INTERNATIONAL ATOMIC ENERGY AGENCY

RAF 8/029

SUSTAINABLE DEVELOPMENT OF GROUNDWATER RESOURCES IN THE AFRICA REGION – TECHNICAL REPORT.

NAMIBIA: ASSESSMENT OF THE RECHARGE TO THE STAMPRIET ARTESIAN BASIN TO FORMULATE A GROUNDWATER MANAGEMENT PLAN FOR SUSTAINABLE USE OF THE RESOURCE IN THE SOUTHEAST KALAHARI IN THE REPUBLIC OF NAMIBIA.

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September 2002

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1. Preface

During the latter part of 1998, when JICA gave its intention to finance a Hydrogeological Study of the Stampriet Artesian Basin with a view to establishing a Management Plan, the International Atomic Energy Agency (IAEA) was approached to lend their expertise to specifically understanding the recharge mechanism into the system. Various aspects of Isotope Hydrology were incorporated during the study. Assistance was rendered by the IAEA, specifically with expertise in the field of Isotope Hydrology, for the donation sampling equipment and chemicals necessary to undertake the sampling programmes, and for the financing of the numerous chemical and isotope analyses. Counterpart training by the IAEA also formed a valuable aspect of this project.

Skills from various disciplines were incorporated during this study including experts from the IAEA, local consultants with specialised knowledge of the area and people with post-graduate knowledge of the area. Both stable and radioactive isotopes, which were incorporated in the study, helped to understand many aspects concerning recharge as well as other aspects of the Hydrogeology of the Basin. However many questions were raised that were not completely answered through this study, and it is clear that further work will have to address these aspects. This Ministry would like to thank the IAEA for its vital role in assisting to understand the various hydrogeological processes through the use of Isotope Hydrology, throughout this three year project.

2. Introduction

2.1. Project background and objectives

Investigations early last century that led to the discovery of the Stampriet Artesian Basin (SAB, see figure 1), which is one of the largest aquifer systems in the country, have resulted in the development of five towns and extensive agricultural development. Although stock farming is the major industry, irrigation has increased considerably over the past years and is currently the major water user in the Basin. As the SAB is a water control area, a water management plan for the area was needed, and it became necessary to do a detailed assessment of the system in order to prevent over-exploitation and assure optimal use of the reserve.

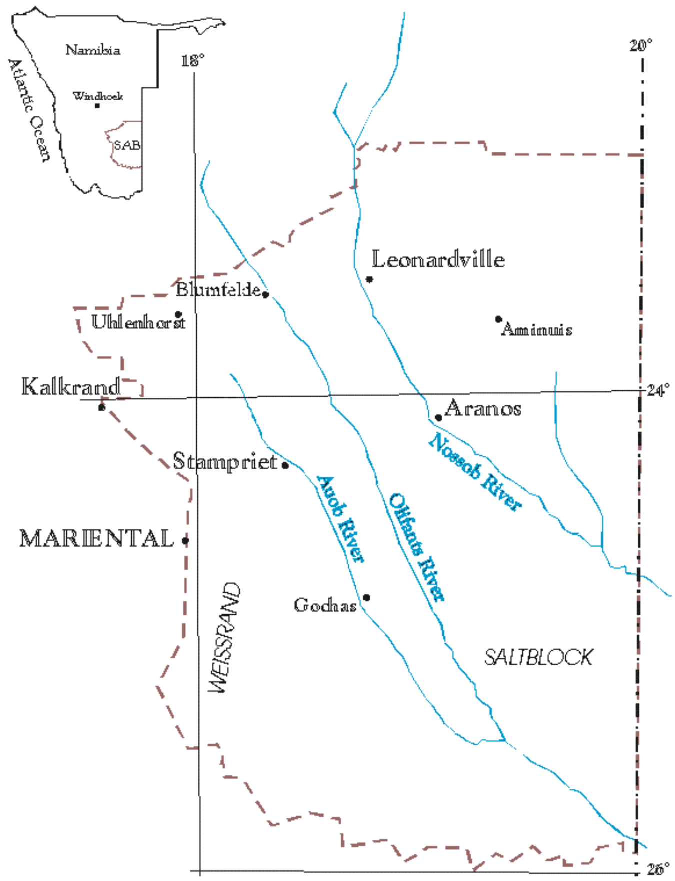

Figure 1: Locality map of Stampriet Artesian Basin (SAB).

For this reason funding was requested for a detailed study of the SAB and the Japanese Government agreed to support such a project. It was essential to construct a management plan based on a better knowledge of the aquifers of the Basin. The understanding and the quantification of the recharge play a key role in constructing such a management plan. While JICA assisted with the investigation of the aquifers, the water quality, the setting up a monitoring system and the construction of a management plan for the aquifer, the IAEA was approached to provide assistance for the assessment of recharge by means of isotope studies.

2.2. National components

In order to manage the excessive abstraction, DWA needs to understand the nature of the entire aquifer system. Accordingly, the Government of Namibia requested the Government of Japan (Japan International Cooperation Agency, JICA) to carry out an investigation of the groundwater flow and recharge mechanism of the Southeast Kalahari Artesian Basin (Stampriet Artesian Basin) and to formulate a groundwater management plan for sustainable groundwater usage. When the IAEA RAF/8/029 project had to be formulated it was decided that optimum use of the financial and manpower resources could be achieved if the isotope study would compliment the Japanese investigation and vice versa.

2.3. Regional aspects

Although the Stampriet Artesian Basin stretches some distance into the neighbouring countries of Botswana and South Africa, it is believed that there is no great potential beyond the Namibian borders, partly because the aquifer appears not to extend far into Botswana and partly because of quality problems at its downstream end near and on the other side of the Namibian/South African Border. However, in the context of aquifer recharge in semi-arid areas, the recharge mechanism of the Stampriet Artesian Basin incorporating the isotope related findings, are of wider interest on the subcontinent.

3. The Namibian Stampriet Artesian Basin Project[1]

3.1. Abstract

Complementary with investigations of the concurrent JICA sponsored project, that aims at establishing a management plan of the Basin, isotope investigations of groundwater in the Kalahari- and the underlying generally confined Auob- and Nossob aquifers were done. This was supplemented by the drilling of exploration boreholes in the supposed recharge areas, water quality analyses and the monitoring of water-levels, rainfalls and floods.

From earlier investigations large databases of water borehole data, chemical analyses, ^{14}C and ^{18}O determinations and core information from some 30 coal exploration boreholes, were available. These data, together with data obtained from the Japanese study which included a hydrocensus of existing boreholes, a geophysical survey, an extensive exploration drilling and sampling program, formed the basis of the IAEA isotope study. Additional exploration drilling and water sampling for isotopes and chemistry by the Department of Water Affairs augmented by satellite image processing by the German *Bundesanstalt für Geowissenschaften und Rohstoffe* (BGR) during the Namibian Hydrogeology Map Project, yielded the following results:

The Basin is subdivided into a north-northeastern half (east of the Nossob River) and a south-southwestern half. Towards the northwest and western Perimeter of the southwestern half of the basin extensive karstification of the calcrete occurs that covers large parts of the area. During larger rainfall events water drains quickly towards these depressions that have formed through dissolution of calcrete where water is protected from evaporation. Through faults, fractures and weathered layers this water finds its way into the various aquifers. Response of the piezometric water levels occurs within weeks. The recharge areas and the mechanism in the North and Northeast are still unclear.

Dissolution of calcrete apparently leads to locally variable initial ^{14}C activities (further investigation required). Stable isotope data are indicative of different ^{2}H and ^{18}O levels during the last pluvial period when the moisture might have come from the nearer Atlantic instead of the Indian Ocean, that is the present rainfall source.

Keywords: Aquifer, Climate, Isotopes, Karst, Rainfall, Recharge

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[1] *This technical report is a condensed version of the project report "Applying environmental isotopes to a hydrogeological Model of the Stampriet Artesian Basin" (Kirchner et al., 2002). The appendices mentioned herein refer to this project report.*

3.2. Introduction

3.2.1. Background

The study of stable and radioactive environmental isotopes can contribute significantly to the understanding of a hydrogeological system. In the case of the Southeast Kalahari (Stampriet) Artesian Basin (SAB), with its superimposed aquifers, some of which are confined over large areas, such a study is even more important for the understanding of the complex hydrogeology. Therefore, the aim of this IAEA project is to study the recharge mechanism of the aquifer system through the application of environmental isotopes. The main issues to be addressed are to:

- delineate the recharge areas in the SAB
- determine the recharge rate of the system, and
- provide an estimation of the sustainable yield of the aquifers.

Significant progress was made towards attaining these aims, but fully achieving them proved to be an extensive task, that was not possible within the limited scope of this project. The extent of the success in delineating the potential recharge areas is described below, but it is evident that considerably more research will be required to fully understand the recharge rate of the system and accordingly also the safe yield. It was important that, in parallel to this research project, the Japanese Government sponsored a research project through their Japan International Cooperation Agency (JICA). Although the JICA project did not concentrate on the natural recharge aspects of the SAB, their study provided valuable insights into the hydrogeological system as a whole, which are invaluable for this IAEA project (JICA Study Team, 2002).

3.2.2. Previous work

Investigations into the Stampriet Artesian Basin (SAB) began when artesian water had been struck in an exploration borehole that was drilled in the Auob River at Stampriet during 1910 (Range, 1912). At the outbreak of World War I several more holes had struck the artesian aquifer, most of them in the Auob River below Stampriet. During the 1920s the Irrigation Department measured the pressure of the artesian holes regularly. Frommurze (1931) from the South African Geological Survey reported on head losses and did some investigations into the potential recharge areas of the artesian sandstone. During the search for coal, that occurs in other parts of the Southern African Karoo Basin, the Coal Commission headed by Martin (Coal Commission, 1961) collated all geological information that was then known. The structure and stratigraphy of the SAB were well documented in the report. An oil exploration core borehole drilled by the Artnell Exploration Company (Wilson, 1964) penetrated the Karoo in the deepest southeastern part of the SAB and Heath (1972) investigated that area of the basin, where the lower Karoo is exposed. Investigations for coal then continued in the Aranos part of the basin and some 30 core boreholes were drilled (Castelyn, 1983; CDM, undated; Kingsley, 1985; Marsh 1986).

With further agricultural development in the SAB and the discovery that in an area east of Kalkrand and in the so-called Saltblock in the Southeast of the basin that the water quality is unsuitable even for stockwatering, the Council for Scientific and Industrial Research (CSIR) was commissioned to investigate these areas and eventually conduct a groundwater quality investigation of the entire country. With all these Institutes being involved in this SAB investigation, a wealth of isotopic data was gathered, test boreholes were drilled and aquifer data collected (e.g. Tredoux et al., 1978). As more and more applications to drill more boreholes in the SAB reached the Department of Water Affairs (DWA) the necessity increased to determine the size of the groundwater resource. Nawrowski (1986, 1987, 1989) started an investigation to determine the water consumption in the upper parts of the basin where irrigation is a major consumer.

3.3. Environmental setting

The SAB lies in the in the southeastern part of Namibia and occupies an area of approximately 70 000 km^2 (see Fig. 1). It is largely a dune-covered area with calcrete-underlain plains in the west and north. The Auob and Nossob Rivers cross the area flowing from North and Northwest (at an altitude of about 1350 m) to the Southeast (dropping to about 950 m en route).

3.3.1. Climate and hydrology

The SAB has a mean annual rainfall (mainly from January to April) between 150 to 300 mm and a potential evaporation between 3000 and 3500 mm/a. The rivers mentioned only flow locally after heavy thundershowers but during extraordinary high rainfall years there may be continued runoff (even across the South African border) for a week or more. The former tributaries of the Auob River, i.e. Oanob and Schaap rivers outside and to the Northwest of the SAB are blocked by dunes and their waters largely evaporate. The Olifants River further east enters the study area but large floods are not known to have flowed past Olifantswater West (about 20 km south of Blumfelde, see Fig.3).

The actual groundwater recharge is dependent on the intensity of the rainfall, the land surface characteristics, and the thickness of the sand cover. During average and below average rainy seasons, little if any recharge, occurs. However, wherever surface runoff can collect on pervious surfaces, mainly in an above average rainy season, with exceptional storm events, a much greater possibility of groundwater recharge exists. Such heavy rainfall events occur approximately once every 20 years.

Alien *Prosopis* trees not only cover large parts of the river valleys but also occur to a lesser degree in areas outside the valleys. This vegetation is thought to have a significant influence on the evapotranspiration of water out of the system and thereby partially impede recharge.

3.3.2. Geology

Further to Paul Range's discovery of artesian water at Stamprietfontein and the coal exploration (Range, 1914 and 1915) boreholes were drilled after World War I when farms were issued along the Auob and Nossob Rivers. By the 1980s a schematic conceptual model of the SAB had been developed that showed the Nossob and Auob artesian aquifers sandwiched between shale, recharged in the NW and dipping in a southeasterly direction.

Drilling results of the boreholes drilled under the JICA and IAEA projects and re-evaluation of previous logs of water- and core boreholes together with JICA geophysical traverses and processed airborne geomagnetic data have considerably refined the knowledge of this Karoo Basin (see figure 2 and Supporting Report of the JICA Study, PCI 2002).

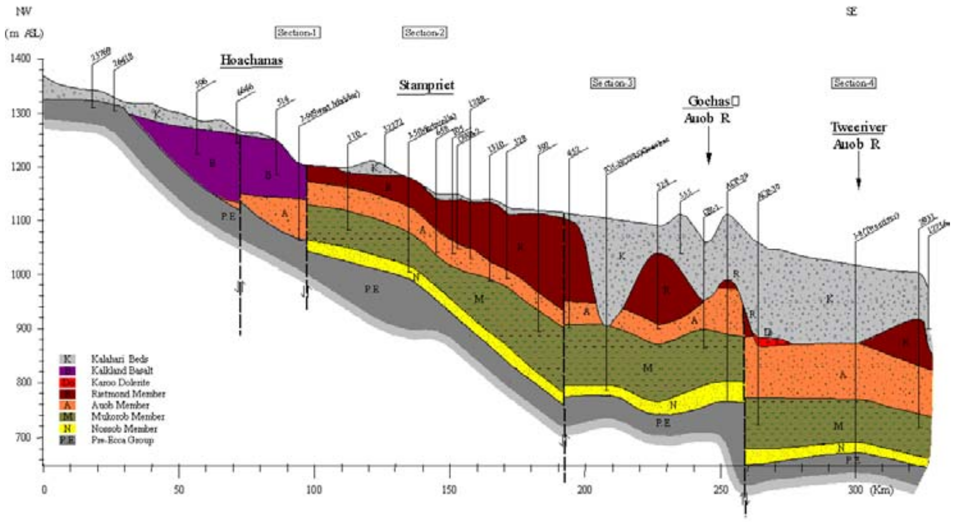

Figure 2: Cross-section through the SAB along the Auob River (after PCI, 2002).

3.3.3. Hydrogeology

The SAB consists of superimposed unconfined and confined aquifers, formed by a succession of sedimentary rocks deposited in a basin of the Nama System bedrock. The succession dips in a southeasterly direction with water levels and piezometric heads following similar patterns. Extended faulting particularly in the Northwest and Northeast, and the extensive intrusion of dolerite dykes and sills added a significant degree of complexity to the initial concept of equally spaced sandstone layers serving as aquifers. The complexity of the SAB was underscored by the extensive JICA research project, which showed that pre-Kalahari erosion also played an important role in changing the hydrogeological properties of the aquifers in the SAB.

Unconfined aquifer system

The unconfined aquifer system can include the Kalahari beds, the Kalkrand Basalt and partially also the Upper Rietmond Formation. The latter consists mainly of sandstone and subordinate shale bands, and as with the other members in this aquifer group, the water-bearing properties can vary significantly and some of the lower layers can even serve as an aquiclude for the underlying Auob aquifer. The distribution of each of the three aquifer units differs and in places only one of them may occur, while elsewhere two, or in limited areas, even all three, may be present.

