De Hoop	Potgietersrus	A6N069	2429AA00010	1977	52	0634/011
De Hoop	Potgietersrus	A6N070	2429AA00009	1977	53	0634/011
Makapansgat	Potgietersrus	A6N078	2429AA00007	1980	54	0634/011
Lisbon	Potgietersrus	A6N079	2428BB00001	1980	55	0633/881A
Blinkwater	Potgietersrus	A6N083	2428BB00002	1985	57	0633/881A
Roodepoort	Potgietersrus	A6N503	2328DB00001	1972	58	0676/363
Gilead	Potgietersrus	A6N505	2328DB00002	1972	60	0676/523
Grootvallei	Potgietersrus	A6N514	2428DB00452	1975	62	0590/361
Grootvallei	Potgietersrus	A6N515	2428DB00856	1975	63	0590/361
Blinkwater	Potgietersrus	A6N534	2428BB00004	1977	64	0633/881A
Sterkloop	Pietersburg	A7N013	2329CD00009	1979	71	0677/834
Lorgensry	Soutpansberg	A7N019	2329BA00001	1985	73	0722/099
Sterkloop	Pietersburg	A7N506	2329CD00013	1968	90	0677/834
Sterkloop	Pietersburg	A7N509	2329CD00025	1972	92	0677/834
Sterkloop	Pietersburg	A7N511	2329CD00023	1972	94	0677/834
Weltevreden	Pietersburg	A7N513	2329CD00020	1972	96	0677/834
Weltevreden	Pietersburg	A7N514	2329CD00024	1972	98	0678/023
Combro	Pietersburg	A7N529	2329AC00001	1968	102	0721/257
Sterkloop	Pietersburg	A7N538	2329CD00006	1974	104	0721/665
Sterkloop	Pietersburg	A7N539	2329CD00014	1974	106	0721/665
Sterkloop	Pietersburg	A7N549	2329CD00010	1972	108	0677/834
Zandrivierspoort	Pietersburg	A7N556	2329DA00002	1969	110	0678/023
Matjeskraal	Pietersburg	A7N580	2329DC00002	1977	115	0678/144
Goedgedacht	Delmas	B2N500	2628BA00059	1975	132	0477/309
Tuinplaas	Waterberg	B3N012	2428DC00002	1975	135	0590/444
Portugal	Potgieterdsrus	B5N011	2429AA00011	1968	138	0634/580
Modderfontein	Potgieterdsrus	B5N013	2429AC00002	1968	140	0634/580
Wildebeespan	Potgieterdsrus	B5N018	2429AC00004	1962	142	0634/050
Doelen	Potgieterdsrus	B5N031	2429AC00003	1972	144	0634/050
Zuurbekom	Roodepoort	C2N006	2627BD00032	1957	148	0475/528
Gemspost	Randfontein	C2N011	2627BC00052	1963	150	0475/528
Gemspost	Randfontein	C2N012	2627BC00051	1963	152	0475/528
Rietfontein	Johannesburg	C2N308	2627BD00036	1980	156	0475/528
Dudfield	Lichtenburg	C3N021	2625BB00031	1975	161	0471/853
Elandsfontein	Lichtenburg	C3N032	2626AA00012	1977	162	0472/279
Klipbankfontein	Lichtenburg	C3N035	2626AA00006	1978	163	0472/309
Kliplaagte	Lichtenburg	D4N037	2525DD00029	1973	166	0508/649
Kliplaagte	Lichtenburg	D4N066	2625BB00022	1978	168	0508/649
Grootfontein	Lichtenburg	D4N080	2525DD00031	1977	170	0508/649
Valleifontein	Lichtenburg	D4N103	2525DD00025	1977	171	0508/649
Grootfontein	Lichtenburg	D4N105	2525DD00020	1977	172	0508/649
Grootfontein	Lichtenburg	D4N111	2525DD00036	1977	173	0508/649
Grootfontein	Lichtenburg	D4N112	2525DD00037	1977	174	0508/649
Mooimeisiesfontein	Lichtenburg	D4N115	2525DD00047	1977	175	0508/649
Mooimeisiesfontein	Lichtenburg	D4N116	2625BB00018	1978	176	0508/649
Blaauwbank	Lichtenburg	D4N119	2625BB00016	1977	177	0508/649
Blaauwbank	Lichtenburg	D4N122	2525DD00028	1978	178	0508/649
Lareystryd	Lichtenburg	D4N123	2625BB00028	1977	179	0508/649
Armoedsvlakte	Vryburg	C3N072	2624DC00024	1982	190	0432/136
Commonage	Vryburg	C3N073	2624DC00025	1982	191	0432/136
Swartfontein	Vryburg	C3N075	2624DC00026	1982	192	0432/136

APPENDIX C

ADDITIONAL INFORMATION ON EACH OF THE SITES FOR WHICH GROUNDWATER LEVEL INFORMATION IS DISPLAYED IN THE MAIN TEXT

Water level recording station A2N011
(Refer to figure 8 in text)

Recording station	A2N011		
NGDB Number	2426CD00102		
Farm	Parys		
District	Thabazimbi		
Coordinates	Lat	24	50
	Long	26	41
Elevation (mamsl)	~1200		
Catchment	A24J		
Geology	Archaean granite, Derdepoort		
Mean Annual Precipitation (Oct-Sep) in mm		611	0586/523
MAR source	WR90 Rainfall zone A3D		



From 1:250 000 topographical map 2426 Thabazimbi (not to scale).
Note: The town Molatedi to the west of recorder A2N011 is approximately 50km WSW of Thabazimbi.

