CHAPTER 7 WATER QUALITY AND ISOTOPE ANALYSIS

7.1 Introduction

7.1.1 Background and Need for Study

Water quality can be a limiting factor in the exploitation of groundwater as much as the available quantity of water limits the usability of the resource. It is known that relatively good quality groundwater occurs in the northern areas and most of the central parts of the Stampriet Artesian Basin. However, it is also known that high salinities and nitrates are found at the western edge of the Basin near Kalkrand. In addition, the southeastern part of the Basin shows extremely high groundwater salinities, which render the water unsuitable for any agricultural purpose. For this reason, the particular area is called the "Salt-Block". The high fluoride concentration in the groundwater in this area causes fluorosis amongst the livestock that destroys their joints and renders them immobile after ingesting the water for a number of years.

It is also known that the groundwater has a significant nitrate concentration in many parts of the Basin. Along the Auob River near Stampriet the groundwater is of excellent quality for irrigation but along the Nossob River, near Leonardville, the artesian water is of a sodium bicarbonate nature and is unsuitable for irrigation.

Environmental isotope measurements complement the hydrochemical studies as it provides information on the recharge processes and the "age" of the groundwater. The stable isotopes in particular provide considerable additional information on processes such as evaporation and concentration during or after recharge.

This chapter discusses the water quality in the various aquifers and sub-aquifers of the Stampriet Artesian Basin, mainly using the hydrochemical data collected during the present JICA project. Ten boreholes, sampled several decades ago, were included in the present sampling survey and enabled a preliminary evaluation of long-term water quality changes in the Basin. At the same time, the hydrochemical and environmental isotope data serve to establish the hydrogeochemical relationships in the various aquifers and their sub-units, where relevant.

7.1.2 Terms of Reference

The following aspects were considered as being relevant to a hydrochemical and isotope investigation of the Stampriet Artesian Basin:

1) Determine the water quality from point to point and interpret hydrochemical evolution in each aquifer, where relevant

2) Link hydrochemical evolution to environmental isotopes, recharge processes and other potential aquifer phenomena, e.g. mixing of groundwater from different aquifers

3) Survey the water quality in the various aquifers and their sub-units for determining the suitability of the water for the various purposes, e.g. potable water, stock watering, irrigation, and other potential uses

4) Consider usability of hydrochemistry, also in combination with other indicators, for identifying leaky borehole casings

5) Determine in-situ hydrochemistry down the borehole and determine its applicability for interpreting rock-water interaction, identifying leaky borehole casings, and other potential uses

6) Investigate the prevalence of nitrogenous pollution using $^{15}N/^{14}N$ ratios

7.1.3 Parallel IAEA Project Coordination and Linkage to JICA Project

In parallel to the current project financed by JICA, the IAEA is supporting an investigation in the same area with a broader application of environmental isotopes for the assessment of the recharge area(s) and the recharge rate. Issues specifically adressed were:

1) to delineate the recharge areas in the basin

2) to determine the recharge rate of the system

3) to provide an estimation of the sustainable yield of the aquifers

The two projects are of a complementary nature as the JICA project is directed at an investigation of the geology, hydrogeology, and the hydrochemistry of the whole Southeast Kalahari Artesian Basin, while the IAEA project is mainly addressing the problems pertaining to the recharge. The basic plan is to ensure that the two projects, viz. the IAEA project and the JICA project, complement each other without any unplanned overlap. This can be achieved relatively easily, as the Department of Water Affairs staff involved with the IAEA project are fully aware of the isotope sampling being undertaken for the purposes of the JICA project. Furthermore, as one of the JICA team members (Dr Tredoux) is also a member of the IAEA study team, coordination of the IAEA project with the JICA project is possible. Results, including hydrochemical analyses, are being shared in order to ensure that both projects benefit and to avoid any duplication of effort.

7.2 Hydrochemical Information

7.2.1 Utilization of Hydrochemical Information

In this report, the analysis of the hydrochemistry of the artesian basin is based mainly on the existing interpretations and the analytical data gathered during the JICA project surveys. Further integration of the earlier data is needed for extending the hydrochemical interpretations. Linking analytical data with the earlier chemical analyses is essential for this purpose.