The Upper Rietmond Formation occurs over most of the SAB, except in the extreme western part, and is generally overlain by Kalahari beds. The Kalkrand Basalt occurs in the northwestern part of the SAB, in some places is overlain by a thin Kalahari cover. Dolerite dykes or sills may occur below, in, or above the Rietmond Formation. The three geological units, i.e. the Kalahari, basalt and partially also the Upper Rietmond, are all unconfined and recharge water can freely enter, often through a Kalahari cover. Thus, although the chemical nature of the host rock and the groundwater may differ, the groundwater in these unconfined aquifers is essentially considered as one hydrological "type" of groundwater. That does not imply that it forms a contiguous water body, as in some areas no water, or only a perched water table, may be found.

Confined aquifers

Over large areas of the SAB the sediments of the Nossob, Mukorob and Auob form confined aquifers. The piezometric level gradient follows the surface water drainage system and the aquifer systems in the SAB discharge in a southeasterly direction. The local flow direction may vary in parts of the SAB, but the JICA project has confirmed that the recharge to the confined aquifers has to take place in the northern, northwestern and western parts of the SAB. Therefore, these areas have received most attention for the purposes of this project and a number of boreholes have been drilled there. Over most of the area the Auob and Nossob sandstones constitute the confined aquifers. Outcrops exist on the western Weissrand, and near the northern boundary of the basin where the confining shale may be absent. The Auob Member (Prince Albert Formation of the Karoo Sequence) consists of up to three sandstone layers with intercalated shale bands. Its reported total thickness varies between 27 and 153 m (cf. Table 1, see also Miller in PCI, 2002). It is overlain by the Rietmond shale and rests on the Mukorob Member (mainly shale about 60 to 100 m thick). Sandwiched between the Mukorob and the underlying Dwyka Group is the Nossob Member (also Prince Albert Formation) that can be subdivided into two sandstone layers divided by a shale layer. The thickness of the Nossob Member varies between 6 and 36 m.

In a paleo-valley entering Namibia at about 24°S, stretching towards Gochas and then turning SSE, a pre-Kalahari erosion has cut through the Rietmond and down to the lowermost Auob sandstone layer. The so-called Saltblock lies SE of the valley. Here the groundwater quality in all aquifers is poor.

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3.4. Methodology

3.4.1. Sampling methods

During the first phase of the project samples for isotopes (^{2}H, ^{3}H, ^{18}O and ^{14}C) were taken from selected existing boreholes throughout the Basin, from newly drilled production and from exploration holes drilled in the supposed recharge areas. Some of the samples collected during the hydrocensus were also analysed to fill gaps in the stable isotope analysis network. During the second phase sampling and exploration drilling was restricted to the assumed recharge areas at the western, northwestern and northern edges of the Basin. Where possible individual strikes were sampled (grab or pump), e.g. with the EDL method (see Kirchner et al., 2002) or by using packers. All isotope samples were also chemically analysed.

Fifty-seven (57) samples were analysed for macro chemistry and 412 samples for environmental isotopes (56 boreholes, 5 seasonal rainfall collectors, 26 rainfall events and 29 river runoff samples).

3.4.2. Field and laboratory analytical processes

In some cases the chemical analyses were filtered and for a considerable number of samples the temperature, pH, and alkalinity were also measured in the field. No further conservation, etc. measures were applied. Isotope samples taken by B. Verhagen were concentrated according to the Schonland Institute method (barium precipitate) while for the remaining samples the acidification and sodium hydroxide precipitation method of the CSIR was used. Except for some nitrogen samples the Schonland Institute performed all isotope analyses. Chemical samples were sent to laboratories in Windhoek (NamWater or Analytical Laboratory Services).

3.4.3. Quality control

Regarding isotopic data, the respective laboratories were responsible for the control. Problematic results such as the Schonland ^{13}C measurements were corrected and/or repeated. For a few samples coordinates had not been measured. These samples could not be properly located and linked to the borehole database. Considerable problems were encountered with some of the earlier chemical analyses done by Analytical Chemical Services, many of which did not balance. The main reasons were (i) inconsistent reporting with e.g. Ca being expressed either as Ca or as $CaCO_3$ or (ii), more serious, acidification of unfiltered samples.

3.5. Investigation results

3.5.1. Drilling in the Blumfelde area

The Department of Water Affairs in Namibia has made a significant contribution to the IAEA project by providing drilling services over a long period. It is known from the water level gradients and the hydrochemistry that recharge water enters the artesian sandstones also from the Weissrand Plateau. Thus, in 1999, when a number of boreholes were drilled for water supply on the Weissrand Plateau (e.g. on the farms Goamus, Nooitgedacht, Noronaub, and Glencoe), they were linked to the IAEA project. These boreholes are relatively near the Weissrand, but far enough eastward for the artesian aquifers to be confined. Each of the boreholes was screened in a particular aquifer and samples were taken at various stages during the drilling and, where relevant, also at the end of test pumping.

It was decided to add nine boreholes (see Table 1) northwards along the Olifants River past Blumfelde up to a point where the artesian sandstones would wedge out against the bedrock at the edge of the basin.

Table 1: Exploration boreholes drilled in the Blumfelde area by the DWA.

WW No	Farm No	Farm Name	Latitude (°S)	Longitude (°E)	Final depth (m)	Final rest WL (m)	Aquifer
39872	M096	Neu Simmern	-23.56040	18.31643	156	11.00	Nossob
39873	M094	Gumuchab-Ost	-23.52893	18.29247	136	9.40	Auob
39874	M103	Neumark	-23.59896	18.34573	78	Artesian	Kalahari/ Rietmond
39875	M096	Neu Simmern	-23.56078	18.31613	18	7.60	Auob
39876	M096	Neu Simmern	-23.56035	18.31656	76	7.65	Auob
39877	M094	Gumuchab-Ost	-23.52849	18.29252	72	9.50	Basalt
39878	M103	Neumark	-23.59311	18.32595	192	18.00	Auob
39880	M103	Neumark	-23.59293	18.32592	40	28.00	Kalahari/ Rietmond
39881	M097	Neu Loore	-23.55683	18.35345	168	22.80	Basalt/ Rietmond

3.5.2. Investigation on sinkhole structures

3.5.2.1 Desk study and field observation

During the "Uhlenhorst cloud burst" Schalk (1961) investigated an event where in the night from 24 to 25 February 1960 up to 489 mm of rain was recorded in an area between Uhlenhorst and Derm. He calculated that about 100 Mm^3 of water may have recharged the groundwater and stated that the nearest artesian borehole on Klein Swartmodder started flowing again (with a head of 1.4 m) within about three weeks after the cloudburst. This event gave a first indication of a potential recharge area. Tredoux et al. (1978) reported on chemical and isotopic investigations in the SAB. From isochrones it appeared that there is at least a recharge area N of Stampriet and one on the Weissrand. Vogel (1982) postulated a northern recharge area around Lidfontein.

Three development projects are currently conducted that affect the Stampriet Artesian Basin (SAB). These are the JICA SAB aquifer management project; the IAEA recharge investigation project and the HymNam hydrogeological map project. Analysis of the new satellite photos in connection with the HymNam project (Schaeffer, pers. communication) has indicated "sinkholes" on the Weissrand and in an area around Uhlenhorst (see Figs. 3 and 4). Work done by the BGR in connection with the Hydrogeological Map of Namibia (van Wyk et al., 2001) indicated sinkhole structures in the wider Uhlenhorst area and on the Weissrand.

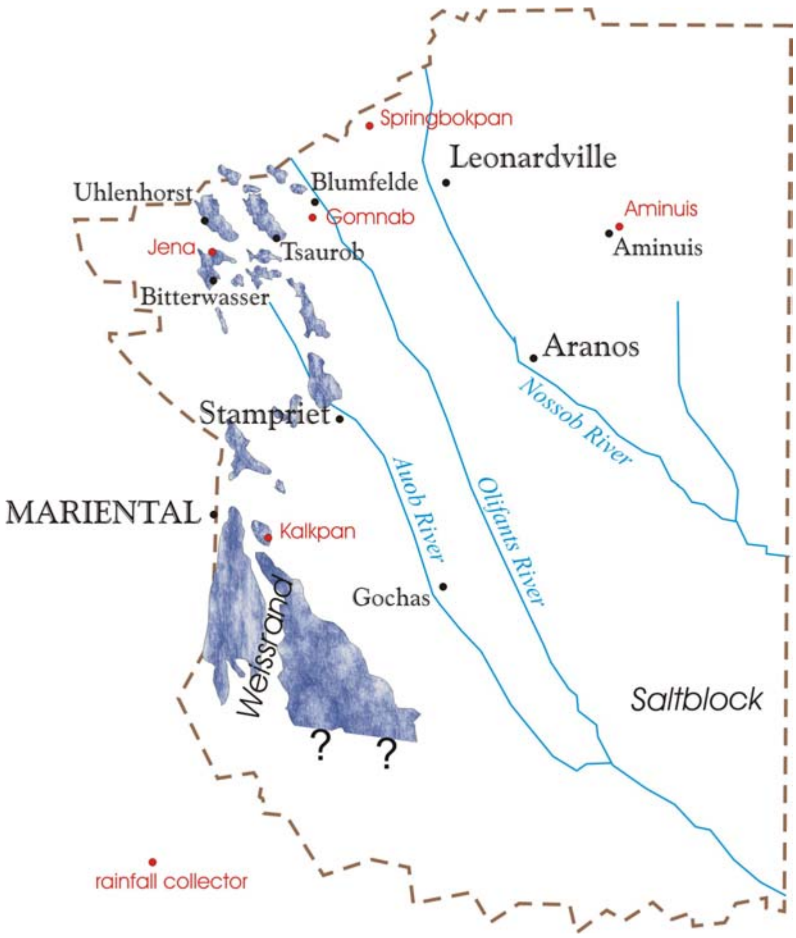

Figure 3: Extent of areas with sinkhole structures from Satellite images (no images were available for the southern part of the area).

LANDSAT images and aerial photographs (1:50 000) together with basic borehole data, geology and chemical analyses (DWA and the Hydrocensus Database) were used to detect these sinkhole-recharge-systems. Fracture traces, lineaments and sinkhole structures were clearly visible on both the LANDSAT images and aerial photographs.

Pan-like structures, developed from karstification in the Kalahari calcrete, were identified as possible recharge/intake areas of the artesian basin. These surface depressions/sinkholes vary in diameter and shape (circular to ellipse) and form local surface drainage accumulation points.

Field investigations (May 2001) in the Uhlenhorst area showed that these dark spots were small depressions in a calcrete-covered area. On the aerial photos it can be seen that the surrounding seems to drain towards these "sinkholes" but on the ground this is not clearly recognisable. The depressions are about 0,5 to 1.0 m deep and typically between 50 and 100 m in diameter (see Fig. 5 and 6).

While the calcrete areas have a vegetation cover of grass and dispersed small shrubs with occasional Witgat trees (on Klein Begin bordering Uhlenhorst) the depressions have an outer ring of Gabba bush with occasional Blinkblaar wag 'n bietjie while the centre is loosely covered with Driedoring. Here the soil consists of predominantly medium-grained sand with a small fine sand to silt fraction.

At the time of the visit, roads were still wet and water was standing in ditches next to the road. Pans were full of water but the "sinkholes" were dry. At other places in the area, for instance at Tsaurob, "sinkholes" were found that had a greater clay or silt deposits in the centre with traces of water still standing there. In between the sinkholes (and at other places) there are pans of varying size that may contain fresh, brackish or salt water. "Sinkhole" development does not take place everywhere but only in certain stretches.

From these observations the following karstification development is deduced for the calcrete-covered areas: In areas where calcrete is underlain by more permeable rock, rainwater percolates at a faster rate through the calcrete. This leads to dissolution of calcium carbonate. The greater permeability can be due to an underlying sand or sandstone; to a weathered basalt surface; or to fault- and fracture zones in the basalt.

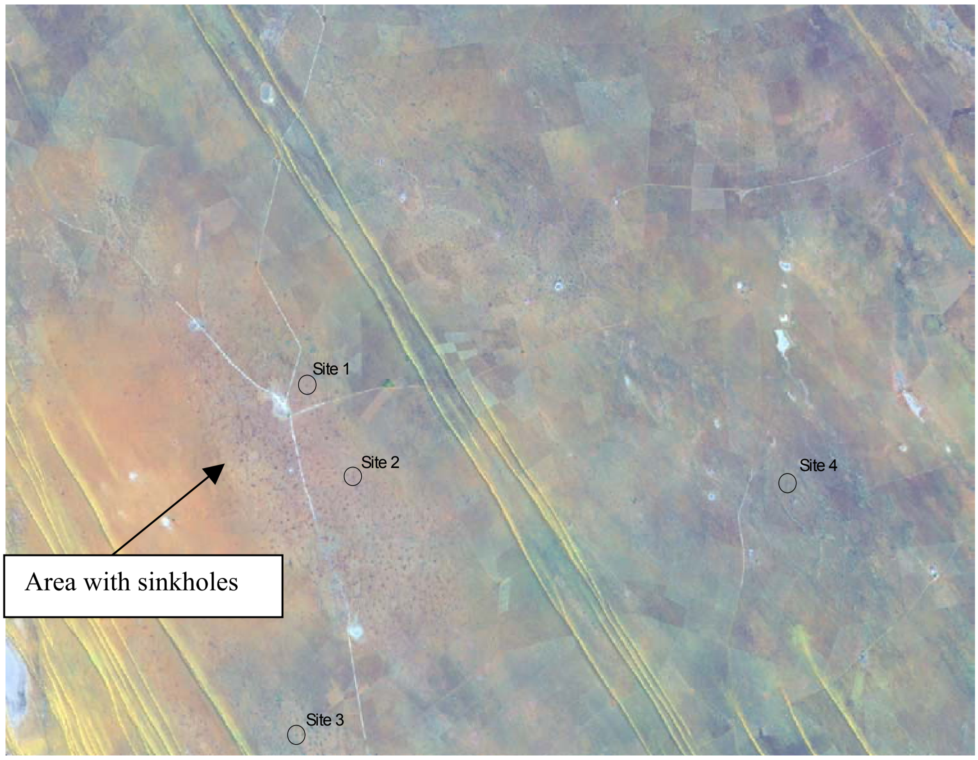

Figure 4: Dark dots near road intersection (Uhlenhorst) identified as potential sinkhole structures and approximate positions of the targeted drilling sites in the Uhlenhorst surrounding.

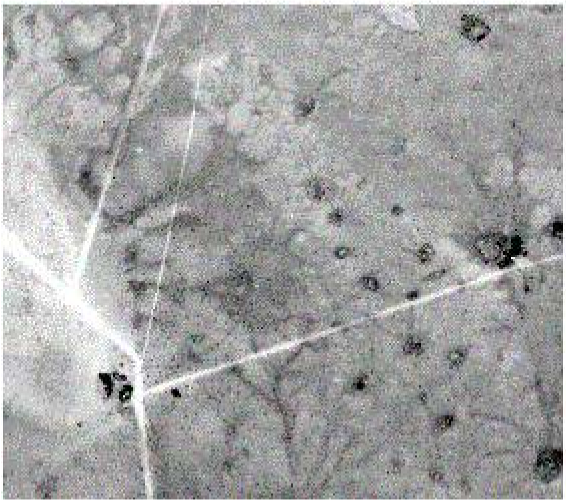

Figure 5: Aerial photo of an area near the Uhlenhorst road junction.