Water level recording station A7N514
(Refer to figure 9 in text)

Recording station	A7N514		
NGDB Number	2329CD00024		
Farm	Weltevreden		
District	Pietersburg		
Coordinates	Lat	23	56
	Long	29	26
Elevation (mamsl)	~1300		
Catchment	A71A		
Geology	Hout River gneiss, Limpopo Mobile Belt		
Mean Annual Precipitation (Oct-Sep)	486	(0677/834)	
MAR source	WR90 Rainfall zone A7A		

From 1:250 000 topographical map 2328 Polokwane (not to scale).

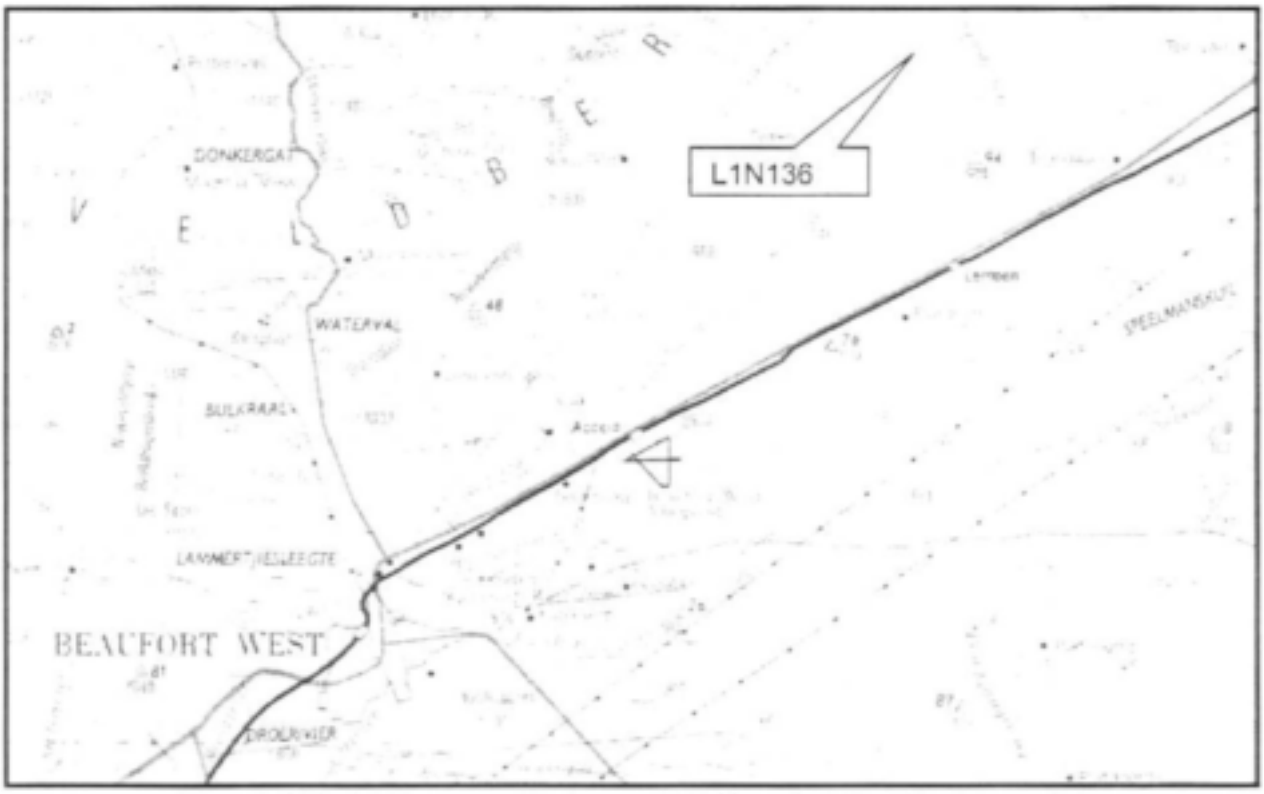
Water level recording station F5N001
(Refer to figures 10 and 30 in text)

Recording station	F5N001		
NGDB Number	3018CC00018		
Farm	Moordenaarskraal		
District	Vanrhynsdorp		
Latitude	30	49	
Longitude	18	03	
Elevation (mamsl)	300 (Approximate)		
Reference datum (mamsl)	300		
Catchment	F50D		
Geology	Kamieskroon gneiss		
Rainfall recorder	0157/647		
Rainfall District	1 (close to corner of 1, 2, 5 and 14)		
Rainfall region	A2		
Summer rainfall	Hydrological year October – September		
Mean Annual Precipitation (Oct-Sep) in mm	103		
MAR source	WR90 Rainfall zone F5A		
Rainfall recorder coord	Lat	30	47
	Long	17	52
SPI index	UCT		

From 1:250 000 topographical map 3018 Loeriesfontein (not to scale).
Note: The recording station is approximately 30km SSE of the town of Garies.