7.2.2 Sources and Extent of Existing Chemical Data from Earlier Surveys

1) CSIR survey

The CSIR Groundwater Quality Map surveys involved a hydrocensus and sampling campaign over the whole of Namibia and considerable effort was made to collect all available information about the boreholes and to procure reliable water samples for accurate and detailed analysis. From the earlier data groundwater “problem areas” were identified and these were initially targeted for detailed study. For this reason, the field surveys commenced at Kalkrand, which was considered a problem area in view of the high nitrate concentrations that led to methaemoglobinaemia and infant mortalities. The study area included the area underlain by the Kalkrand Basalt. The detailed survey started in 1967 and was completed in 1968. From 1968 to 1970 the second survey was carried out in the “Salt-Block” in view of the extreme salinity of the groundwater in that area. This survey covered the whole of the area with poor quality groundwater and this extended beyond the southern boundary of the Stampriet Artesian Basin. Several of the later surveys, e.g. those carried out in Namaland, and elsewhere, also included small parts of the Stampriet Artesian Basin. Several years later, in 1974, this was followed by hydrochemical and isotope studies covering the remainder of the Stampriet Artesian Basin as delineated in the Subterranean Water Control Area. Subsequently all data related to the Stampriet Artesian Basin was collated in one report (Tredoux *et al.*, 1979). Where possible, the borehole information collected during the hydrocensus was used to link the sampled boreholes to the available geological borehole logs in the Geological Survey files. In this way, many of the boreholes were classified according to the aquifer(s) from which groundwater could be derived. The hydrochemical survey involved approximately 4000 water samples on which a whole range of analyses was carried out. Therefore, a wealth of hydrochemical data was available which provided the necessary material for a doctoral dissertation (Tredoux, 1981).

The borehole hydrocensus included all relevant information about the borehole depth, water strikes, yield, date drilled, the use(s), and other information. The chemical analysis included the main cations and anions as well as a number of trace constituents such as strontium, bromide, iodide and boron.

The main shortcoming of the survey was the lack of accurate geographical coordinates as these could only be obtained from the available maps. This remains the major obstacle in identifying the relevant boreholes for linking the high quality hydrochemical data to the DWA well numbers and the relevant hydrogeological information. Wherever possible, water levels were measured during the survey of the Stampriet Artesian Basin. To determine borehole elevations, microbarometers were read at the wellhead and correlated with a recording barometer located at a nearby base station of known elevation.

2) DWA laboratory chemical analytical data

The DWA has operated a chemical analytical laboratory since 1965 until it was handed over to Namwater in 1997. The older analyses are arranged according to farm numbers, or by town identification in those cases which relate to town water supply. Most new DWA boreholes drilled have had water samples taken after drilling and often during test pumping. Information to be gained:

(1) Chemical analytical data for WW boreholes where indicated on analysis sheets. Part of this has been done. The DWA borehole database includes ***partial*** analytical data (TDS, SO_4, NO_3, and F) with no sampling date.

(2) Series of chemical analyses for town supply boreholes. These records were, however, found to be incomplete at this stage.

3) Other sources of information

(1) Namwater recent analyses (since 1997). Initial information indicated that the data, that can possibly be obtained, consist of recent chemical analyses of town supply boreholes. The regions have to send in samples twice per annum for the individual boreholes, which form part of the water supply system. For the farms little new information is available. The main reason is that farm owners now have to pay for analyses and very few private borehole chemical analyses are presently being done.

(2) Borehole drilling permit files. Each borehole drilled in the Artesian Water Control Area had to have a permit application. With the permit application all information on previous boreholes had to be submitted with a map of the farm showing the positions of the boreholes. This is as a very valuable source of information for identifying

boreholes and linking analytical information with hydrogeological borehole data.

7.2.3 Electronic Capturing of Earlier Data

All CSIR geohydrological and hydrochemical data pertaining to the CSIR surveys in the artesian basin have been captured electronically. This is now available in Excel file format. For identification purposes the names of the sampling points as identified by the farmers when surveyed, were included in the database. Nearly one thousand of the boreholes were preliminarily linked to DWA borehole numbers and these were also captured. Not all of these were accurate, but a large percentage is correct.

As many of the DWA analyses (see par. 7.2.2 2)) as possible were captured including all possible details given on the analysis sheets. Many of these analysis sheets included DWA borehole numbers (WW series) and other this information such as sampling date, borehole depth.

7.2.4 Present JICA Project Surveys

1) Hydrocensus

During the hydrocensus carried out in collaboration with the DWA, the surveyors measured the electrical conductivity (EC) at a number of the boreholes. The instructions were only to measure the EC at boreholes, which, at the time of measurement, had been pumped sufficiently long, to ensure that the volume of water in the borehole had been displaced several times. A random selection of more than 1300 of these boreholes has also been sampled. The purpose of these samples was to have them available for analysis as part of the parallel IAEA project. Eventually a number of boreholes were selected for stable isotope analysis as well as electrical conductivity and chloride analysis. Full chemical analyses were not carried out in view of the length of time elapsed since sampling. The stable isotope data for 88 of these boreholes were used for this report.

2) Special sampling surveys

Three special sampling surveys were carried out at preselected boreholes for chemical and isotope analyses. These surveys yielded usable chemical analytical data for a total of 265 water sources, including the 19 JICA boreholes. The planned number of 50 isotope samples for various analyses was also taken and the results were used for this evaluation.