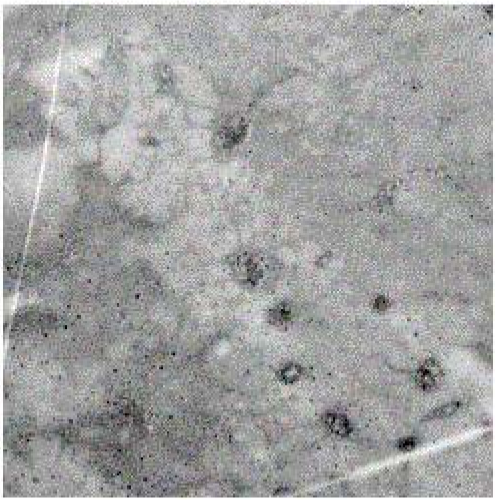

Figure 6: Enlargement of aerial photo (Fig. 5) showing “sinkholes” and drainage lines.

As the “sinkhole” gets larger more fines are washed in and deposited at the deepest point in the centre. Whether the sinkholes are sealed from the top or impermeable fines build up from the bottom of the sinkhole still needs to be determined. As long as the water in the hole can still percolate downwards in the outer regions of the sinkhole it remains fresh. When the sinkhole gets larger and the bottom increasingly sealed the sinkhole becomes a pan. Evaporation increases. First carbonates are deposited and later other salts as well. In the process the pan becomes first brackish and later salty.

3.5.2.2 Site selection and drilling program

Site selection

Three NNW – SSE trending sinkhole zones can be recognised on the satellite images: one on the farm Reussenland and Bitterwasser, a second one on Uhlenhorst, Klein Begin – Jena and a third (less prominent) one stretching from the Karlsruhe area to Tsaurob. These indications and the site selection criteria defined below were used to define the investigation areas of the 2nd round of drilling and sampling. Site Selection Criteria were based on low TDS/EC, restricted NO_3, sinkholes/no drainage system developed, sufficiently higher water level than piezometric heads in nearby (sub)artesian holes and sufficiently high ^{14}C values if already available.

Drilling programme

To provide information on the recharge area(s), recharge rate and age of groundwater, a total of 15 boreholes were drilled in or near the possible intake areas to the artesian sandstone (see Table 2).

Table 2: Exploration boreholes drilled in sinkhole areas.

Borehole No.	Location	Aquifer Type	Lat. [S]	Long. [E]	Elev. (mamsl)	Depth (m)	Water level (mbgl)
WW40004	Klein Begin M535	Kalkrand Basalt	-23.68717	17.97931	1295	60	18.07
WW40005	Klein Begin M535	Kalkrand Basalt	-23.69171	17.98372	1295	48	17.86
WW40006	Bitterwasser M116	Kalkrand Basalt	-23.86712	17.95967	1268	78	20.90
WW40007	Tsaurob M106	Kalahari	-23.74549	18.20701	1279	24.6	4.95
WW40007	Tsaurob M106	Auob	-23.74549	18.20701	1279	152	40.97
WW40008	Jena M117	Kalkrand Basalt	-23.75886	18.01779	1281	48	16.63
WW40009	Bitterwasser M116	Kalkrand Basalt	-23.86403	17.95227	1270	57	21.42
WW40010	Karo M081/002	Kalkrand Basalt	-23.63193	18.05764	1302	48	9.37
WW40011	Tsaurob M106	Kalahari/Rietmond	-23.74511	18.20632	1276	50	4.00
WW40015	Tsaurob M106	Kalahari/Rietmond (cemented); Auob (open hole)	-23.73392	18.19711	1283	156	39.68
WW40016	Tsaurob M106	Kalahari/Rietmond (cemented); Auob (open hole)	-23.73360	18.21218	1281	156	35.85
WW40017	Tsaurob M106	Kalahari/Rietmond	-23.74600	18.20742	1279	36	5.60
WW40018	Gompou L490	Kalahari/Rietmond	-23.88513	19.12509	1468	128	Dry
WW40019B	Biesiepan L748	Auob + Kamtsas Quartzites	-22.91757	19.10457	1474	252	177.75
WW40084	Themaat R210/002	KH/RM (cemented); Auob	-24.69302	18.26827	1200	150	33.40
WW40085	Themaat R210/002	Kalahari/Rietmond	-24.70365	18.26042	1200	90	22.63

Drilling procedure

The air percussion drilling method was applied for hard (Kalkrand Basalt) and stable rock (semi-consolidated Kalahari/Rietmond and Auob formations). The rotary drilling method, using a direct mud circulation, has been used to support and penetrate unstable formations (unconsolidated Kalahari Beds). In some boreholes, a combination of the two methods was applied, mud rotary for the upper unstable Kalahari formations and air percussion drilling for the underlying Auob formation. Cement grouting was used to seal off the overlying Kalahari/Rietmond formation thus preventing contamination/mixing/leaking of the groundwater from the Auob aquifer into the Kalahari/Rietmond or vice versa.

Exploration boreholes

Exploration holes in the Uhlenhorst area have been drilled in "sinkholes" on Bitterwasser, Klein Begin, Jena, Tsaurob and Karo to determine the lateral (E-W) and the N-S extension of the postulated recharge zones; on Biesiepan NW of Aminuis; and on Themaat some 30 km ESE of Mariental on the Weissrand. The detailed information on these boreholes and other exploration boreholes drilled by the DWA is listed in Kirchner et al., 2002.

3.5.2.3 Conclusions

Boreholes drilled inside sinkholes on fracture traces deliver higher yields and are of better quality (lower EC's) than boreholes drilled in isolated sinkhole structures. Salinity of groundwater increases towards the Southeast.

Kalahari Beds & Rietmond Member

The Kalahari formation is made up of aeolian sands and poorly sorted fluvial deposits, variously cemented by calcrete (fine to coarse grained unconsolidated to semi-consolidated sands). At the base of the Kalahari, poorly sorted conglomeratic fan deposits result in high yielding boreholes (18 – 40 m^3/h) – Tsaurob boreholes (Site 4 on Figure 4): WW40007, WW40015, WW40017.

The underlying Rietmond Member of the Prince Albert Formation consists of alternating varicoloured sandstone (micaceous – muscovite) and shales. The basal shale units (yellow and black shales) are useful markers determining the base of the Rietmond member. The JICA survey regarded Kalahari and Rietmond as one hydrogeological unit due to the absence of an impermeable layer between the two formations.

Water struck in the Rietmond formation wrongly appeared to have higher yields than waters in the Kalahari. Packer tests, measuring the flow of groundwater, show that the Rietmond strikes yielded very little water, although, during drilling, it seemed that the Rietmond yielded more water than the overlying Kalahari. The increase in yield must be attributed to the development of the permeable zones (removal of fine sands) in the Kalahari Beds during the drilling. This phenomenon was observed in three Tsaurob Kalahari/Rietmond boreholes (WW40007, WW40011, W40017).

Auob Formation

The Auob formation was found in five locations and varied in thickness between 79 m (WW40019B-Biesiepan) in the Northeast; thicknesses of 47 m, 52 m and 57 m (Tsaurob: WW40016; WW40015; W40007) in the Northwest; and 30 m (WW40084-Themaat) in the west. Water occurs in the three sandstone formations (A5, A3, A1) with the lower sandstone (A1) yielding more water than the upper two sandstone layers. Four Auob boreholes were drilled through the Auob into the Mukorob formation.

3.5.3. Environmental isotopes

3.5.3.1 Environmental isotope distribution in rainwater

Rainwater samples were collected at seven rainfall stations and rainfall collectors were placed at five locations. As a part of the rainfall sampling programme, a set of five rainfall collectors were deployed in the presumed recharge areas in the northern, north-western and western parts of the Basin. Most of these are located at places where the rainfall is measured (see Appendix 6 in Kirchner et al. 2002, for details). These rainfall collectors are designed to prevent evaporation of the collected rainwater and they were only emptied in July 2001 at the end of the 2000/2001 season. The samples are intended to provide a weighted "mean" value for the stable isotopes and, particularly, for the chloride concentration in the precipitation. The only maintenance needed, is the removal of leaves, large insects and other objects that may end up on the gauze in the entry funnel. Analytical results for the five rainfall collector stations are listed in Table 3 (see also Fig. 3).

Table 3 : Rainfall collector results for the 2000/2001 rainy season.

Farm Name	Farm No	^{18}O ‰	^{2}H ‰	D_{excess} ‰	Cl, mg/L
Onderombapa, Aminuis	L330	-3.3	-15	11.5	0.7
Springbokpan	L534	-5.2	-28	13.8	0.6
Gomnab	M104	-5.2	-29	12.4	0.8
Jena	M117	-4.7	-26	11.7	1.1
Kalkpan	R087	-6.5	-41	11.3	18.5

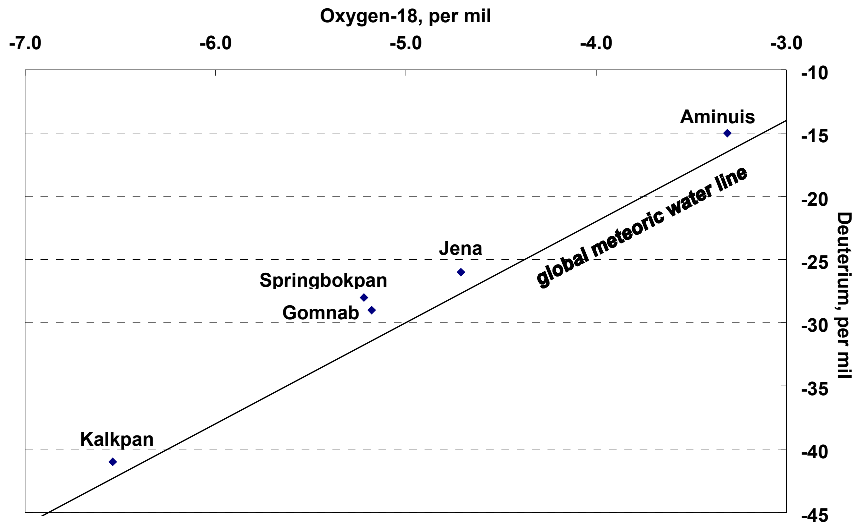

Figure 7: Rainfall collector results for the 2000/2001 rainy season.

The first four stations are located in the northern part of the basin from Aminuis in the east to Jena in the west. The fifth one was located on the Weissrand in the Southwest. The chloride values are the most important results from the rainfall collectors and these values are considered to represent the input values for chloride into the groundwater. There is a slight increase from east to west with the one at Kalkpan being a complete outlier. Investigation showed that this collector had been tampered with and the gauze and the Ping-Pong ball in the entry funnel had been removed. As a consequence, foreign material could enter the collector and the chemical results are not considered to be representative of that of the rain. None of the samples showed any evaporative signal and the points are actually slightly above the world meteoric line (i.e. $D_{excess} > 10$). It is also evident that the isotopic composition of the water in the collectors is not representative for the groundwater. This follows from the fact that all rainfall events, large and small, contribute to the sample in the collector but not all rainfall events contribute to groundwater recharge.

The chemical and isotope composition of the water in the rainfall collector thus represents a "mean" value for the rainfall. The differences in the isotopic composition of the rainwater of smaller (<30 mm) and larger (>30 mm) events are shown in Table 4.

Table 4: Differences in rainwater isotopic composition during smaller and larger events.

Rainfall station	Month	Event(s)	δ^2H ‰	$\delta^{18}O$ ‰	D_{excess} ‰
Jena	March 2001	< 30 mm	-33.4	-4.85	5.4
	April 2001	< 30 mm	-21.2	-4.63	15.8
	April 2001	> 30 mm	-6.8	-2.66	14.5
	April 2001	> 30 mm	-68.0	-10.67	17.4
Kleinhütte	April 2001	< 30 mm	-33.3	-5.81	13.2
	April 2001	> 30 mm	-66.1	-10.47	17.7
Gomnab	April 2001	< 30 mm	-13.6	-3.83	17.0
	April 2001	> 30 mm	-69.9	-10.87	17.1
	April 2001	> 30 mm	-37.0	-6.33	13.6
Windhoek	April 2001	< 30 mm	-45.2	-7.14	11.9
	April 2001	> 30 mm	-97.1	-14.08	15.5

3.5.3.2 Environmental isotope distribution in floodwater

As explained above, the collection of surface runoff in the sandy Kalahari is considered important for groundwater recharge, at least with respect to the unconfined aquifers. Therefore, when it was realised that the 1999/2000 rainy season could yield above average rainfall, a special attempt was made to obtain flood water samples from a number of strategic points along the three rivers, both at points where the rivers enter the SAB and at points within the SAB. The sampling programme for the 2000/01 season is detailed in Appendix 6 (in Kirchner et al., 2002). The idea was to obtain an indication of the isotopic composition of the water that is available for recharging the various aquifers. It was planned to determine the chronology of the flood pattern at various places along the rivers, e.g. when the flood started, when it reached its maximum, and gradually subsided. It is obvious that it would be ideal to use flood hydrographs, i.e. at places where the DWA has gauging stations with measuring weirs and recorders installed. Thus, where possible, sampling was arranged to take place at weirs and at road bridges where the flood pattern could be monitored. Subsequently, the points when the stable isotope samples were taken could then be identified on this time scale. Using this approach, variations in isotope concentrations over the flood period could be linked to the flood hydrographs and provide a semi-quantitative idea of the isotopic composition of the water that could potentially recharge the (unconfined) aquifers. It is noted that the isotope variations during the flood will depend on differences in isotopic composition of the rain showers, which in turn will depend on the rainfall intensity. The isotope signal observed will also depend on the time lag and distance between the point of precipitation and the sampling point. Finally, evaporation of the runoff from the rivers and eventual ponds that may form in the riverbeds will modify the isotopic composition.

The heavy rainfall at the end of February and early March 2000 resulted in a flood within the Auob River, that was sustained for at least two weeks, while in the Olifants River it only lasted a few days, and in the Nossob River it was even of shorter duration. However, only partial flood hydrographs could be obtained from the DWA recorders. These floods followed earlier ones of December 1999, also occurring in the lower reaches of the rivers. At this stage it would seem that the February 2000 floods were largely due to local heavy precipitation. The total rainfall for Olifantswater West, M102, for February 2000, was 256.8 mm of which 109.3 mm was recorded on 29 February 2000. Then only the Olifants River briefly started flowing until 2 March. Reportedly, the flood only reached the southern boundary of the farm Olifantswater West.

Following the (now outdated) arrangements in 2000 (see Appendix 6 in Kirchner et al., 2002), floodwater samples were taken at four points on the Auob River, three on the Olifants River and two on the Nossob River. A pan near Bulwana, R229, on the southern Weissrand Plateau, to the west of the Auob River, was also sampled. The information from the samplers was correct at the time and the information is only provided for keeping track of the sampling details for record purposes. Some of the persons involved had moved and were no longer available and a new programme was drawn up for 2001 and more detailed flood data were collected.

It was not expected that floods would again occur In the 2001/2002 rainy season, particularly as the rainfall in the early season was well below average. However, preparations were made in the event of heavy rainfall events and this actually occurred towards the end of the rainy season in April 2001. Similar sets of sampling stations were used and the updated programme used in 2001 is given in Appendix 6 (in Kirchner et al., 2002).

3.5.3.3 Hydrochemistry and environmental isotopes in groundwater

3.5.3.3.1 Hydrochemistry

Extensive hydrochemical evolution takes place in each of the SAB aquifers as described by Kirchner & Tredoux (1975), Tredoux & Kirchner (1981) and Tredoux (2000). It was shown that particularly in the confined aquifers high sodium percentages develop and high alkalinities are reached. In the Nossob aquifer, the hydrochemical evolution already reaches an advanced stage near the northern edge of the SAB. These interpretations are not repeated here but should be kept in mind when interpreting the environmental isotope results, particularly in the recharge areas. More detailed information on the chemistry in those areas is provided under the chapter 3.6. All chemical analysed under Project RAF/8/029 as well as earlier ones relating to isotope analyses done in the past are listed in Appendix 3 (in Kirchner et al., 2002).