Water level recording station L1N136
(Refer to figure 11 in text)

Recording station	L1N136		
NGDB Number	3222BA00112		
Farm	De Hoop		
District	Beaufort West		
Coordinates	Lat	32	12
	Long	22	45
Elevation (mamsl)	~900		
Catchment	L11F		
Geology	Adelaide Fomnation, Beaufort Group		
Summer rainfall	Hydrological year October – September		
Mean Annual Precipitation (Oct-Sep) in mm		190(092/386)	
MAR source	WR90 Rainfall zone L1B		



From 1:250 000 topographical map 3222 Beaufort West (not to scale).

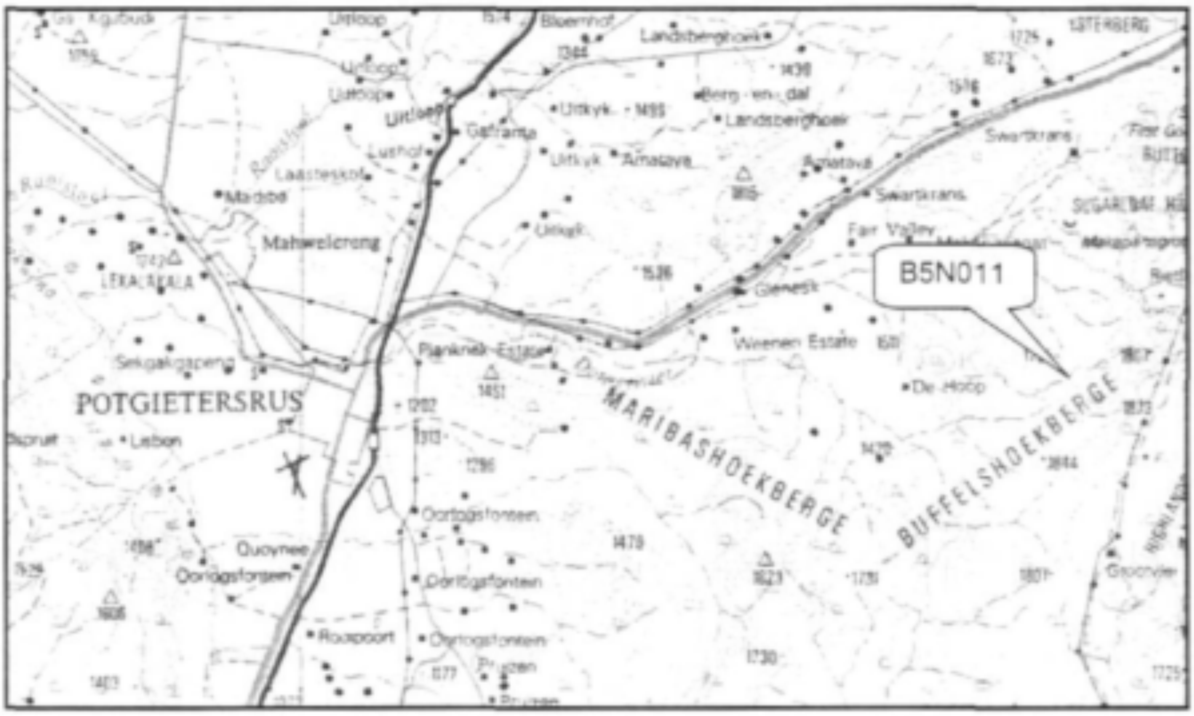
Water level recording station B5N031
(Refer to figure 12 in text)

Recording station	B5N013		
NGDB Number	2429AC0003		
Farm	Doelen		
District	Potgietersrus		
Coordinates	Lat	24	23
	Long	29	00
Elevation (mamsl)	~1100		
Catchment	B51E		
Geology	Letaba rhyolite, Karoo Supergroup		
Summer rainfall	Hydrological year October – September		
		610	
Mean Annual Precipitation (Oct-Sep)		0634/580	
MAR source	WR90 Rainfall zone AB5A		

From 1:250 000 topographical map 2428 Nylstroom (not to scale).

Water level recording station B5N011
(Refer to figure 14 in text)

Recording station	B5N011		
NGDB Number	2429AA00011		
Farm	Portugal		
District	Potgietersrus		
Coordinates	Lat	24	11
	Long	29	13
Elevation (mamsl)	~1800		
Catchment	A61F		
Geology	Malmani dolomite, Transvaal Supergroup		
Summer rainfall	Hydrological year October – September		
Mean Annual Precipitation (Oct-Sep)	610	0634/580	
MAR source	WR90 Rainfall zone A6F		



From 1:250 000 topographical map 2428 Nylstroom (not to scale).