3) Sample collection and analysis

Samples were collected according to instructions and are considered to be representative of the particular water sources. Sampling is a tedious process involving travelling large distances and due to this problem and also delays experienced in the submission and analysis, aliquots of the later samples were preserved for the determination of nitrate for preventing microbiological denitrification. Four boreholes were also resampled in order to provide confirmation of the repeatability of the sampling and analysis (see below).

4) Analytical quality control

Analytical quality control was exercised by several means. The cation-anion ionic balance was calculated for each sample and was confirmed to be within five percent for all analyses. Four boreholes were resampled and submitted for analysis at different times. In two cases duplicate samples were submitted under different numbers for confirmation of the analytical precision. The results were generally satisfactory and are given in Table 7.1.

7.2.5 Present IAEA Project Surveys

As explained above, the IAEA is supporting an investigation in the same area using environmental isotope methods for the assessment of the recharge area(s) and the recharge rate. Results, including hydrochemical analyses, will be shared in order to ensure that both projects benefit and to avoid any duplication of effort.

1) Hydrocensus data

As indicated above, a random selection of more than 1300 of the hydrocensus boreholes were sampled. The purpose of these samples was to have them available for analysis as part of the parallel IAEA project. Eventually approximately 100 samples were selected for analysis. However, in view of the length of time that had elapsed between sampling and sample selection, full chemical analyses were not carried out. Only electrical conductivity and chloride were measured in addition to the stable isotope analysis. The stable isotope data for 88 of these samples were used for this report.

2) New boreholes drilled

Until May 2001 a total of 16 boreholes have been drilled, at least half of which are shallow (< 50 m deep). Chemical analytical data is available for the first eight boreholes and these will be incorporated into the hydrochemical database together with those for the new boreholes.

3) Existing boreholes and spring surveys

Limited surveys were carried out covering existing boreholes and springs. The total number of these boreholes is relatively small and the representativeness of the samples obtained from the springs will have to be investigated. The data will contribute to the overall coverage of the basin and should be included where relevant and possible.

7.2.6 Changes of Water Quality with Time

Many boreholes have been sampled two or three decades ago and were resampled during the present project. A number of these were found in the DWA analytical data files. Analytical data for a selection of ten boreholes that could be linked with certainty to the ones sampled in the present JICA survey are reported here (see Table 7.2).

7.2.7 Linking of Earlier Data with Present JICA and IAEA Project Information

The hydrochemical database developed within the JICA project comprises some 265 chemical analyses. This provides coverage of approximately four per cent of the existing boreholes, i.e. about one in 25 boreholes. The isotope database comprises 50 determinations of each of radioactive and stable isotopes. This will be complemented by isotope data for approximately an additional 150 water sources analysed as part of the IAEA project. Together the database will still be relatively small for the 60 000 km^2 study area and will comprise one hydrochemical analysis for every 5 or 6 farms.

The former Groundwater Quality Map survey included hydrochemical and isotope studies covering the whole of the Stampriet Artesian Basin. This was complemented by a hydrocensus covering all available borehole information. The hydrochemical survey comprised more than 4000 water samples analysed for a wide range of constituents. These also included boron, bromide, iodide, strontium and others. Approximately 1800 of these samples were also analysed for ^{18}O and a smaller number for ^{14}C and other isotopes. Therefore, a wealth of hydrochemical, isotope and other data are available representing a significant monetary value of several N$ million.

Although the new sampling runs only increased the existing number of chemical analyses by approximately six percent, the source aquifer could be identified with reasonable confidence, definitely so in the case of the new JICA boreholes. Thus the data gathered are more valuable than implied by the number of six percent. Nevertheless, a further detailed analysis could eventually be carried out making full use of the remaining ninety per cent of the future database. Such an evaluation is considered essential for the modelling and long-term management of the Stampriet Artesian Aquifer. The best approach to obtain such aquifer data appears to be through consolidation of the available information on:

1) Chemistry, isotopes and borehole information from the CSIR Groundwater Quality

Map Survey. Months of work have previously gone into the aquifer identification. Continuing this task will capitalize on the earlier effort.

2) Information contained in the DWA groundwater database as partly classified by PCI

3) The recent Hydrocensus information

4) DWA chemical analyses recently captured and available in electronic format

5) With Dr Miller's detailed analysis of boreholes logs available in digital format it will considerably refine the aquifer identification

6) Hard copy data from the Nawrowski investigations could be used for additional information, but this may be much more time consuming because the data will have to be abstracted from the original questionnaires

With the exception of the new JICA boreholes, some uncertainty exists in the determination of water quality and the source aquifers for the other boreholes. These include incomplete or incorrect information in the groundwater database, leaking borehole casings, and many other problems. Extending the database by including as much as possible of the earlier information will increase the total coverage of all boreholes to some 65% or more, and for at least 50% of the total number of boreholes, source aquifers can be identified. This would ensure an excellent coverage of the basin as a whole. Water quality changes in the artesian sandstones over the 25 to 30-year intervening period were considered to be very small but recent comparisons would seem to indicate otherwise. For this reason, developing a database incorporating all the earlier data may be even more important. The need for such a task has already been discussed but the task itself has not been commissioned.