3.5.3.3.2 Environmental isotopes

During investigations in the 1970s (Tredoux et al., 1978) and early 1980s (Vogel et al., 1982); under the Japanese JICA study (PCI, 2002); and also during the present IAEA project hundreds of groundwater samples were analysed for environmental isotopes. Most of the older analyses have been captured and are provided in Appendix 4 (in Kirchner et al., 2002) together with those done under the current RAF/8/029 project. Further discussion and interpretation will be done under chapter 3.6.

3.6. Discussion and Interpretation

3.6.1 Stable isotopes

The results are portrayed on maps showing the outline of the proclaimed subterranean water control area. The deuterium (δ^2H) values in the unconfined aquifer system increase from the Northwest to the Southeast (see Figure 8). This agrees with the direction of the topographic gradient. However, the difference in elevation is only 350 to 400 m, which will allow a maximum increase of 10 ‰ in δ^2H due to the altitude effect. The difference is somewhat greater and, therefore, the water was possibly also subjected to evaporation. The low values along the lower Nossob are recharge processes, which will be discussed in more detail below. The parallel JICA project also contributed analytical data for these figures as approximately one-third of the stable isotope analyses (^2H and ^{18}O) were carried out as part of that project.

Except for the extreme south, deuterium ratios in the Auob aquifer do not vary significantly over the basin (see Figure 9). This would indicate that once the groundwater has reached the aquifer, no evaporation or other process could significantly affect the stable isotope concentrations. Only mixing with water from another source can change the stable isotope composition. Over most of the eastern and northern part of the SAB the δ^2H ratio is slightly below -50 ‰. In the Stampriet-Aranos-Gochas area the δ^2H ratios are consistently between –50< -45. Three sampling points between Hoachanas and Stampriet have δ^2H ratios < -50 ‰. This gives the impression that Stampriet is dissected from its presumed recharge area and this will need further investigation. The higher δ^2H ratios in the area southeast of Gochas agree with the ratios in the unconfined aquifer system, confirming that the two aquifers are in direct hydraulic contact in this area.

Figure 10 shows a consistent pattern for the distribution of deuterium in the Nossob aquifer. The extremely high δ^2H value (-20 ‰) at borehole WW36986 on the Weissrand contrasts with the nearby borehole WW39853 (J7N) with a more realistic value of -50 ‰. The δ2H value of borehole WW36986 is not considered to be representative of the Nossob aquifer. Thus the borehole may need to be resampled after inspection of the borehole casing with a borehole camera. Similarly, the sample from borehole WW39856 (J8N), at the confluence of the Olifants and Auob Rivers at Tweerivier in the Southeast, possibly gave an incorrect deuterium value. The borehole has an extremely low yield and it was difficult to flush. At the time of sampling the borehole may still have been contaminated with foreign water.

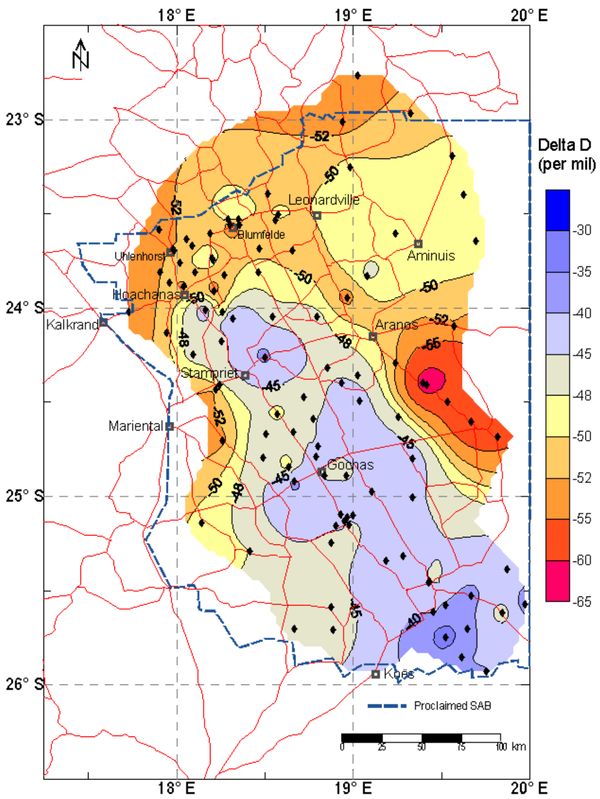

Figure 8: Deuterium ratios (delta D) in the unconfined aquifer system (Kalahari, basalt and Rietmond).

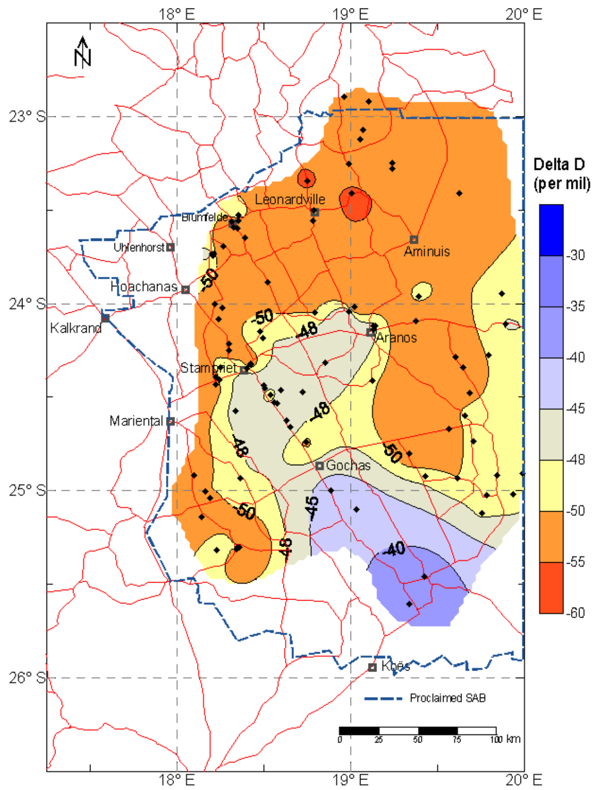

Figure 9: Deuterium ratios (delta D) in the Auob aquifer.

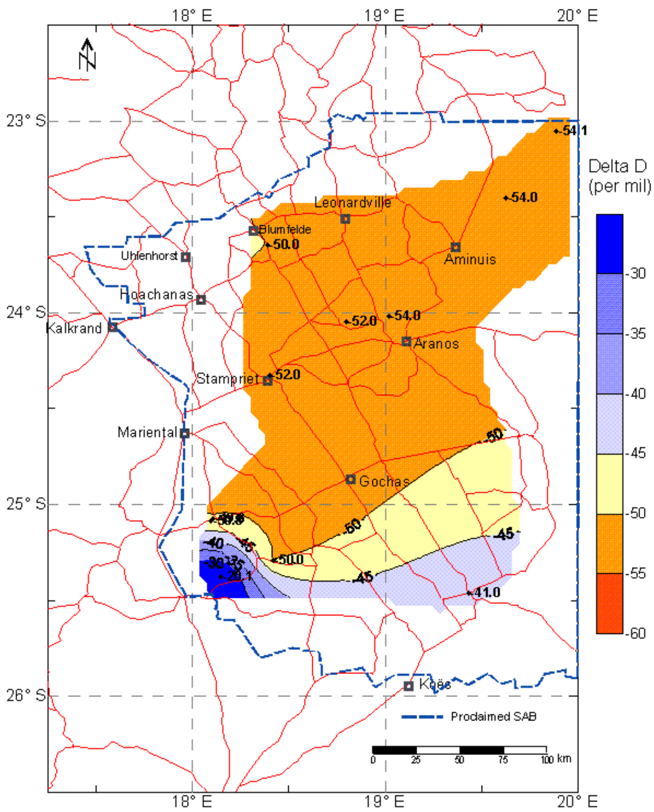

Figure 10: Deuterium ratios (delta D) in the Nossob aquifer.

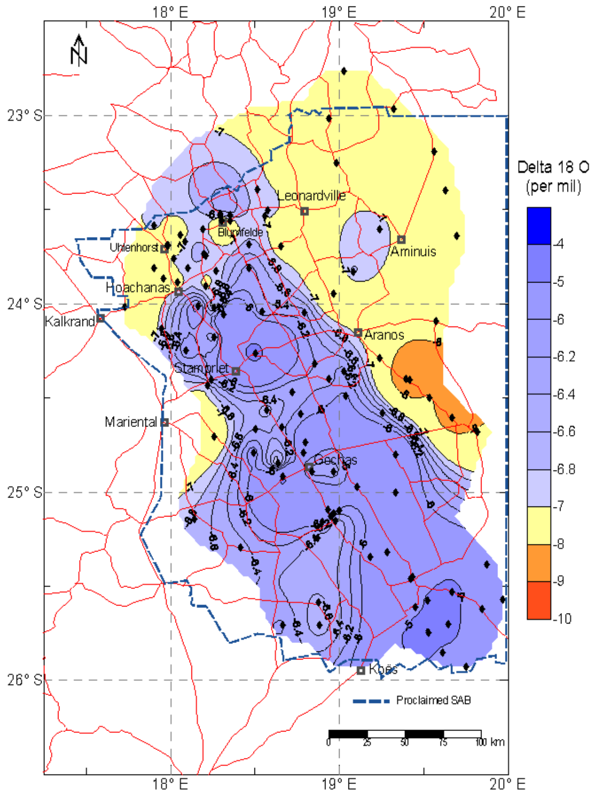

Figure 11: Oxygen-18 ratios (δ [18]O) in the unconfined aquifers (Kalahari, basalt & Rietmond).

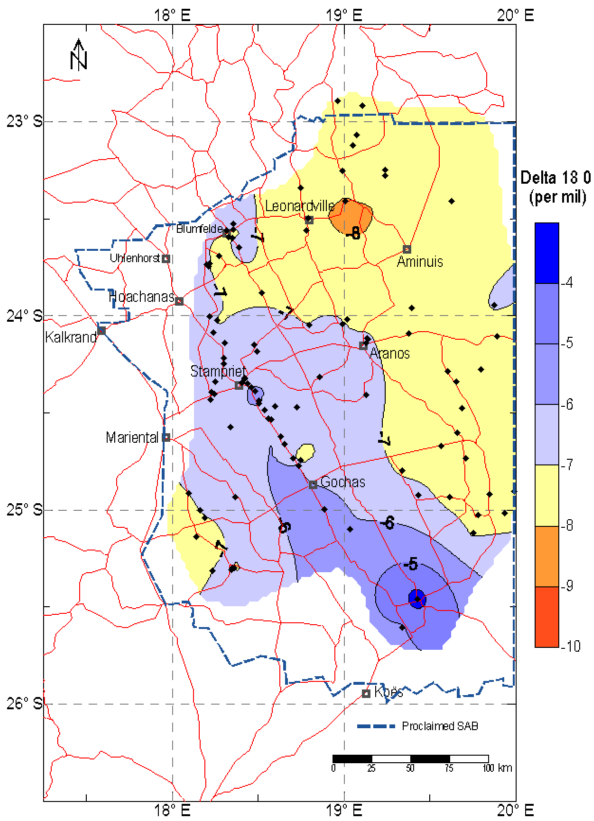

Figure 12: Oxygen-18 ratios (δ [18]O) in the Auob aquifer.

Initially it would seem that the $\delta^{18}O$ distribution in the unconfined aquifer system differs from that of deuterium, but it may be partially related to the choice of contour intervals (see Figure 11). In the unconfined aquifers, the values increase in a southeasterly direction along with the topographic gradient and the groundwater flow direction. In this aquifer system evaporation or evapotranspiration is possible over most of the basin. The few higher $\delta^{18}O$ values in the unconfined aquifer near Stampriet are conspicuous, and could be related to isotopically enriched irrigation return flow. The low values (up to –9.0 ‰) in the Kalahari aquifer along the lower reaches of the Nossob River are also clearly evident and are ascribed to rapid local river recharge of the unconfined aquifer following rainfall events of greater magnitude.

In the Auob aquifer the $\delta^{18}O$ values in the southwestern half of the basin are consistently above –7.0 ‰ while they are smaller than –7.0 ‰ in the northeastern half of the basin (see Figure 12). In the extreme south, the values are comparable with those of the unconfined aquifer system. These higher values are ascribed to the ingress of groundwater from the overlying unconfined aquifers in the vicinity of Gochas where the shale aquiclude of the Auob aquifer has been eroded.

In the Nossob aquifer (see Figure 13) the same two boreholes, WW36986 and WW39856 (J8N), with high deuterium (δ^2H) values, also have anomalously high $\delta^{18}O$ values.

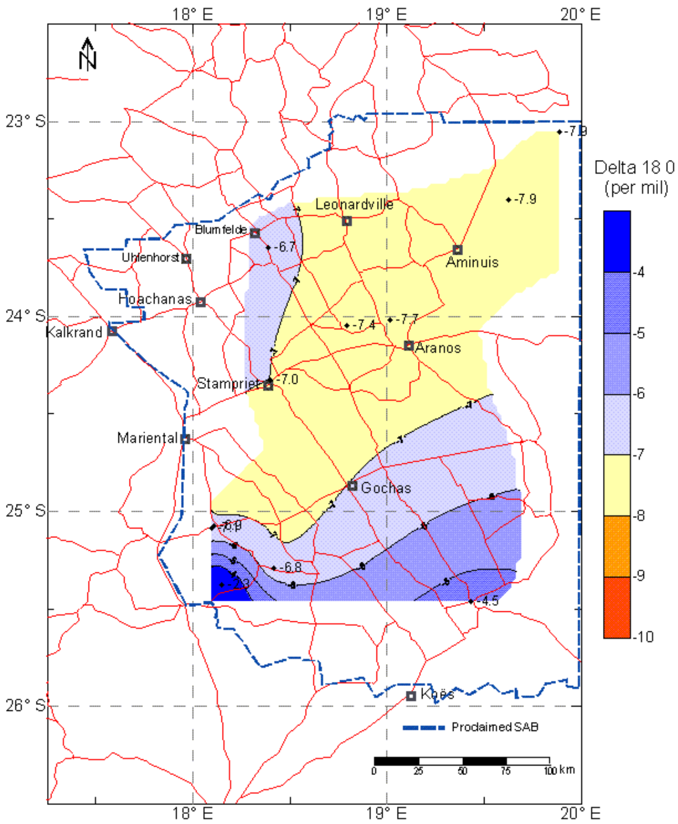

Figure 13: Oxygen-18 ratios ($\delta^{18}O$) in the Nossob aquifer.

In Figure 14a all the available stable isotope data points are plotted together. The graph also shows the meteoric water line and a linear regression line for the Kalahari groundwater. The main feature is that most of the points plot along a linear regression line with a slope of about 5, that agrees with a typical evaporation line. Thus virtually all the groundwater in the basin has been affected by evaporation. The isotope data for the unconfined aquifer system of the Kalahari, basalt (Kalkrand Formation) and the Rietmond Formation are plotted separately in Figure 14b. This clearly shows the distribution of the points along the evaporation line. Two of the boreholes along the lower reaches of the Nossob River with low values for both variables can clearly be seen in the lower left-hand corner of the graph. These waters are close to the meteoric water line and have, therefore, not been significantly affected by evaporation. This is of importance, as it would indicate that the floodwater dissipated quickly before the water had a chance to evaporate at the surface.

The graph for the Auob aquifer (Figure 14c) shows that the deviation from the meteoric water line is generally less pronounced for the Auob groundwater, except for a few outliers, which may be incorrectly classified or may have leaky borehole casings. Most of the points representing Nossob groundwater also plot in this part of the graph (see Figure 14d). The only exception is borehole WW36986 on the Weissrand.