Water level recording station A7N549
(Refer to figure 15 in text)

Recording station	A7N549		
NGDB Number	2329CD00010		
Farm	Sterkloop		
District	Pietersburg		
Coordinates	Lat	23	54
	Long	29	24
Elevation (mamsl)	~1100		
Catchment	A71A		
Geology	Hout Rivier gneiss		
Summer rainfall	Hydrological year October - September		
Mean Annual Precipitation (Oct-Sep)	486 (0677/834		
MAR source	WR90 Rainfall zone D4A		

From 1:250 000 topographical map 2328 Polokwane (not to scale).

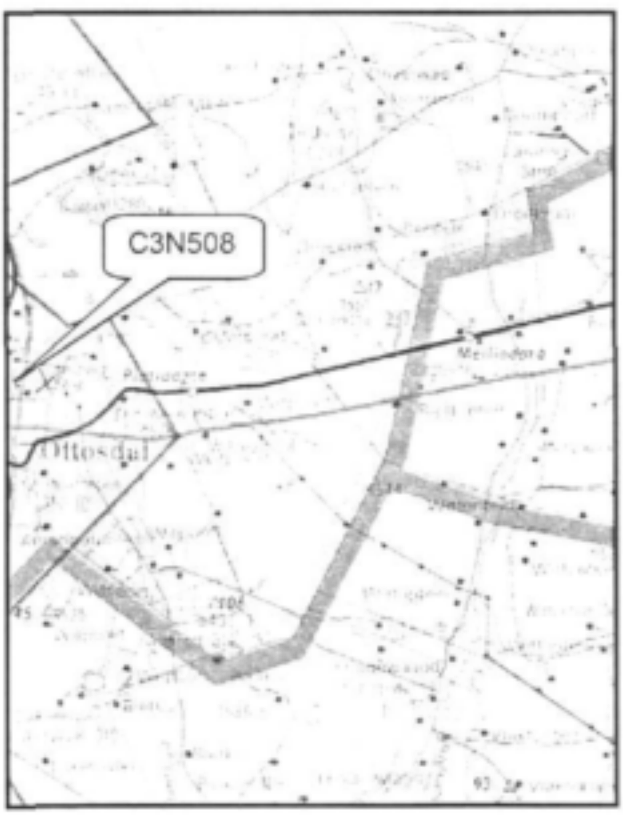
Water level recording station M1N005
(Refer to figures 16 and 36 in text)

Recording station	M1N005		
NGDB Number	3325CB00002		
Farm	Prentice Kraal		
District	Uitenhage		
Coordinates	Lat	33	38
	Long	25	26
Elevation (mamsl)	250 (Approximate)		
Reference datum (mamsl)	250		
Catchment	M30A		
Geology	Kirkwood Formation		
Rainfall recorder	0034/762		
Rainfall District	12		
Rainfall region	B2		
Summer rainfall	Hydrological year October - September		
Mean Annual Precipitation (Oct-Sep)	481		
MAR source	WR90 Rainfall zone M3A		
Rainfall recorder coord	Lat	33	42
	Long	25	26
SPI index	UCT		

From 1:250 000 topographical map 3324 Port Elizabeth (not to scale).

Water level recording station C3N508
(Refer to figures 17,27 and 32 in text)