The consolidation of the different data sets is of importance for further development of the JICA model because these data will provide a sound basis for identifying the aquifers from which the majority of the boreholes abstract their water.

It is estimated that the investment needed could be as little as 5% of the monetary value of the earlier data, while the net result will represent a significant enhancement of the outcome of the JICA project, the monetary value of which will far exceed the investment.

7.2.8 Hydrochemical Profiles

Chemical equilibria in groundwater establish themselves at a specific temperature and pressure. Changes in temperature and pressure will cause a shift in the concentrations of reactants and products as a new equilibrium condition is established. This affects a number of physico-chemical parameters in groundwater, including pH, Eh and dissolved gases. It is commonly accepted that such parameters have to be measured at the wellhead. However, even though such measurements approach the true hydrochemistry more closely, they still do not allow determination of the actual groundwater composition in the aquifer. Thus in-situ measurements are the preferred option.

Until recently, the measurement of the oxidation-reduction or redox potential (Eh) has been difficult and attempts to obtain subsurface readings had to be very innovative (e.g. Mannheim, 1961). In other cases readings were taken from flowing boreholes in order to get an indication of subsurface conditions (Germanov *et al.,* 1959). As a consequence of large improvements in sensor technology, much more reliable measurements are presently possible down a borehole, at much higher pressures and higher temperatures, than were possible even at the surface two decades ago. It is, therefore, not surprising that down the hole physico-chemical logging is practised much more widely and involves measurement of many more parameters than before.

In an attempt to better understand the hydrochemical equilibria, a total of 17 boreholes were logged for determining the hydrochemical profiles under various conditions. In one case the logging was repeated after three weeks in order to determine the reliability of the technique. The results are described in section 7.4.2 below.

7.3 Stable and Radioactive Isotope Information

7.3.1 Utilization of Isotope Information in Hydrogeology

The naturally occurring stable isotopes hydrogen (H), deuterium (D), oxygen-16 (^{16}O), oxygen-18 (^{18}O), carbon-12 (^{12}C) and carbon-13 (^{13}C) and the radioactive isotopes tritium (T or ^{3}H) and carbon-14 (^{14}C), are useful tools in groundwater studies (Weaver, Talma & Cavé, 1999). In areas where nitrates present a problem, the isotopes nitrogen-14 (^{14}N) and nitrogen-15 (^{15}N) should be added to the list. The main hydrogeological uses of isotopes have been summarised as follows:

1) To provide a “signature” to a particular water type
2) To identify the occurrence of mixing of two or more water types
3) To provide residence time information about groundwater
4) To provide information concerning travel times and groundwater velocities
5) To provide information on water-rock interaction
6) To provide information on the source(s) of constituents, e.g. nitrate in groundwater

The isotope abundances are expressed in the form of isotopic ratios and compared to natural isotopic ratios, which serve as the generally accepted standard. The deviation of the measured isotopic ratio from the standard ratio is expressed in parts per thousand, i.e. permil (‰). For hydrogen and oxygen the standard is SMOW (Standard Mean Ocean Water) and for carbon it is PDB (Pee Dee Belemnite).

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

When water vapour condenses to form rain, fractionation takes place in the reverse direction, with the liquid being isotopically heavier than the vapour. The fractionation during evaporation is thus largely the reversed during condensation and the first rain to fall from a water vapour over the ocean would have an isotopic composition of about –3 ‰. If this rain again forms a vapour, ^{18}O will be selectively removed from the vapour phrase and d^{18}O of the vapour will become progressively more negative as the rain continues to fall. By this process of Rayleigh fractionation, rainfall becomes progressively lighter in both dD and d^{18}O as it occurs further away from the ocean source. The dD and d^{18}O values in precipitation generally plot close to the straight line called the **(Global) Meteoric Water Line** (GMWL).

Water with an isotopic composition falling on the meteoric water line is assumed to have originated from the atmosphere and to be unaffected by other isotopic fractionation processes. The evaporation from open water and exchange with rock minerals are two of the more commonly observed processes causing deviations from the meteoric water line. Temperature has a dominant effect on isotopic fractionation and variations in isotopic concentrations in precipitation can relate to climate and altitude. This dependency on temperature produces seasonal isotope variations, latitude variations, and amount effects, which means that the larger rainstorms tend to have a lower heavy isotope content. In the regional hydrological studies the altitude effect can be used to differentiate groundwater derived from recharge areas at different elevations. In general, there is about a 0.3 ‰ decrease in d^{18}O, and a 2.5 ‰ decrease dD per 100 m increase in elevation.