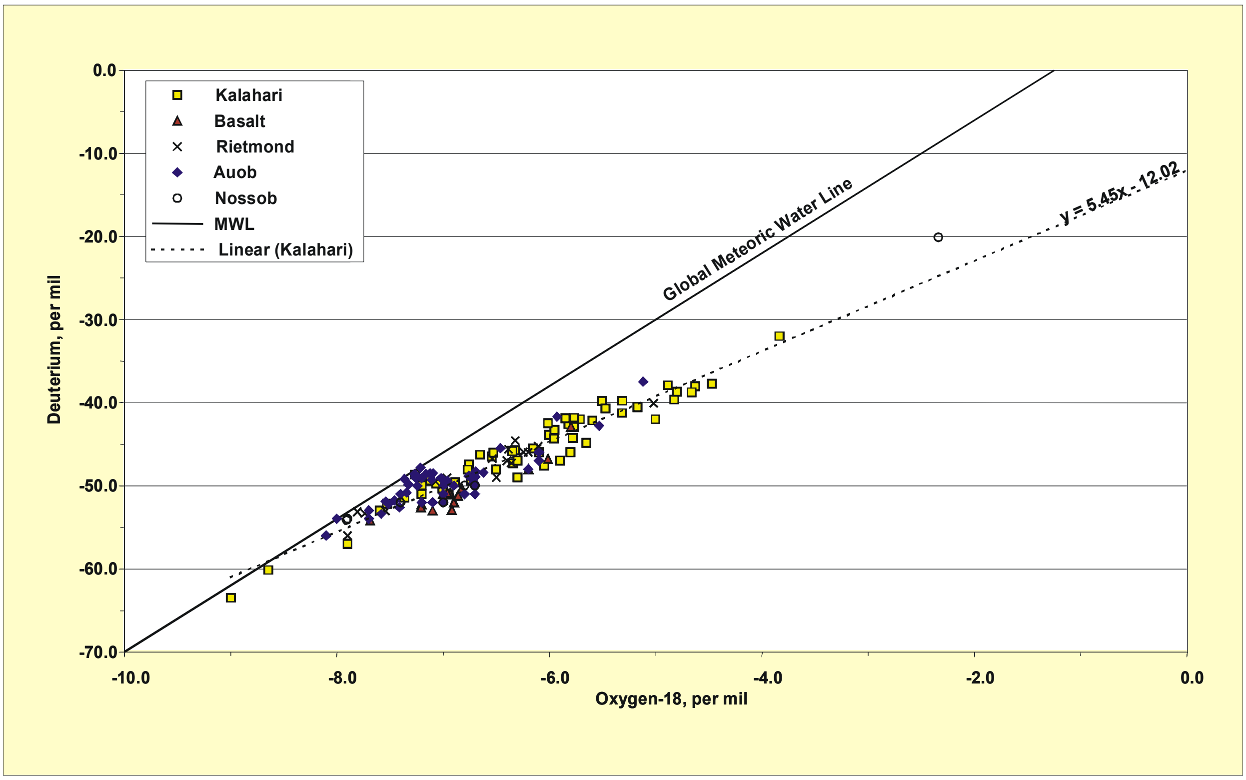

Figure 14a: Stable isotope relationship in all aquifers.

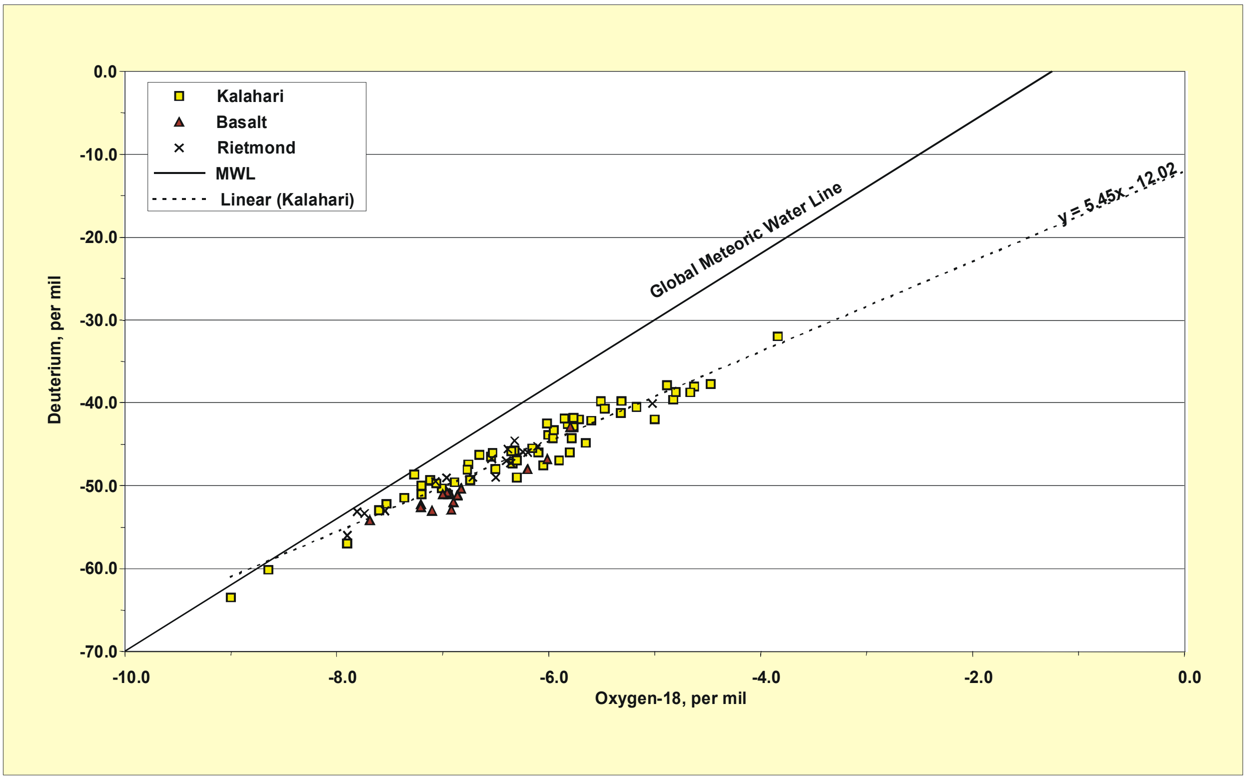

Figure 14b: Stable isotopes relationship in the unconfined aquifer system: Kalahari, basalt & Rietmond.

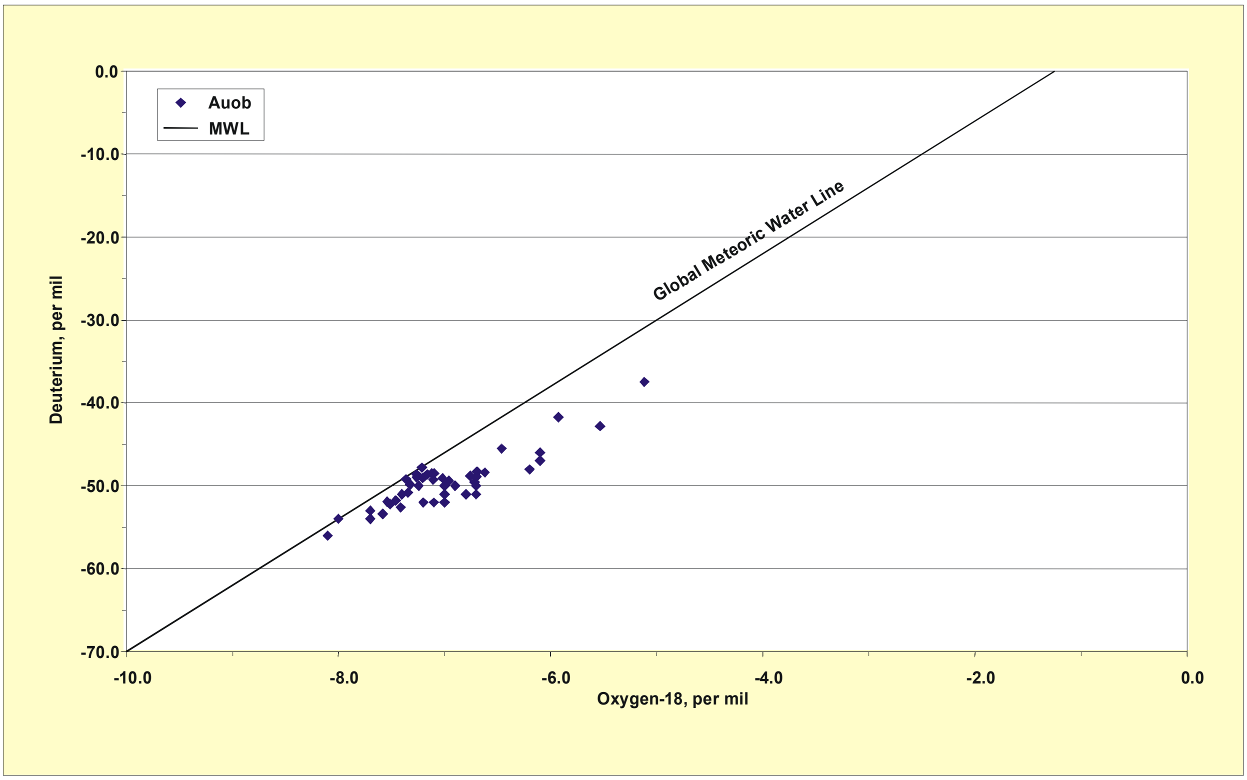

Figure 14c: The stable isotope relationship in the confined Auob aquifer.

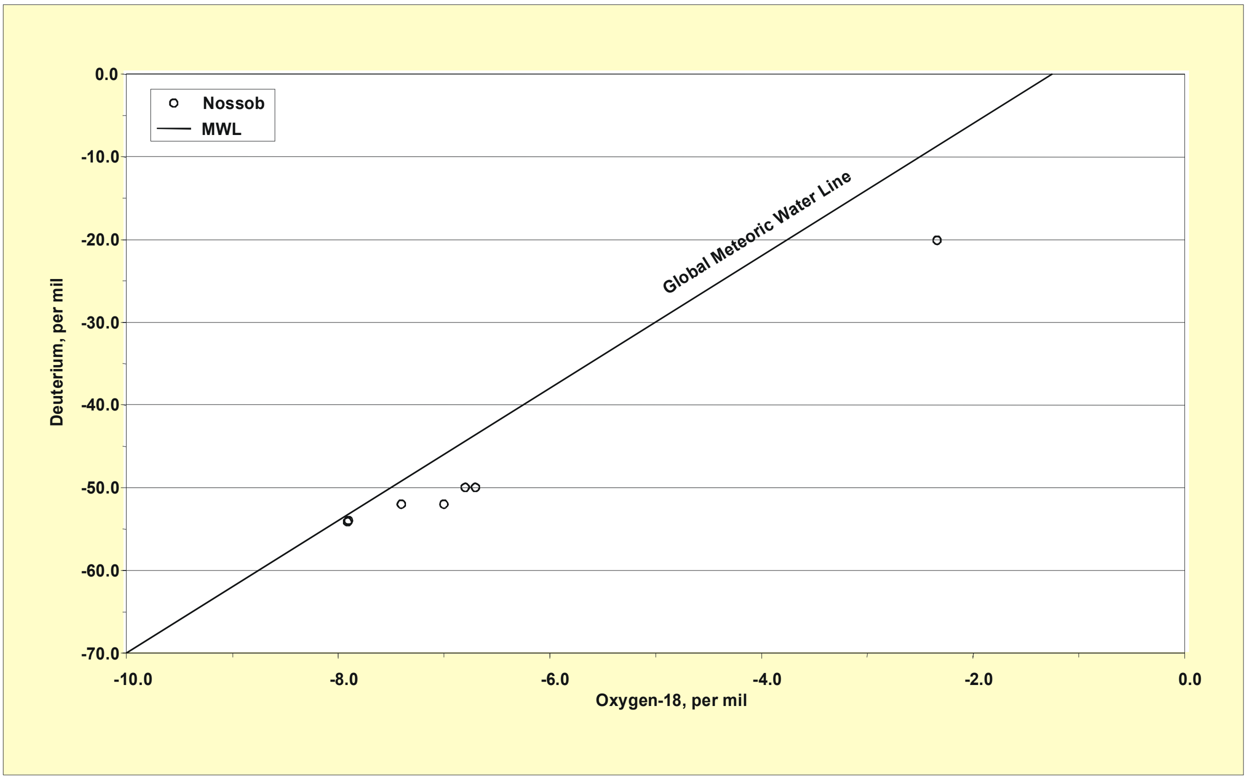

Figure 14d: The stable isotope relationship in the confined Nossob aquifer.

It is noteworthy that groundwater, depleted in ^{18}O and deuterium, was also found in a hand dug well located on the farm Doornboompan, L542, in an area between the Olifants and the Nossob Rivers several km from the nearest river. The well has a diameter of 1.5 m and, although it is covered, the surface area of the water is large enough to allow evaporation and the isotope data show slight signs of evaporation. On the farm Versailles, M67, located northwest of Uhlenhorst, an open water body, considered to be a spring, was sampled. It had a high deuterium content but showed strong signs of evaporation. Despite the high evaporation that can be expected in these circumstances, and the presence of thousands of birds, the spring has a very low electrical conductivity of 21.1 mS/m and a very low chloride content of 3 mg/L. In most cases it is most difficult to sample a spring at the point where it issues. Mostly such a point (or points) is difficult to locate and special efforts will have to be made to procure representative samples of the issuing water. The problem is also evident when considering the data for Rietquelle, near Aminuis.

When extrapolating the line (with a slope of 5) connecting the data points for the Versailles spring and the Doornboompan well to the meteoric water line, it intersects the line approximately at $\delta^{18}O = -15$ ‰ and $\delta D = -110$ ‰. This is in the same range as the data for the exceptional floodwater in the rivers. The fact that the isotopically depleted water can be found in a well and a spring, which are nearly 100 km apart, raises the prospects that more occurrences of this anomalous water can be found. If this is the case and the movement of such water bodies could be monitored, it would contribute significantly to the understanding of the groundwater recharge mechanisms.

The global meteoric water line (MWL) is defined by the relationship:

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

The δD and $\delta^{18}O$ values are defined in terms of standard mean ocean water (SMOW) but the water vapour has a δD excess of 10 ‰. In general, the deuterium excess is defined as (Gat, 1996):

$$D_{excess} = -8 * \delta^{18}O + \delta D \text{ ‰}$$

The distributions of the deuterium excess of groundwater in the three aquifer systems are plotted in Figures 15a to 15c. A D-excess value of 10 ‰ would represent points falling on the meteoric water line, while lower values would indicate a deviation from this line, mostly due to evaporation after precipitation. Such points generally plot along an “evaporation line” with a slope of 5.