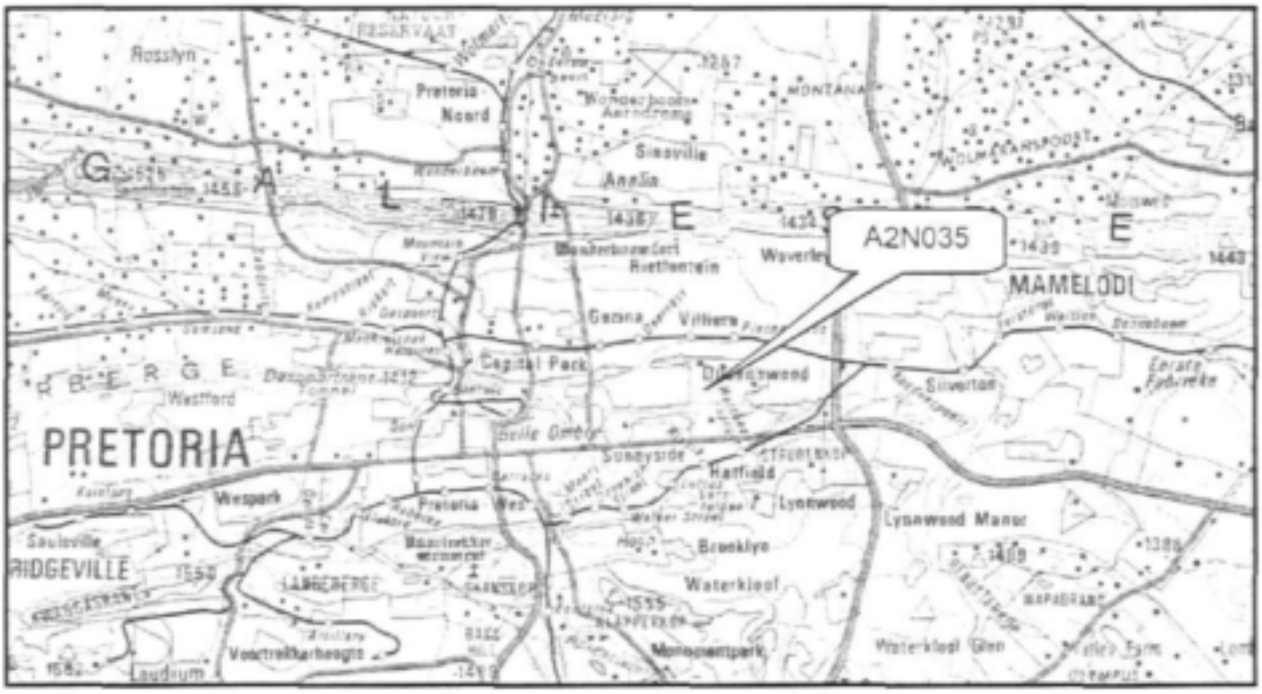
Recording station	C3N508			
NGDB Number	2625AD00001			
Farm	Boschkoppie			
District	Delareyville			
Latitude		26	29	
Longitude		25	24	
Elevation (mamsl)	1400 (Approximate)			
Reference datum (mamsl)		1400		
Catchment	D41B			
Geology	Allanridge Fm, Ventersdorp			
Rainfall recorder	0471/269 (DWAF)			
Rainfall District	90 (close to boundary between 90 and 92)			
Rainfall region	F3			
Summer rainfall	Hydrological year October – September			
Mean Annual Precipitation (Oct-Sep)		474(0433/512)		
MAR source	WR90 Rainfall zone D4A			
Rainfall recorder coord	Lat	26	32	(0433/512)
	Long	25	18	(0433/512)
SPI index	UCT			



From 1:250 000 topographical map 2626 East Rand (not to scale).

Water level recording station A2N035
(Refer to figure 18 in text)

Recording station	A2N035		
NGDB Number	2528CA00014		
Farm	Rietondale		
District	Pretoria		
Coordinates	Lat	25	44
	Long	28	14
Elevation (mamsl)	~1400		
Catchment	A23D		
Geology	Silverton Fm, Pretoria Group		
Summer rainfall	Hydrological year October – September		
Mean Annual Precipitation (Oct-Sep)	733	0513/404	
MAR source	WR90 Rainfall zone A2H		



From 1:250 000 topographical map 2528 Pretoria (not to scale).

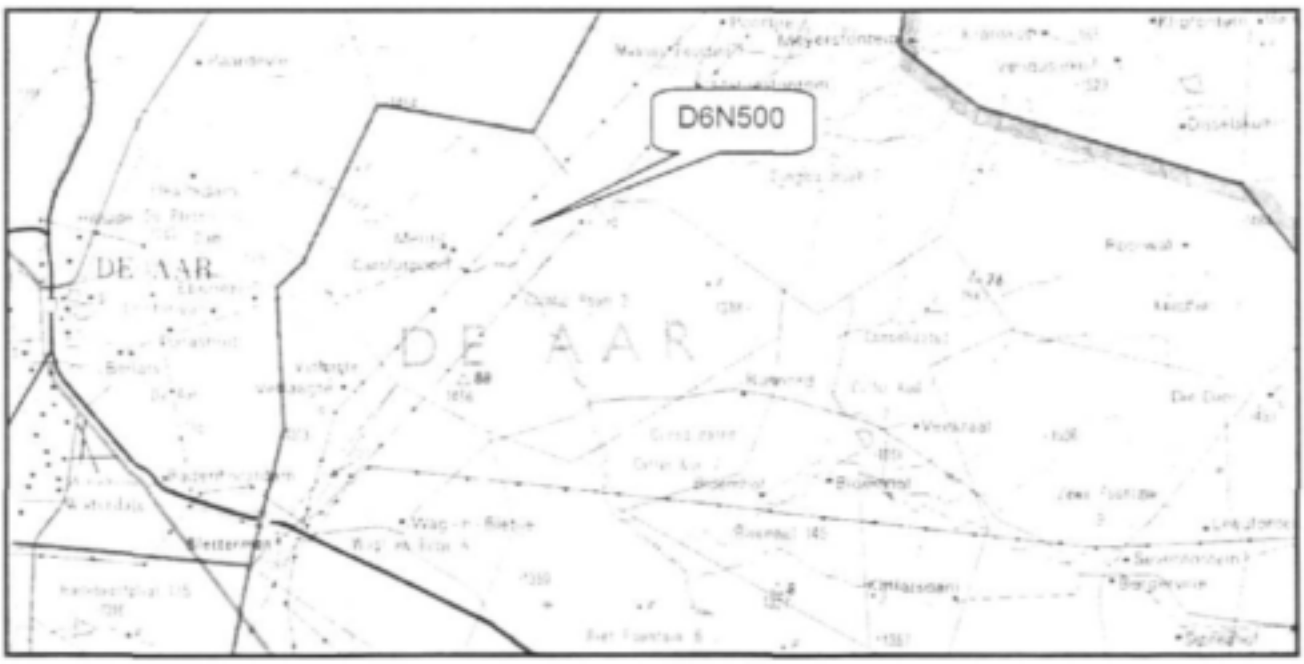
Water level recording station A6N505
(Refer to figures 25 and 37 in text)