Nitrate occurrence in groundwater is a worldwide problem. The causes are primarily the increased population density resulting in greater pressure on groundwater resources. The common sources of nitrate in groundwater in developed countries are: agriculture (i.e. fertilizer application, animal wastes, etc.), wastewater treatment and sludge disposal, industry, etc. In developing countries the main a cause of nitrate is inappropriate on-site sanitation. In all these cases disposal rates are on the increase and the resourcefulness of society is being challenged to protect groundwater resources. In general, natural nitrogen fixation in the root zone in the soil is reduced when nitrogen becomes available from other sources. However, in the arid regions, these balancing mechanisms are not operational as nitrates, generated by nitrification of soil organic-N during dry periods, leach and accumulate beyond the root zone. Under the right conditions (meteorological, soil, hydrogeological, etc) the nitrate can be flushed from the unsaturated zone into the groundwater. In such areas, the groundwater nitrate levels produced in this way can exceed recommended drinking water standards and expose the users to risks that are not clearly warranted. The low recharge rates in arid regions exacerbate this feature since the limited volume of recharge cannot significantly dilute the nitrate.

Nitrogen isotope ratios (^{15}N/^{14}N) expressed as d^{15}N ‰ have been employed as indicators of the source of nitrate in groundwater with some success in many places. The characteristic isotope values of nitrogen in nitrate from different sources have been empirically established in various locations and these appear to be consistent elsewhere.

The reasons for the characteristic ^{15}N variations in groundwater nitrate from different sources can only be described qualitatively at this stage. There is a need for more quantitative information on the processes that convert organic-N to nitrate and their isotopic changes. The nitrification processes are mainly occurring in the unsaturated zone. Once the nitrate reaches the groundwater, the chance of nitrate reduction is generally small, unless a carbon source, e.g. carbonaceous shale is available. The denitrification process changes the isotopic ratio and this possibility has to be taken into account when anomalous values are considered. Denitrification can be ascertained by measuring the ^{18}O isotopic ratio in the nitrate ion.

The determination of the so-called groundwater "age" utilises the radioactive isotopes carbon and tritium. These nuclei decay at a constant rate, which means that each has a fixed half-life after which time period 50 percent of the initial number of nuclei have decayed.

Three **carbon** isotopes occur naturally: stable ^{12}C and ^{13}C, and radioactive ^{14}C (radiocarbon). 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). d^{13}C in soil carbon dioxide is determined by the d^{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 d^{13}C and alkalinity may occur due to interaction between water and rock during transit through the aquifer. Chemicals/isotope changes that may occur include:

1) Dissolution of calcite, aragonite, or dolomite from limestone, which introduces relatively heavy carbon.

2) Oxidation of organic matter, which introduces relatively light carbon.

3) Transport of carbon dioxide gas from the soil atmosphere, which also introduces relatively light carbon.

4) Weathering of silicate minerals that will convert dissolved carbon dioxide to bicarbonate, thus increasingly alkalinity and pH without changing the ^{13}C content of the water at all.

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

(Drever, 1988).

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

There are some complications in the behaviour of ^{14}C in groundwater, causing difficulties in determining the absolute age of a groundwater. When the ^{14}C concentration is measured at several points along the flow line within an aquifer, the differences in age between the points, and hence the flow velocity can be determined (Vogel, 1967). 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. 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.

For the purpose of this study the ages of the water samples were calculated from the ^{14}C content based on a simple "piston flow" model. An initial ^{14}C content of 90 pmc was used to allow for the dissolution of inactive carbonate from the soil and aquifer material. This estimate is based on the fact that samples with a ^{14}C concentration lower than 90 pmc had no tritium. The formula used for the age calculation is:

$$T = 8267 * \ln (100\, q / A)$$

where T is the model age for a radiocarbon content of A in pmc, and q is the dilution factor. More detailed age calculation can be done based on chemical, stable isotope and flow pattern considerations.

While the minimum detection level of the analytical system equals 0.4 pmc (twice the standard deviation of the analysis) it is prudent to consider the likelihood of some contamination during sample handling. For this reason the minimum detection level is estimated at 0.8 pmc and samples below this level are considered to be older than 40 000 years.

Mixing between different water types in an aquifer presents a further complication. A low ^{14}C concentration may mean that relatively old water is at hand or it may mean that it is a mixture of relatively "young" water and "old" water. The proper interpretation of ^{14}C

measurements in groundwater requires knowledge of the flow of the water, the sources of dissolved inorganic carbon in the water and a conceptualisation of the chemical processes in the subsurface. Chemistry, other isotopes and basic geohydrological observations and measurements are required to establish this (Drever 1988).