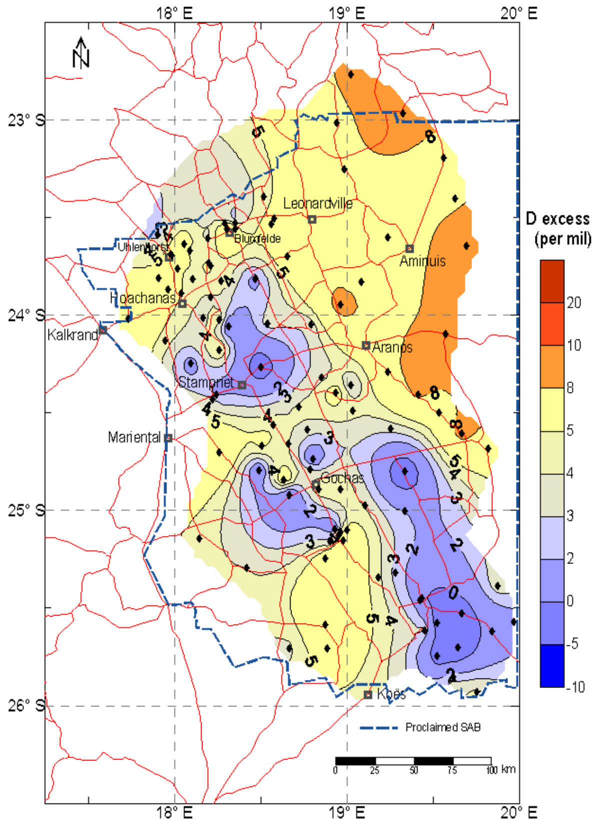

Figure 15a: Deuterium excess in the unconfined aquifer system (Kalahari, basalt & Rietmond).

In the unconfined aquifer system, the only areas where the D-excess approaches values close to the meteoric water line (i.e. > 8 ‰), are located along the Nossob River, to the east of Aminuis and Aranos, and near the northern edge of the SAB (see Fig 15a). Considering the higher values along the Nossob River, it is postulated that the recharge process along parts of the main river systems differs from that in other parts of the basin. Floodwater rapidly seeps into the sandy, permeable Kalahari beds after brief exposure to evaporation causing only a slight deviation from meteoric isotope ratios. Furthermore, the low δ^2H and $\delta^{18}O$ isotope ratios along the lower reaches of the Nossob River indicate that the recharge mostly occurs after extreme storm events.

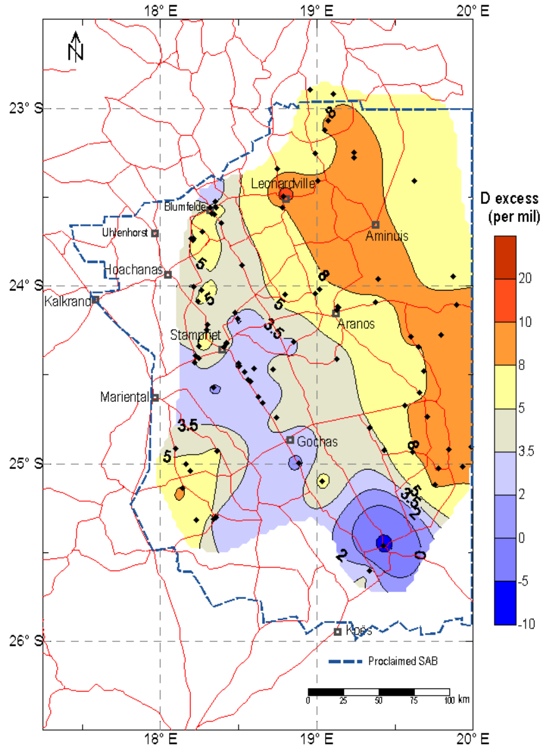

Figure 15b: Deuterium excess in the Auob aquifer.

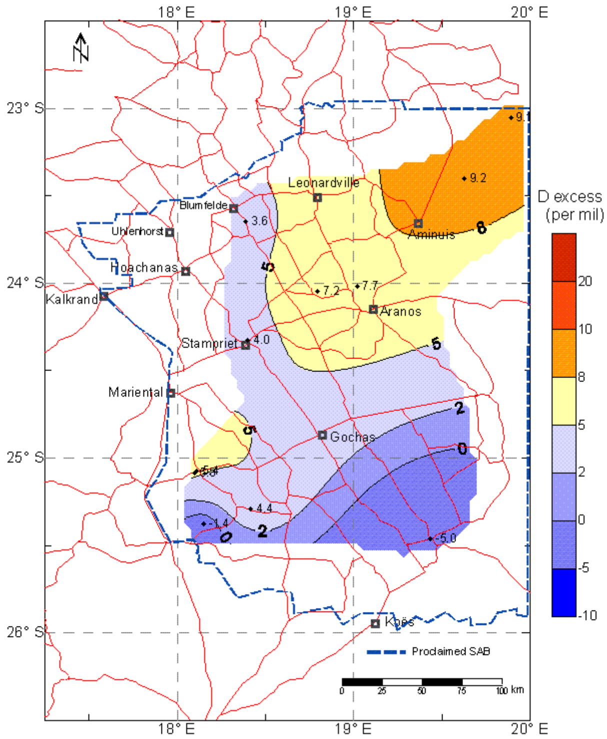

Figure 15c: Deuterium excess in the Nossob aquifer.

In the Auob aquifer, the area with higher deuterium excess values (> 8 ‰) is considerably larger, but is mainly restricted to the area to the east of the Nossob River. The Auob aquifer is confined over most of this area and can presumably only be recharged in the north, both from a hydrogeological viewpoint and considering the piezometric levels. In a small area in the extreme northern part of the SAB the unconfined aquifer has a similar stable isotope composition (δD, $\delta^{18}O$ and deuterium excess) similar to that of the Auob aquifer. This could presumably be a recharge area for the Auob sandstone.

The distributions of the δD, $\delta^{18}O$ and deuterium excess values support a hypothesis of a contiguous water body in the Auob aquifer in the area where the D-excess is > 8 ‰. The groundwater in the southern half of this area (along the Botswana border) may have a somewhat different origin, as the δD (and $\delta^{18}O$) ratios are slightly higher (see Figs 9, 12 and 15b).

It is evident that in the unconfined aquifers the deuterium excess is generally < 5 ‰ in the western and southeastern part of the SAB (see Fig 15a). If it is assumed that the deviation from the meteoric water line is largely the effect of evaporation, it is evident that the unconfined aquifers are subject to evaporation over the larger part of the SAB. Low deuterium excess values (< 2 ‰) occur near Stampriet, to the west of Gochas, and particularly in the Salt Block area southeast of Gochas. The low deuterium excess values at Stampriet are accompanied by higher δD and $\delta^{18}O$ ratios, confirming the effect of evaporation (see Figs 8, 11 and 15a). It is possible that this area is affected by drainage of irrigation water enriched with heavier isotopes.

Similarly to the unconfined aquifers, the Auob also has deuterium excess values below 5 ‰ in the southwestern part of the SAB (see Fig 15b). However, in contrast to the unconfined aquifers, these values seldom reach levels below 2 ‰. The extremely evaporated water in the southeast is not considered to be representative of the native groundwater in the Auob aquifer because this borehole (WW39855, J8A) had a very deep water level (approximately 180 m below surface) and an extremely low yield. This means that proper flushing of the borehole (by bailing) was impossible and it is likely that the sample was contaminated and the isotope results should be disregarded.

Whereas the deuterium distribution (Fig 9) gives the impression that the Auob aquifer at Stampriet may be dissected from its recharge area, the $\delta^{18}O$ and deuterium excess values (see Fig 12 and 15b) indicate the possibility of groundwater could reach Stampriet from the northwest and potentially also from the north. Provided all the aquifers were correctly identified, the variations in the stable isotope concentrations potentially indicate the presence of different water bodies. This may also relate to the depth of penetration into the Auob aquifer and the presence of interbedded shale in the aquifer. It is also possible that areas of higher and lower transmissivity and other characteristics may affect groundwater movement and cause more “stagnant” conditions and higher ages (see below) as in the Olifantswater West area.

Based on the stable isotope concentrations, natural recharge must enter the Nossob aquifer from several directions. Although the δD and $\delta^{18}O$ ratios are within narrow ranges over most of the SAB (see Figs 10 and 13), the low deuterium excess in the Blumfelde – Stampriet area and on the Weissrand (Fig 15c) indicates that evaporation occurred before recharge. The two negative values in the south are considered to be unrepresentative samples.

3.6.2 Carbon-14

Using the ^{14}C determination as a tool for dating groundwater may be problematic because the initial pmc concentration may be unknown. A starting value of 85 pmc (Vogel & Ehalt 1963) is often used but according to Geyer (1993 as reported in Geyh, 2000, p. 101) initial values can range between 55 to 65 and (over) 100 pmc. It is interesting to note that none of the contributions of the latest volume of the Hydrogeology Journal (Feb. 2002) on groundwater recharge uses ^{14}C for dating but rather for determining flow velocities. Even that may have some difficulties if inorganic carbon is added or exchanged along the flow path. The dissolution of organic matter or carbonate minerals within the aquifer may add “old” or “dead” (i.e. no detectable ^{14}C), carbon to the water, giving an erroneously old age. Chemical and isotope changes that may occur include:

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

Many of these processes occur in one or more of the aquifers. In the unconfined aquifers carbon may also be lost from the water by precipitation of a carbonate mineral or by loss of carbon dioxide gas. In all aquifers dissolution of calcite or other forms of calcium carbonate takes place. In the basalt weathering of silicate minerals takes place. In the confined aquifers ion exchange and further dissolution of calcium carbonate occurs. Bacterial denitrification takes place in the confined aquifers with concomitant oxidation of organic matter in the aquifer matrix. The contribution of carbon from these sources can sometimes be estimated from the $^{13}C/^{12}C$ measurements and chemical arguments enabling corrections to be made. In general, ^{13}C is used to identify sources of carbon and the processes occurring underground. It is particularly valuable for distinguishing between carbon derived from organic matter (light) and carbon derived from carbonate minerals (heavy) (Drever, 1988). The behaviour of the $^{12}C/^{13}C$ ratio in groundwater is determined by the relative influences of the carbon dioxide present in the soil due to plant respiration and the interaction with the carbonates present in the aquifer rock. This subsurface system can be complex and the most important application of ^{13}C data is in process identification (Domenico & Schwartz, 1990). $\delta^{13}C$ in soil carbon dioxide is determined by the $\delta^{13}C$ of the local plants. Dissolution of solid carbonate by this acid solution increases the ^{13}C content of the resulting water. Further changes in $\delta^{13}C$ and alkalinity may occur due to interaction between water and rock during transit through the aquifer. Rather than converting the measured activities to conventional ages the ^{14}C concentrations in terms of percent modern carbon (pmc) are discussed below.

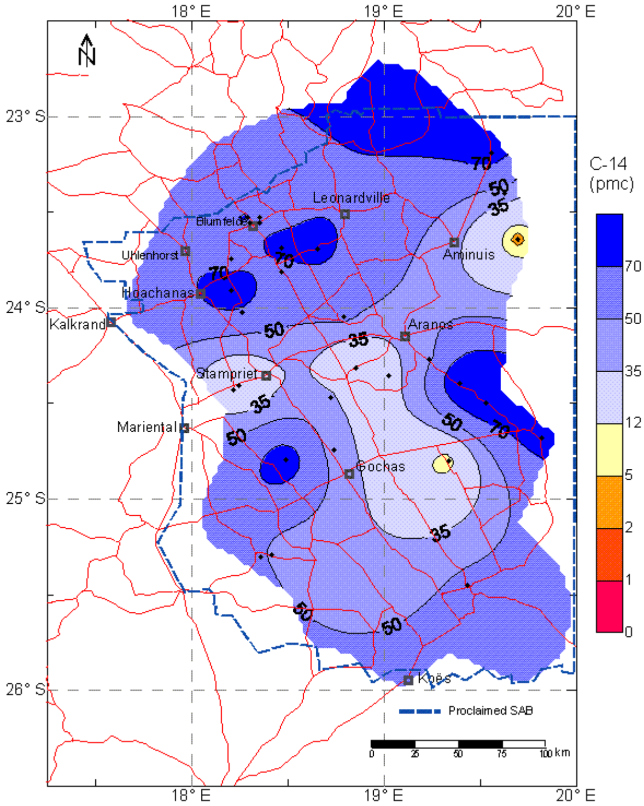

Figure 16a: Carbon-14 (pmc) in the unconfined aquifer system (Kalahari, basalt & Rietmond).

Particularly with regard to ^{14}C, many results were obtained from the work of Vogel *et al.* (1982). The ^{14}C concentrations used for the maps are given as "percentage modern carbon (pmc)", and the results for the unconfined aquifer system are shown in Figure 16a. The aquifer system can receive recharge over most of the basin and ^{14}C concentrations are relatively high (> 70 pmc) in certain areas. These areas are located in the extreme northern part to the east of the Nossob River, in the northwest between Hoachanas and Leonardville, on the Weissrand in the west, and along the lower reaches of the Nossob River. The high ^{14}C concentrations (86.9 and 77.7 pmc for boreholes WW1843 and WW20786 respectively) and high values along the Nossob River southeast of Aranos support the conclusions drawn from the stable isotopes and confirm recharge from the riverbed during flood events. Younger water (54.9 pmc) of good quality also occurs along the lower reaches of the Auob River at borehole WW39854 (J8K) at Tweerivier. This borehole is located in the Salt Block and is surrounded by very low pmc, highly saline water. This confirms the importance of floodwater recharge to the unconfined aquifers in the basin. The very low pmc groundwater in the Salt Block area was not sampled and the closest point was borehole WW39849 east of Gochas with 6.2 pmc. As explained above, the unconfined aquifer at borehole WW39854, that is located further south, is recharged by floodwater from the Auob River. Only two of the boreholes included in the dataset for the unconfined aquifers had less than 12 pmc and in only one case (borehole WW39849, J6K, east of Gochas) the source aquifer could be identified with complete certainty.

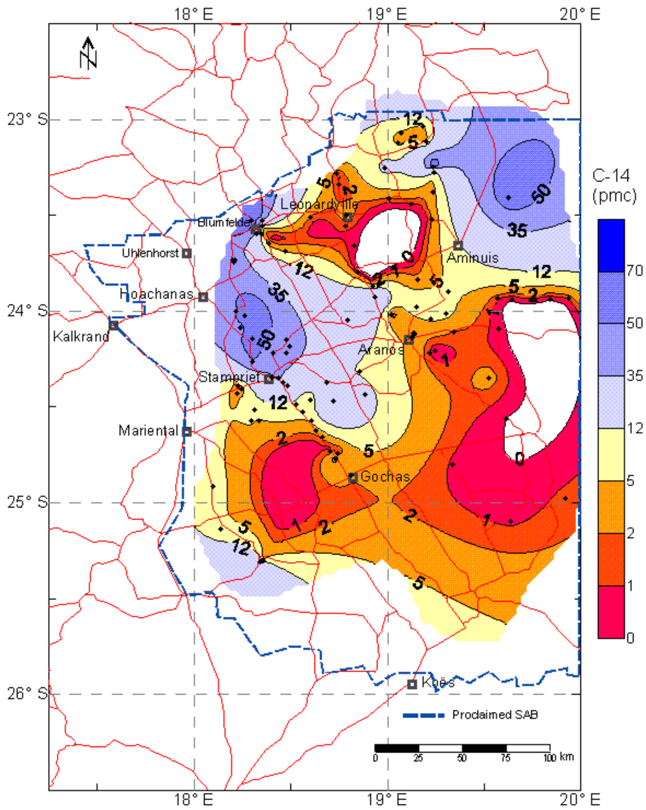

Figure 16b: Carbon-14 (pmc) in the Auob aquifer.