Recording station	A6N505		
NGDB Number	2328DB00002		
Farm	Gilead		
District	Potgietersrus		
Coordinates	Long	23	28
	Lat	28	47
Elevation (mamsl)	~1100		
Catchment	A61G		
	Lebowa		
Geology	granite		
Summer rainfall	Hydrological year October – September		
Mean Annual Precipitation (Oct-Sep)	475	0676/523	
MAR source	WR90 Rainfall zone A6E		

From 1:250 000 topographical map 2328 Polokwane (not to scale).

Water level recording station D6N500
(Refer to figure 28 in text)

Recording station	D6N500		
NGDB Number	3024CA00328		
Farm	Caroluspoort		
District	De Aar		
Coordinates	Latitude	30	38
	Longitude	24	09
Elevation (mamsl)	1400 (Approximate)		
Reference datum (mamsl)	1400		
Catchment	D62C/D62D		
Geology	Shale, Tierberg Formation, Ecca Group		
Rainfall recorder	0170/639		
Rainfall District	54		
Rainfall region	K2		
Summer rainfall			
Mean Annual Precipitation (Oct-Sep)	320		
MAR source	WR90 Rainfall zone D6C		
Rainfall recorder coord	Lat	30	39
	Long	24	22
SPI index	UCT		



From 1:250 000 topographical map 3024 Colesberg (not to scale).

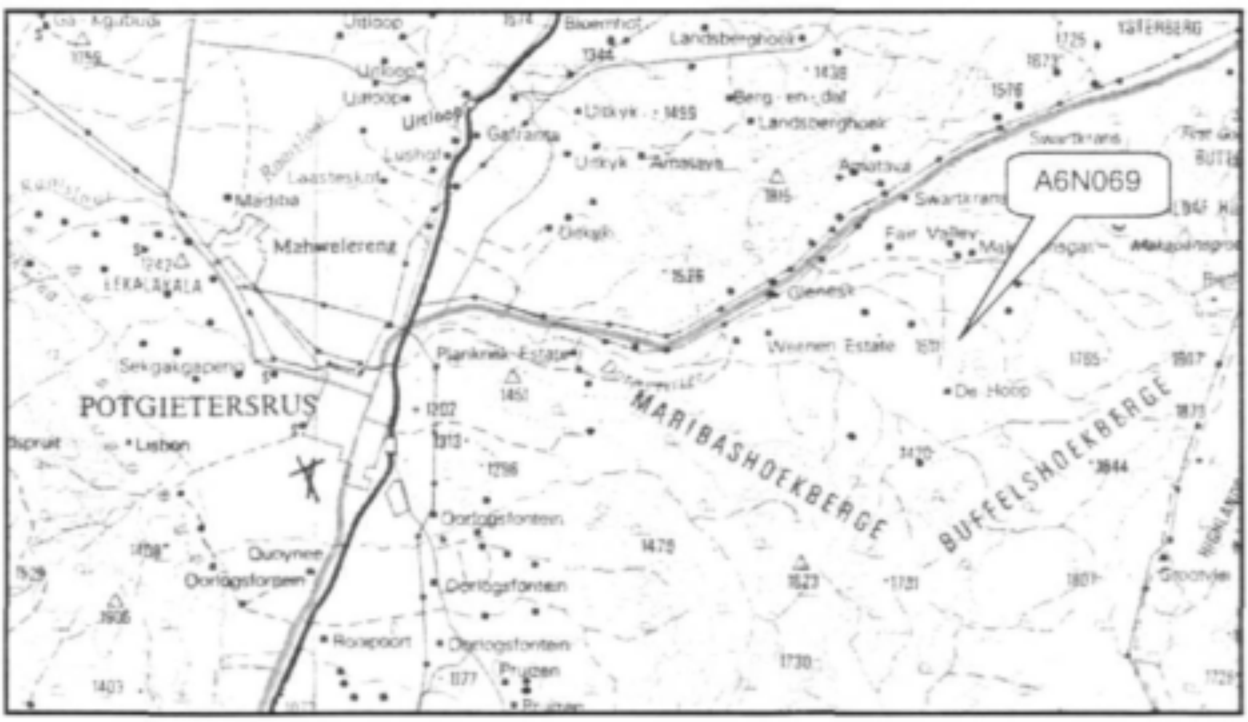
Water level recording station D4N522
(Refer to figure 29 in text)

Recording station	D4N522			
NGDB Number	2625AD00001			
Farm	Boschkoppie			
District	Delareyville			
Latitude		26	29	
Longitude		25	24	
Elevation (mamsl)	1400 (Approximate)			
Reference datum (mamsl)	1400			
Catchment	D41B			
Geology	Alanridge Fm, Ventersdorp SG			
Rainfall recorder	0471/269 (DWAF)		0433/512 (WR90)	
Rainfall District	90 (close to boundary between 90 and 92)			
Rainfall region	F3			
Summer rainfall	Hydrological year October - September			
Mean Annual Precipitation (Oct-Sep)	474	(0433/512)		
MAR source	WR90 Rainfall zone D4A			
Rainfall recorder coord	Lat		26	32(0433/512)
	Long		25	18(0433/512)
SPI index	UCT			

From 1:250 000 topographical map 2624 Vryburg (not to scale).