Tritium (^3H or T) is a radioactive isotope of hydrogen having mass 3 and a half-life of 12.3 years. The radioactive decay of tritium to ^3He is accompanied by the measurable emission of beta particles, which renders tritium detectable at very low concentrations. The tritium concentration in the water is expressed as the ratio of tritium atoms to hydrogen atoms:

One **tritium unit (TU)** is defined as a ratio of $T/H = 10^{-18}$.

Tritium is generated both by natural (cosmic radiation) and man-made (thermonuclear devices) processes. Most tritium produced in the atmosphere is rapidly oxidised to HTO and incorporated in the hydrological cycle. The natural production of tritium introduces about 5 TU to precipitation and surface water. In the saturated zone, this water is isolated from the atmosphere and the decreasing tritium concentration due to the radioactive decay could provide a useful water-dating tool. However, the mixing of waters, and the large inputs of atmospheric tritium added by hydrogen bomb testing since 1952 complicates the age determination.

In Southern Africa, the tritium in the rainfall produced by the nuclear weapons testing reached levels of 60 to 80 tritium units in the 1960s and this has since reduced to about 5 TU. Although exact age determinations are impossible, semi-quantitative data obtained from tritium studies can be informative in groundwater investigations. Examples are:

Water with zero tritium (in practice < 0.5 TU) has a pre-1952 age.

Water with significant tritium concentrations (in practice > 5 TU in the southern hemisphere) is of a post-1952 age.

Water with little, but measurable, tritium (between 0.5 and 5 TU) seems to be a mixture of pre- and post-1952 water.

7.3.2 Sources and Extent of Existing Isotope Data from Earlier Surveys

1) CSIR studies

Approximately 1800 samples were collected for ^{18}O analysis during the CSIR survey of the basin. No deuterium analyses were carried out at that stage. All these results are available in the reports (Tredoux *et al.*, 1979) and they have also been captured electronically together with the chemical analytical data. Linking and identification of the sampling points will be necessary.

The isotope group of the CSIR (now called Quadru) have organised several sampling campaigns following the hydrochemical survey. Most of these results are in a separate report published in 1982 (Vogel et al., 1982) and are not included in the hydrochemistry report on the artesian basin.

7.3.3 Present JICA Project Surveys

1) New JICA boreholes

The 19 JICA boreholes were all earmarked for stable isotope and ^{14}C age determination. Those in the Kalahari sediments have also been analysed for tritium where considered relevant in order to confirm the findings of the ^{14}C analyses. In those cases where high nitrate levels were expected from the Kalahari boreholes ^{15}N was included.

2) Isotope surveys

Existing boreholes were selected as widely as possible over the whole basin for ^{14}C and stable isotope analysis in order to complete a total of 50 determinations for each isotope. The ^{15}N isotope overlapped to some extent with the other isotopes, especially tritium, but not all the boreholes selected for isotope determination had a meaningful nitrate concentration. Thus an additional selection was needed to complete the total of 50 analyses for ^{15}N. Only 15 tritium analyses were planned and these were distributed over the JICA boreholes and others as considered meaningful for possibly tracing recently recharged water.

A set of 115 samples taken as part of the chemical survey for the JICA project were analysed for the pair of stable isotopes ^{18}O and ^{2}H through the parallel IAEA project. This complementary data provided a valuable input to the JICA project.

7.3.4 Present IAEA Project Surveys

1) Hydrocensus

Approximately 100 hydrocensus samples were selected in areas that were not adequately covered by the earlier stable isotope studies in the Stampriet Artesian Basin. The selected samples have been analysed for electrical conductivity, chloride and the stable isotopes, ^{18}O and ^{2}H, but the results still need to be fully integrated with the JICA project data. It was not considered wise to analyse the samples for full hydrochemistry, as at that stage they had been standing too long since sampling.

2) Special sampling surveys

A small number of groundwater samples have been taken during three special surveys at the time of the visits of IAEA specialists. These will provide some additional data in areas where data are lacking. These seldom included any ^{14}C age determinations and this is considered the most important parameter for augmenting the existing JICA project information.

3) New boreholes drilled

The new boreholes were initially all drilled in the vicinity of Blumfelde along the Olifants River. Special attempts were made to sample the individual water strikes at various depths and eventually this should provide the much needed groundwater age profiles with depth. It is also important to note that these boreholes were carefully logged geologically in order to ensure that the system of description would link in with the new JICA boreholes. At this stage these boreholes have provided important information regarding the geological strata at the edge of the Stampriet Artesian Basin, which has changed the earlier concepts regarding recharge to the artesian sandstones. These boreholes have now been sampled for stable isotopes as well as ^{14}C and these results are being awaited with great interest.