In the Auob aquifer, even close to the northeastern and northwestern edges of the basin, the maximum ^{14}C concentration in groundwater is approximately 50 pmc (according to assumptions generally used by isotope scientists before applying corrections for geochemical reactions 50 pmc is roughly equivalent to 5 ka, see Fig 16b). From these areas, e.g. north of Stampriet, the ^{14}C concentration decreases, which confirms the confined nature of the aquifer over most of the SAB. The pattern is relatively consistent but in the centre of the area (mainly in an elongated zone along the Nossob River, and extending towards borehole WW39850, J6A, east of Gochas) the ^{14}C concentrations are very low. The areas within the "0" contour lines are largely artefacts of the contour package as very few "0" pmc concentrations were measured in what was classified as "Auob" water. The deduced high ages are inconsistent as far as the relative distance to any potential recharge area is concerned. A certain degree of similarity exists between the occurrence of low pmc values in the Auob aquifer and the concentration of dissolved inorganic carbon (as indicated by the total alkalinity, see Fig 16c). Certain layers of the Auob sandstone are calcareous and the calcium carbonate gradually dissolves in the groundwater. The confining and interbedded shales are rich in sodium and the calcium in the groundwater is exchanged for sodium from the shale. The ion exchange removes calcium from the water, thereby disturbing the chemical equilibrium and allowing further dissolution of calcite (Tredoux & Kirchner, 1981). This repeated process increases the total alkalinity and particularly the concentration of the carbonate species in the water. Thus, in general, the longer the residence time in such aquifers, the higher is the total alkalinity of the water. In addition, biological denitrification takes place (see below), which adds further quantities of bicarbonate derived from the carbonaceous shales. The question remains to what a degree the addition of "dead" carbon affects the ages determined by means of ^{14}C and a correction factor will have to be determined and applied.

In the Nossob aquifer the ^{14}C concentrations are very low, already in the northeastern part of the basin (see Figure 16d). The 26.5 pmc measured at borehole WW39856 (J8N) is considered to be incorrect as it is a very low yielding borehole and the sample may have become contaminated during the extended sampling process. Further sampling of the Auob boreholes at Blumfelde may indicate younger, more recently recharged water, but based on the drilling results and hydrogeological interpretation, this is not considered to be a significant recharge area for the Auob aquifer in the Stampriet area. The groundwater in the Nossob aquifer has seldom more than 5 pmc and has usually less than 2 pmc (see Fig 16d).

The Nossob aquifer is only a viable water resource in the extreme northern part of the SAB and on the Weissrand as in the remainder of the area yields are very low and the quality very poor. The yields are so low that it is virtually impossible to obtain an uncontaminated sample for ^{14}C analysis.

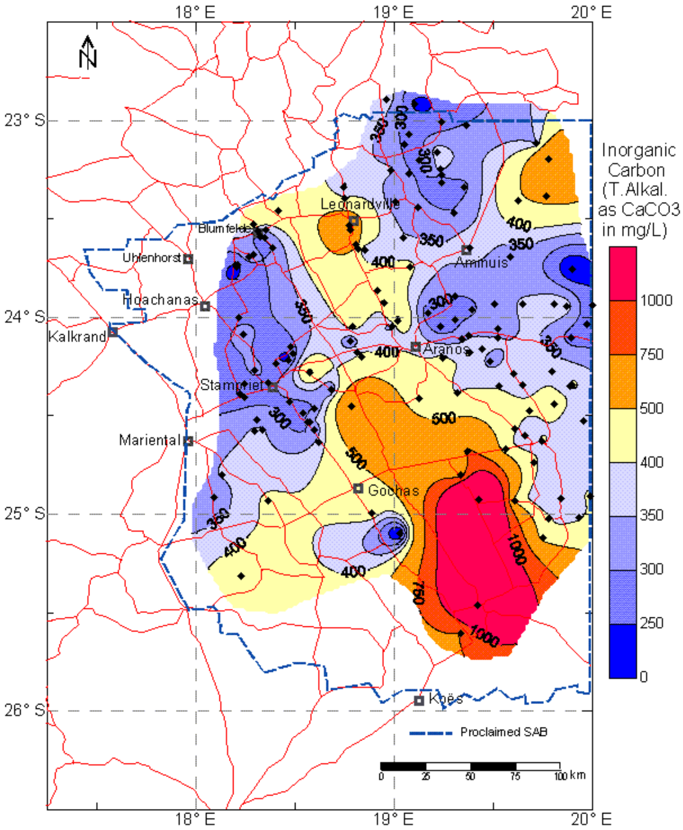

Figure 16c: Inorganic carbon (total alkalinity) in the Auob aquifer.

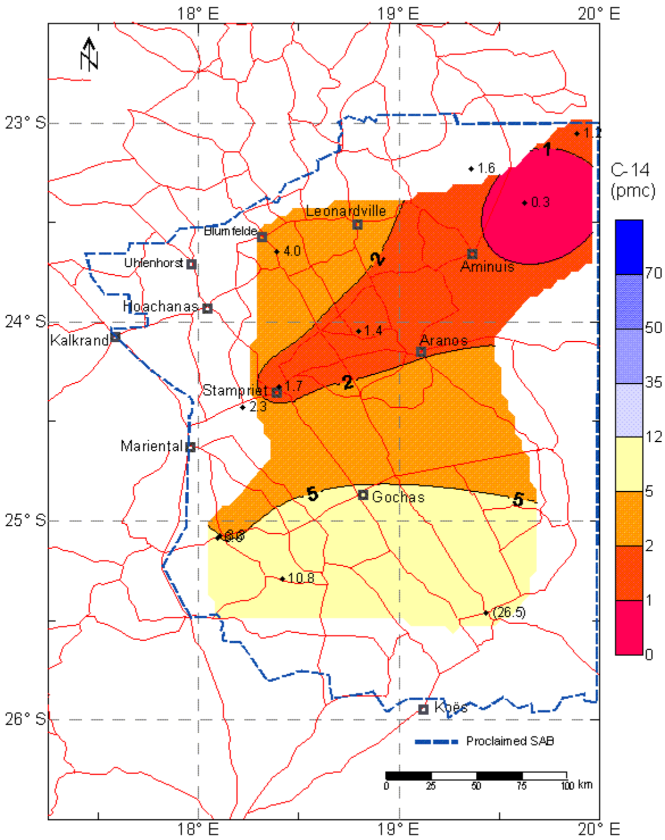

Figure 16d: Carbon-14 (pmc) in the Nossob aquifer.

3.6.3 Tritium

Considering the high ^{14}C ages, very low tritium values can be expected both in the unconfined aquifer (see Figure 17a) and near the recharge areas in the confined Auob aquifer (see Figure 17b). Nevertheless, it is important confirmation that natural recharge is a very slow process. The trace of tritium in a few boreholes in the unconfined aquifer and also in one borehole in the Auob aquifer (on the Weissrand southeast of Mariental) could indicate that younger water may be blended into the aquifer and that a mixture of very old and younger water is abstracted in places. It may possibly also confirm that the ^{14}C ages, particularly in the unconfined aquifers, could be overestimated due to chemical reactions dissolving soil and aquifer matrix carbon without ^{14}C.

Two Kalahari aquifer boreholes along the lower Nossob River mentioned above, which have ^{14}C ages < 2000 a (WW1843 and WW20786), also have traces of tritium, i.e. 0.3 and 0.2 TU. These values are at the detection limit but strengthen the possibility of very young groundwater in that area despite deep water levels, mostly > 70 m below surface.

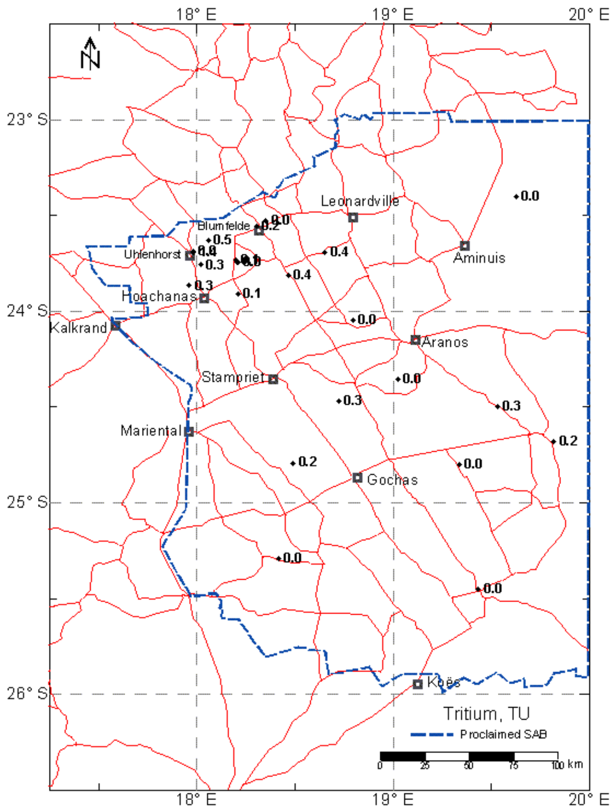

Figure 17a: Tritium concentration in the unconfined aquifer system (Kalahari, Basalt & Rietmond).

3.6.4 Nitrogen-15

The nitrogen isotope ratio ($^{15}N/^{14}N$), expressed as $\delta^{15}N$ ‰ (relative to air), has been determined for approximately sixty samples in the unconfined aquifer system and the Auob aquifer in areas where nitrate occurs. Part of these results was obtained from the JICA project (PCI, 2002). Other results were obtained from Vogel *et al.,* 1982. The results were plotted on maps for providing an overview of the situation (see Figures 18a and 18b). For a large part of the Auob aquifer no data were available. Generally, $\delta^{15}N$ values between +5 and +8 ‰ indicate that the nitrate is from a natural soil/plant origin, while a $\delta^{15}N$ value higher than +10 ‰ may indicate nitrogen from an animal source or on-site sanitation (Heaton, 1984). However bacterial denitrification also changes the ^{15}N isotope ratio and higher isotope ratios at low nitrate concentrations may indicate denitrification (Heaton, *et al.,* 1983).

Although most of the ^{15}N isotopic ratios are low, some of those in the unconfined aquifers are high enough to indicate a potential pollution source (see Fig 18a). These values confirm field observations, which indicate that boreholes, particularly shallow ones, are often inadequately protected against pollution from the surface at stock watering points. In other cases on-site sanitation has not been properly designed and septic tanks and their french drains are too close to the boreholes. In the unconfined aquifer system, a total of eight boreholes sampled for ^{15}N showed potential signs of pollution, with four of these at a level high enough to cause concern. These boreholes should be inspected for further follow-up actions.

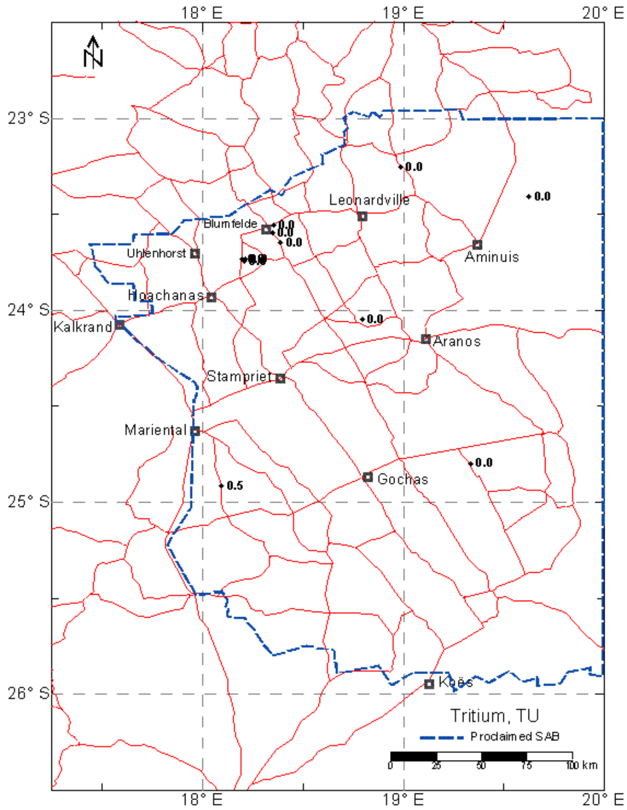

Figure 17b: Tritium concentration in Auob aquifer.

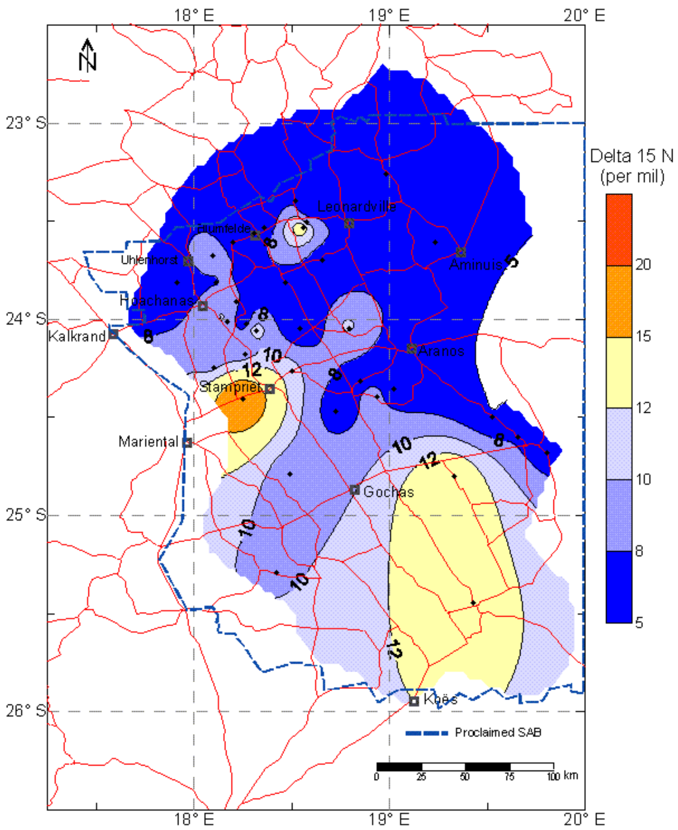

Figure 18a: Nitrogen-15 ratios in the unconfined aquifer systems (Kalahari, basalt & Rietmond).

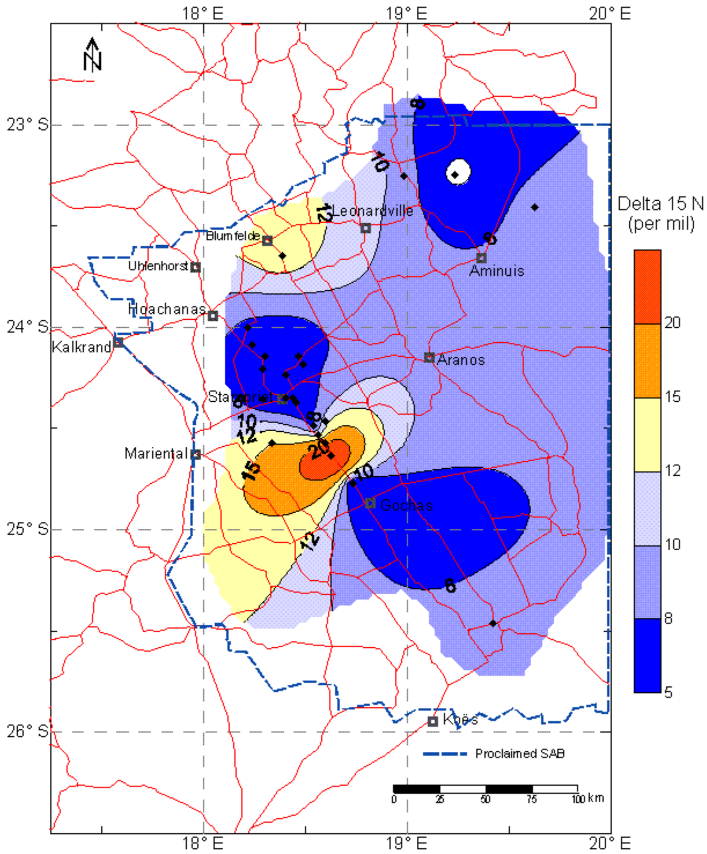

Figure 18b: Nitrogen-15 ratios in the Auob aquifer.