Water level recording station A6N069
(Refer to figures 13 and 31 in text)

Recording station	A6N069		
NGDB Number	2429AA00010		
Farm	De Hoop (near Makapansgat)		
District	Potgietersrus		
Latitude		24	10
Longitude		29	10
Elevation (mamsl)	1500 (Approximate)		
Reference datum (mamsl)	1500		
Catchment	A61F		
Geology	Dolomite, Malmani Group		
Rainfall recorder	0634/011		
Rainfall District	76 (close to boundary between 64 and 76)		
Rainfall region	E3		
Summer rainfall	Hydrological year October – September		
Mean Annual Precipitation (Oct-Sep)	600		
MAR source	WR90 Rainfall zone A6C		
Rainfall recorder coord	Lat	24	11
	Long	29	1
SPI index	UCT		



From 1:250 000 topographical map 2428 Nylstroom (not to scale).

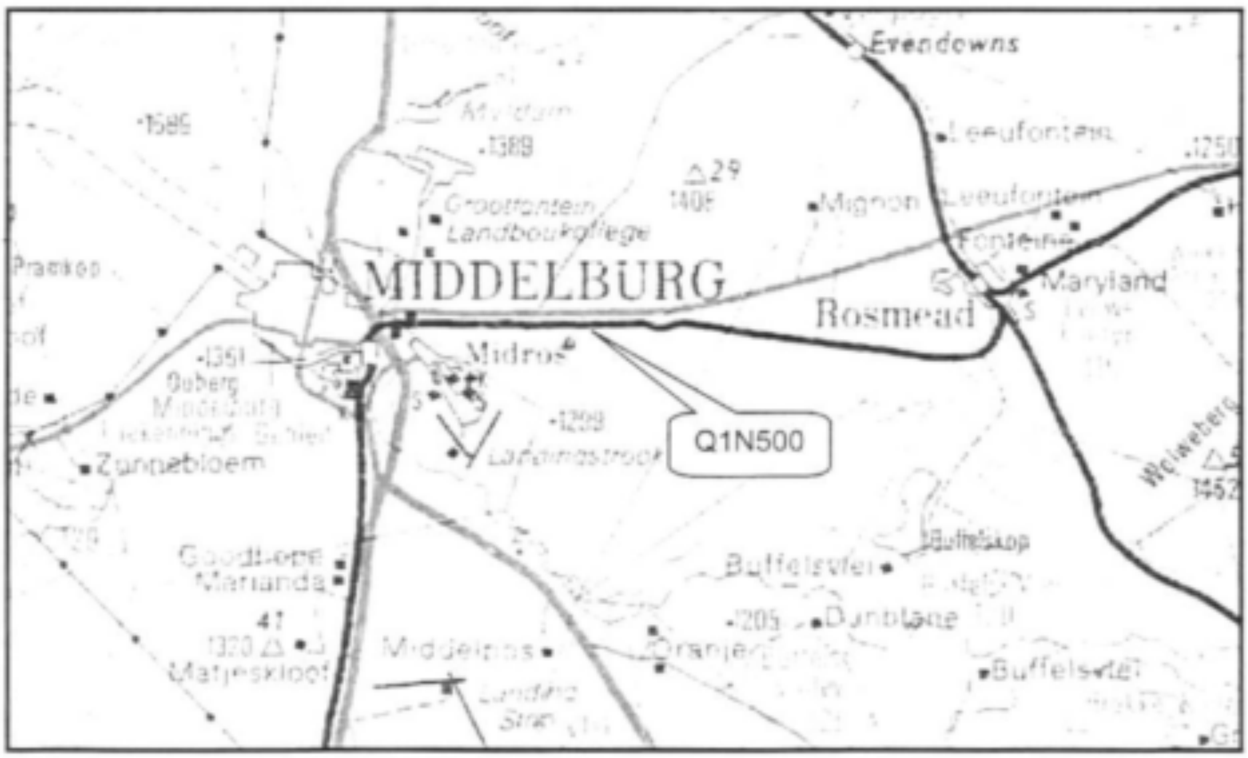
Water level recording station C3N511
(Refer to figure 33 in text)

Recording station	C3N511		
NGDB Number	2624DC00032		
Farm	Commonage		
District	Vryburg		
Latitude		26	57
Longitude		24	43
Elevation (mamsl)	1200 (Approximate)		
Reference datum (mamsl)	1200		
Catchment	C32B		
Geology	Dolomite, Malmanie Group		
Rainfall recorder	0432/136		
Rainfall District	90		
Rainfall region	F3		
Summer rainfall	Hydrological year October – September		
Mean Annual Precipitation (Oct-Sep)	448		
MAR source	WR90 Rainfall zone C3C		
Rainfall recorder coord.	Lat	26	46
	Long	24	35
SPI index	UCT		

From 1:250 000 topgraphical map 2624 Vryburg (not to scale).