Meanwhile further drilling has taken place to the south and also southeast of Uhlenhorst. Mostly these were shallow boreholes ending in the basalt that provided water samples for ^{14}C age determination but in at least one of these new boreholes the Auob formation was encountered near a fault. In this case a ^{14}C age determination will also be carried out on the water from the Auob formation.

The results from the above investigations should be available within the next few months and should make a significant contribution to the understanding of the recharge processes in the Stampriet Artesian Basin, also for the purposes of the JICA project.

4) Rainwater and river runoff surveys

When determining the isotope characteristics of the recharge water, rainwater sampling is essential. A set of five rainfall-sampling stations has been set up within the basin for this purpose. Samples are collected monthly but certain large rainfall events (> 30 mm) have been sampled and are being analysed separately.

The role of the recharge mechanism from the three main river systems to the aquifer systems in the basin is unknown. The unconfined Kalahari sediments and the basalt certainly accept recharge from the rivers during runoff events. It is also possible that the rivers contribute to the recharge of the artesian sandstones, particularly if the thickness of the unconfined (?) Auob sandstone is considered where the Nossob River enters the basin. In view of these questions a sampling campaign was organised and in late February and early March 2000 and again in April 2001 floodwater samples were obtained from all three rivers. In certain cases exceptional isotope results were obtained which may aid in the quest to unravel the problem of recharge to the artesian sandstones.

7.3.5 Linking of Earlier Data with Present JICA and IAEA Project Information

Several isotope surveys were carried out and all of these were collated in 1982 (Vogel *et al.,* 1982). Where possible, the sampling points were identified and reinterpreted according to the present understanding of the hydrogeology. This provided additional coverage, particularly of the Auob aquifer.

7.4 Evaluation and Interpretation of Aquifer Hydrochemistry

In the following paragraphs the results of the hydrochemical surveys carried out as part of this project are discussed. Whereas use was made of the hydrogeological sections for interpreting the groundwater flow, the results are mostly depicted in the form of contour maps and other diagrams.

7.4.1 Hydrochemical Evolution in Each Aquifer

As described elsewhere in this document, the artesian water occurs mainly in two Permian sandstone units of the Karoo Supergroup, the Nossob (base) and Auob members. These are separated by a thick shale aquiclude. For the greater part, the basin is overlain by Kalahari sediments consisting of calcrete-cemented gravel and sandstone at the base followed by sand, local calcrete and calcareous and clayey layers. In the northwest, basalt of Jurassic age overlies the artesian sandstone aquifers. Several NE-trending faults occur in the northeast and east, while a major N-S trending fault occurs near the western margin of the basin. Dolerite sills and dykes intrude the upper part of the succession in the east. Pre-Kalahari erosion features contribute to the complexity of the geological sequences as certain aquicludes and aquifer units have been removed. It should also be noted that in other areas units are lacking, as they have not been deposited.

As mentioned above, the various faults, erosion features, dolerite intrusions, and other phenomena preclude the existence of artesian sandstones that are contiguous over large areas. Nevertheless, despite these complexities, a detailed study of the hydrochemistry seems to indicate that there is considerable continuity in the water bodies. Only a few water types can be identified from point to point. As a result, it was concluded that the groundwater types basically represent three overlying aquifer systems. The uppermost aquifer system is unconfined and comprises formations of different ages and composition, namely the Kalahari sediments, the Kalkrand basalt, and the Upper Rietmond formation, mainly consisting of sandstone. Locally the basalt may impart a somewhat different composition to the groundwater, but overall the hydrochemistry in the unconfined aquifers are relatively consistent and different from the underlying confined aquifers. However, being unconfined, these aquifers display a greater variation in salinity and chemical composition than the confined aquifers.

The confined aquifers consist of the Auob artesian aquifer, which is the main water bearing system in the basin, and the underlying Nossob sandstone at the base. Although the Nossob sandstone exists over most of the basin, it only yields viable quantities and qualities of water in certain parts of the basin.

Despite the complex geology in many parts, the Auob aquifer, which could comprise the Auob sandstone as well as the Mukorob sandstone, acts as a viable contiguous aquifer over most of the northern half of the basin. In the northeastern part of the basin it would seem to have different water qualities in an upper and lower part, which needs further clarification.