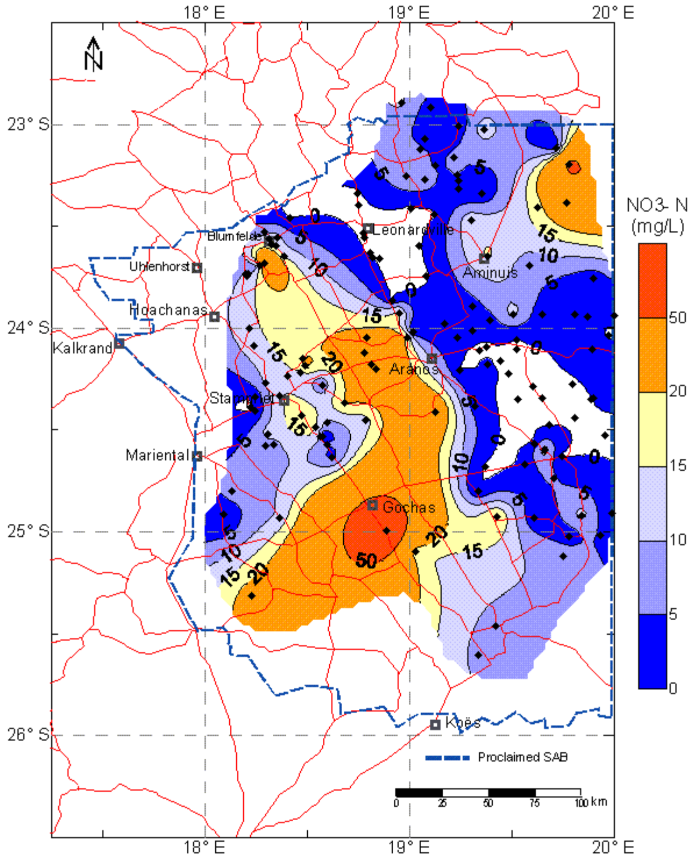

Figure 18c: Nitrate-N distribution in the Auob aquifer.

The groundwater in the Auob aquifer shows significant variations in $\delta^{15}N$ ratios (see Fig 18b). In the area to the northwest and around Stampriet the Auob aquifer has a $\delta^{15}N$ ratio <+8 ‰ which represents the isotopic ratio of natural soil nitrate. Between Stampriet and Gochas this ratio at first changes to >+20 ‰ and then returns to <+8 ‰. Simultaneously the nitrate concentration decreases to zero due to bacterial denitrification and then increases once the pre-Kalahari erosion trough is reached in the vicinity of Gochas where nitrate-bearing water from the Kalahari aquifer can enter (Tredoux & Kirchner, 1981). At Stampriet (and elsewhere) carbonaceous shale and also coal deposits are found associated with the Auob aquifer aquiclude. In the vicinity of Blumfelde, and elsewhere in the basin, nitrate reduction also occurs with a concomitant increase in the $\delta^{15}N$ ratio. Further investigation will provide more detailed data in those areas.

In order to put the nitrate reduction in perspective, the nitrate concentrations are shown in Fig 18c. The decrease in nitrate between Stampriet and Gochas can clearly be identified as well as the increase near Gochas due to the ingress of Kalahari groundwater rich in nitrate. In the north eastern part of the aquifer a similar situation occurs and over the greater part of the area nitrate concentrations are very low or below detection. However, in the central part of the basin, in an area extending in a southeasterly direction from Blumfelde, nitrate concentrations in the Auob aquifer remain consistently above 20 mg/L until it increases further at Gochas. Thus it would seem that nitrate reduction is not occurring in the central part of the basin. This phenomenon needs further study and clarification.

Figure 19 shows the $\delta^{15}N$ ratio against the nitrate concentration in the Auob aquifer. The nitrate concentration in the Auob water varies between < 0.1 and 25 mg/L. However, the $\delta^{15}N$ ratio can only be measured with great difficulty at low nitrate concentrations, and for that reason the low values are not well represented. At low nitrate concentrations the $\delta^{15}N$ ratio increases as a result of bacterial denitrification. In the vicinity of Stampriet the nitrate concentration is mostly between 10 and 15 mg/L but in other areas it can be slightly higher, depending on the nitrate concentration in the recharge area. It would seem that some of the higher values have also undergone partial denitrification.

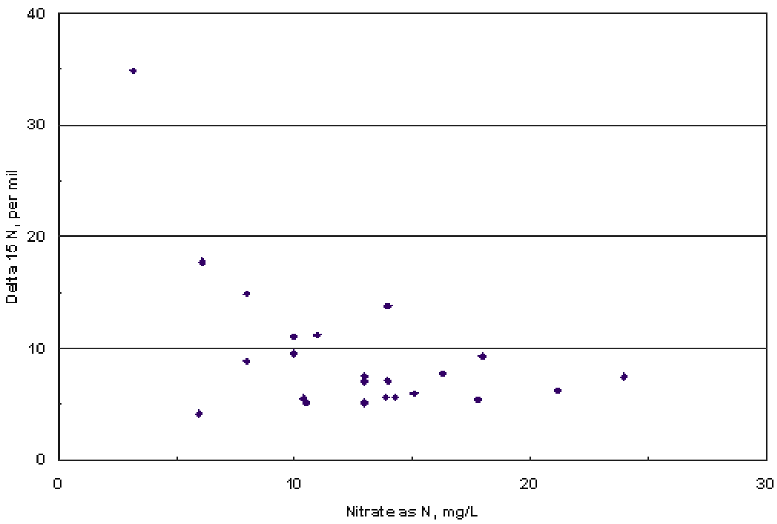

Figure 19: $\delta^{15}N$ vs. Nitrate-N distribution in the Auob aquifer.

3.7 Conclusions

The use of the isotopes has contributed significantly to the understanding of many aspects of the SAB, but also provided further questions and challenges. The full solution of the recharge mechanisms remains elusive. It is evident that a lot more work will have to be done before the recharge mechanisms are properly understood.

Direct rain recharge of the unconfined aquifers in the arid environment of the SAB can only take place when the precipitation can collect on the surface in permeable ponds, or soak away in the sinkhole structures identified during the Hydrogeological Map of Namibia project. In other areas recharge may be very limited and confined to exceptional rainfall events. A certain amount of recharge may also occur along certain parts of ephemeral rivers.

Other evaluations, including the parallel JICA study, have shown that the water levels in the confined aquifers as well as the piezometric levels in the confined aquifers show a marked seasonality, both in the heavily exploited area and near the presumed recharge areas of the confined aquifers. The seasonality in the unconfined aquifers indicates direct recharge practically every rainy season, with larger responses in the exceptionally high rainfall years. The question, however, remains whether the piezometric response in the confined aquifers in (or after) the average rainy season is related to recharge or pressure increases due to the recharge of the overlying unconfined aquifer.

As previously mentioned stable isotopes indicate a subdivision of the Artesian Basin into a northeastern part (Trans-Nossob) and a southwestern part (Cis-Nossob) with a boundary line following approximately the pre-Kalahari Nossob River as shown by Miller (PCI, 2002). While the recharge processes are understood in the Cis-Nossob part further investigations are needed in the Trans-Nossob. Recharge of the overlying unconfined aquifers is also taking place from the main rivers, i.e. the Auob and the Nossob, at least along certain parts of their courses in the SAB. Rainfall and flood recordings at places such as Stampriet, Gochas, Tweerivier, Leonardville and Aranos, together with groundwater level recordings in the unconfined aquifers, should provide detailed information on recharge events involving the main rivers in the area. The importance of the unconfined aquifer systems in the total water supply of the SAB may be underestimated. For this reason, the impact of alien vegetation on the groundwater stored in the unconfined aquifers may also be overlooked.

The “snapshot” of isotope values obtained over a short period of decades, cannot fully describe a hydrogeological system containing water thousands of years old. The isotope and hydrochemical results need to be integrated with water level and other longer-term hydrogeological and meteorological information for developing a proper understanding of the aquifer systems and the natural recharge processes in the SAB. Although some progress has been made with regard to the identification of recharge mechanisms, e.g. the calcrete Karst features, and their role in collection of water for recharge, the delineation of the recharge areas for the artesian aquifers requires considerably more research.

3.8. Recommendations

Following the detailed review of all the isotope results, including those for the remaining new boreholes, potential recharge zones and new study areas should be delineated. Aquifer protection measures are required. The measuring network (water levels and abstraction) needs extension. The proposed actions are:

1. Trans-Nossob: In a first step DGPS borehole elevations and water levels [mamsl] should be determined in holes where the aquifer can be identified. Following the compilation of water-level contour maps, isotopes and hydrochemistry should be used to identify the recharge areas and processes.
2. Further/new recharge hypotheses should be developed and tested, especially in the Trans-Nossob area.
3. Cis-Nossob: The latest Tsaurob radiocarbon analyses should be evaluated to better understand the initial ^{14}C concentrations. Once clarity is obtained, further drilling should be done between Tsaurob and the first artesian holes towards Stampriet. Once the exact flow path is determined quantification of recharge in this area by means of radiocarbon-based flow velocities and aquifer transmissivities appears possible. Installation of additional water level recorders in potential recharge areas will provide the much needed information for finally determining the recharge rates and aquifer potential with confidence through the combination of environmental isotope and hydrochemical data with detailed water level responses.
4. Those rainfall collectors that appear to be affected by dust from the farm yards (containing nitrate and phosphate) should be moved some distance to obtain unpolluted samples.
5. Attention should be given to leaking boreholes. These should be identified; repaired or properly closed and replaced if necessary to protect the resource.
6. Specifically the Boomplaas recorder hole should be closed below the Kalahari and a proper Auob monitoring hole be drilled nearby.
7. The Nossob aquifer borehole WW39851 (J6N) on the farm Cobra, R349, east of Gochas should be resampled. This borehole, although artesian, has such a low yield that the previous sample was contaminated during sampling. Although it is presently equipped with a recorder for determining the piezometric head, it is possible to interrupt recording for a month or two in the dry season for obtaining a representative sample for environmental isotope and chemical analysis. Subsequently, piezometric head recording should continue, as it yields invaluable information on the longer-term response of the aquifer.

4. References

Castelyn, F. J. (1983). Final report, Nama core drilling programme, Grants 1247-1251, 1306, 1309, 1327, 1328, 1333, 1342, 1346-1348. (unpubl. report): Gold Fields Prospecting Co.

CDM. (undated). SWA Coal project (Aranos Basin) (Geological Survey Open File - Economic Geology EG 087): CDM Mineral Services.

Christelis, G., & Struckmeier, W. (Eds.) (2001). Groundwater in Namibia (1st ed.). Windhoek: Ministry for Agriculture, Water and Rural Development, Geological Survey of Namibia, Namibia Water Corporation and Federal Institute for Geoscience and Natural Resources (BGR), Germany.

Coal Commission (1961). Interim report of the Coal Commission of South West Africa: SWA Administration, Windhoek.

Domenico, P. A. & Schwartz, F. W. (1990). Physical and chemical hydrogeology. John Wiley & Sons, New York.

Drever, J. I. (1988). The geochemistry of natural waters. Second Edition. Prentice Hall, New Jersey.

Frommurze, H. F. (1931). Flowing boreholes in the Rehoboth, Gibeon and Gobabis Districts, South West Africa. Trans. geol. Soc. S. Afr., **34**, 129-149.

Gat, J. R. (1996). Oxygen and hydrogen isotopes in the hydrologic cycle. *Annu. Rev. Earth Planet. Sci.*, **24**, 225 - 262

Heath, D. C. (1972). Die geologie van die Sisteem Karoo in die gebied Mariental-Asab, Suidwes-Afrika. Memoir of the Geological Survey of South Africa, Pretoria, **61**, 44.

Heaton, T. H. E., Talma, A. S., & Vogel, J. C. (1983). Origin and history of nitrate in confined groundwater in the western Kalahari. J. Hydrol., **62**, 243 – 262.

Heaton, T. H. E. (1984). Sources of the nitrate in phreatic groundwater in the western Kalahari. J. Hydrol., **67**, 249 – 259.

Kingsley, C. S. (1985). Sedimentological analysis of the Ecca Sequence in the Kalahari Basin, South West Africa/Namibia (unpubl. report): CDM Mineral Surveys.

Kirchner, J. , Tredoux, G., Wierenga, A. & Christelis, G. (2002). Applying environmental isotopes to a hydrogeological Model of the Stampriet Artesian Basin (unpubl. report): DWA: Geohydrology Division.

Kirchner, J. & Tredoux, G. (1975). The Stampriet Artesian Basin, with special reference to the Salt-Block: The chemical composition of the ground-water with respect to geological formations. Paper presented at SARCCUS Meeting, Bulawayo, May 1975, 16 p.

Marsh, S. C. K., & McDaid, J. A. (1986). Final grant report, prospecting grants M46/3/991 and 993 (Unpubl. report): Anglo American Prospecting Services Namibia.

Nawrowski, J. (1986). Progress report No. 1 on the Stampriet Artesian Basin: Results of the borehole survey within the Stampriet-Gochas area (Internal report, File 12/9/2/28 Geohydrological report 3100/9/G21): DWA: Geohydrology Division.

Nawrowski, J. (1987). Progress report No. 2 on the Stampriet Artesian Basin: Results of the borehole survey within the Aranos-Leonardville area (Internal report, File 12/9/2/28 Geohydrological report 3100/9/G22): DWA: Geohydrology Division.

Nawrowski, J. (1989). Progress report No. 3 on the Stampriet Artesian Basin: Results of the borehole survey in area 3, the northwester intake area (Internal report, File 12/9/2/28 Geohydrological report 12/9/G3): DWA: Geohydrology Division.

PCI. (2002). The Study on the groundwater potential evaluation and management plan in the southeast Kalahari (Stampriet) Artesian Basin in the Republic of Namibia: Pacific Consultants International in association with Sanyu Consultants Inc, Tokyo for Japan International Cooperation Agency (JICA).

Range, P. (1912). Geologie des Deutschen Namalandes. (Vol. 2). Berlin: Geologische Landesanstalt.

Range, P. (1914). Das artesische Becken in der Südkalahari. Dt. KolonBl., **25**(8), 368-370.

Range, P. (1915). Ergebnisse von Bohrungen in Deutsch-Südwest-Afrika. (Vol. 11). Berlin.

Schalk, K. (1961). Water balance of the Uhlenhorst cloudburst in South West Africa. CCTA Publ., Nairobi, **66**, 443-449.

Tredoux, G., (2000). Report on Expert Mission to Namibia: 25 September to 6 October 2000. Project: RAF /8/029: Sustainable Development of Groundwater Resources. Task 13: Data evaluation and Training. *Report submitted to IAEA, VIENNA.* CSIR Report No ENV-S-C2000-142

Tredoux, G., Kirchner, J., & Vogel, J. C. (1978). Geohidrologie van die Artesiese Kom Stampriet (Confidential report): CSIR.

Tredoux, G., & Kirchner, J. (1981). The evolution of the chemical composition of artesian water in the Auob sandstone (Namibia/South West Africa), *Trans. Geol. Soc. S. Afr.* **84**, 169 - 175

van Wyk, A. E., Strub, H., & Struckmeier, W. F. (2001). Hydrogeological Map of Namibia 1 : 1 000 000, (1 ed.). Windhoek: DWA of MAWRD, BGR, GSN, NamWater.

Vogel, J.C. & Ehalt, D. (1963). The use of carbon isotopes in ground-water studies. Proc. Conf. on Isotopes in Hydrology, IAEA, Vienna 383-396.

Vogel, J. C., Talma, A. S., & Heaton, T. H. E. (1982). The age and isotope composition of groundwater in the Stampriet Artesian Basin, SWA. (Final report to the Steering Committee for Water Research (unpubl.) Project 400/90615): NPRL/CSIR.

Wilson, E. J. (1964). Vreda R281 No. 1 Stratigraphic test borehole. (Core description): Artnell Exploration Company.