Water level recording station Q1N500
(Refer to figure 34 in text)

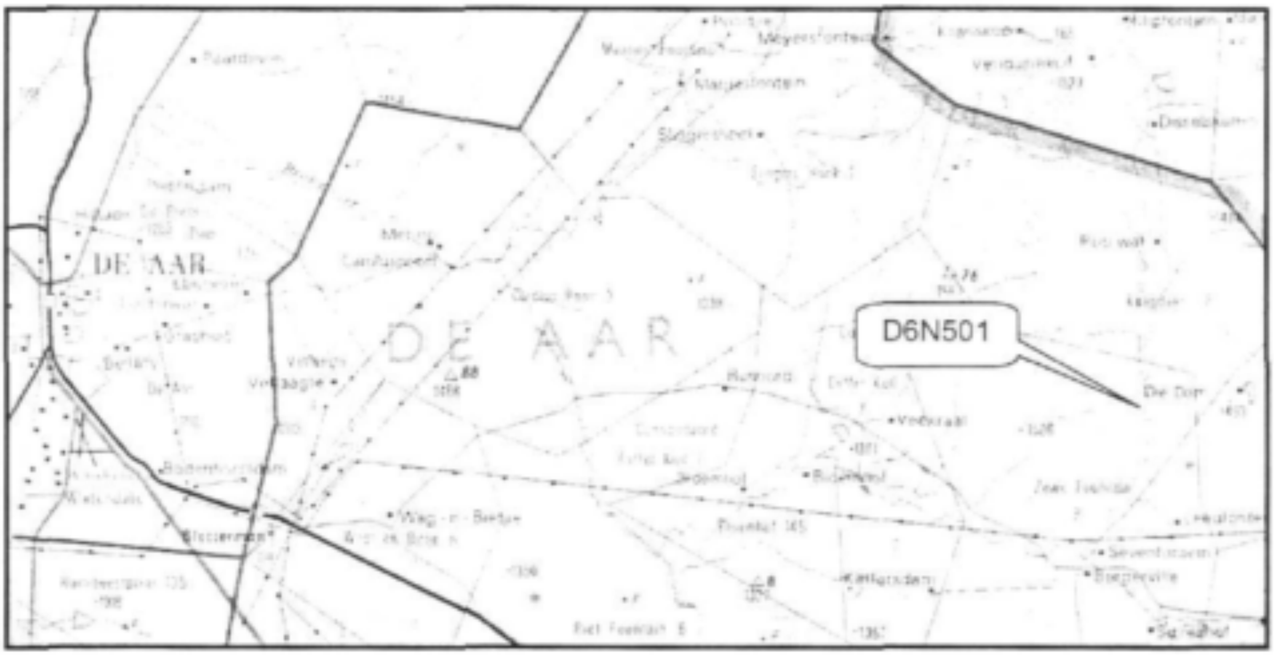
Recording station	Q1N500			
NGDB Number	3125CA00057			
Farm	Grootfontein			
District	Middelburg			
Latitude		31	30	
Longitude		25	3	
Elevation (mamsl)	1300 (Approximate)			
Reference datum (mamsl)	1300			
Catchment	Q14B			
	Adelaide Fm, Karoo			
Geology	Suopergroup			
Rainfall recorder	0120/010			
Rainfall District	40 (almost on 40/41 boundary)			
Rainfall region	D1			
Summer rainfall	Hydrological year October - September			
Mean Annual Precipitation (Oct-Sep)	319			
MAR source	WR90 Rainfall zone Q1D			
Rainfall recorder coord	Lat		31	40
	Long		25	1
SPI index	UCT			



From 1:250 000 topgraphical map 3124 Middelburg (not to scale).

Water level recording station D6N501
(Refer to figure 35 in text)

Recording station	D6N501			
NGDB Number	3024CB00067			
Farm	Zevenfontein			
District	De Aar			
Latitude		30	41	
Longitude		24	21	
Elevation (mamsl)	1400 (Approximate)			
Reference datum (mamsl)	1400			
Catchment	D62C/D62D			
Geology	Tierberg Fm, Ecca Group			
Rainfall recorder	0170/639			
Rainfall District	54			
Rainfall region	K2			
Summer rainfall	Hydrological year October - September			
Mean Annual Precipitation (Oct-Sep)	320			
MAR source	WR90 Rainfall zone D6C			
Rainfall recorder coord	Lat		30	39
	Long		24	22
SPI index	UCT			



From 1:250 000 topographical map 3024 Colesberg (not to scale).

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