In Figure 7.1 the sampling point distributions are shown separately for each of the aquifer systems. As explained above, sampling points in the Kalahari sediments, the Kalkrand Basalt, and the upper Rietmond formation were grouped together for representing the unconfined aquifer system (see Figure 7.1a). The sampling points provide a reasonable coverage of the unconfined aquifer system over most of the basin. The Auob aquifer is the main confined system and occurs over the greater part of the basin. The sampling point distribution is shown in Figure 7.1b. As can be seen, the sampling points provide reasonable coverage in the northeastern parts of the basin and in the central part near Stampriet. The northwestern and southern parts of the basin are insufficiently covered. However, in the extreme northwestern part, the Auob formation is absent. Including the IAEA project data, once full details and analytical results are available, can extend coverage in the northern parts near the Olifants River. The Nossob sandstone occurs virtually over the entire basin, except in the extreme north and northwest. Nevertheless, as explained in the geological and hydrogeological sections of this report, the Nossob aquifer is only of importance as a water-bearing formation in some areas in the northern and western parts of the basin. Only 13 sampling points have been identified over the entire basin and half of these represent the newly drilled JICA boreholes, which provide high quality information. This may provide sufficient coverage over the southeastern parts of the basin where the aquifer is of lesser importance, but the coverage in the northern and western parts may need to be extended (see Figure 7.1c). In the central part, near the northern edge of the basin, this can be achieved by the eventual inclusion of the IAEA boreholes once the full data set is available.

The electrical conductivity (EC) distribution shown in Figure 7.2 gives an overview of groundwater salinity in the basin. In the case of the unconfined aquifer system (see Figure 7.2a) the lowest salinities occur in the northern half and in the southwest, with high salinities in the extreme western and southeastern parts of the basin. In the southeastern parts of the basin the salinity exceeds potable limits and often also the limits for stock watering. In the Auob aquifer (see Figure 7.2b) the groundwater also has a low salinity in the northern half of the basin and in the west. According to the available data, the lowest salinities occur in an elongated zone to the east and parallel to the Nossob River, as well as in the northwest, mainly adjacent to, but also partly below the Kalkrand Basalt outcrop. Higher salinities occur near Leonardville along the Nossob River, but some of the shallower boreholes somewhat further southwards (e.g. WW998) have a similar low salinity water as found further eastwards. Nearer to Aranos, two boreholes on adjacent farms also have different salinities, with the deeper one (WW7940) having a higher salinity than the shallower one (WW33003). Two boreholes (WW262) south and (WW2144) south-southeast of Stampriet have high salinity water, which is not typical for the Auob aquifer in that area. Although the recorded information would indicate that these boreholes should have Auob water, this may need to be confirmed. The JICA borehole J6A (WW39850) clearly indicates that if proper precautions are taken, excellent quality water can be found much further to the southeast of Stampriet.

Similar to the Auob aquifer, the limited information on the Nossob aquifer (see Figure 7.2c) also indicates lower salinities in the north but very high salinities in the southeast. In the low salinity areas the Nossob aquifer mostly has a sustainable yield.

The chloride distributions in the three aquifer systems are shown in Figure 7.3. Chloride is a very important natural tracer for tracking the natural movement of groundwater. Generally, the chloride concentration in the groundwater increases along the flow path by gradual dissolution of sodium chloride from the host rock. In an unconfined aquifer the chloride concentration can also increase through evaporation and evapotranspiration.

In the case of the unconfined aquifer system (see Figure 7.3a) low chloride water occurs mainly in the northern half of the basin in two relatively well-defined zones. In the southwest, on the Weissrand, the chloride concentration is also low. In the southeastern part of the basin the chloride concentration is generally very high except along the lower reaches of the Nossob River. These areas with low chloride (< 100 mg/L) are considered to be the most important recharge areas for this aquifer system, although recharge may also take place elsewhere, but to a lesser extent due to evaporation or other factors such as the permeability of surface deposits. Considering the Auob aquifer (see Figure 7.3b), it is evident that recharge has to take place at the northern edge of the basin. It is also evident that the chloride concentration of the groundwater increases very slowly, not even exceeding 50 mg/L after a flow path of 100 km or more. Recharge is also expected to come from the northwest but the lack of data points in this area prevents this from being displayed. The IAEA project should assist to overcome this problem and to better define the recharge areas.

As indicated previously, the JICA boreholes make an important contribution to the knowledge of the Nossob aquifer. The chloride values are shown in Figure 7.3c. It is evident that at the three well-designed JICA boreholes WW39847, WW39848 and WW39841 low chloride concentrations are found. The very low chloride concentration at borehole WW3974 southeast of Aranos is probably incorrect due to insufficient casing installed in the borehole.

The sulphate distributions in the various aquifer systems are shown in Figure 7.4. Similar to chloride, sulphate is also present in rainwater. It also originates from sulphates such as gypsum. In a well-aerated aquifer without organic material sulphate may also serve as a conservative tracer similar to chloride. In the unconfined aquifer system (see Figure 7.4a) sulphate concentrations are really low over most of the northern half of the basin and also on the Weissrand in the west. The sulphate concentrations rise steeply in the southeast in the Salt-Block area. Concentrations are also high in the basalt in the west.

In the Auob aquifer (see Figure 7.4b), sulphate concentrations are low in an elongated zone to the east of the Nossob River and in a zone in the northwestern part of the basin. Along the northern part of the Nossob River near Leonardville high sulphate levels are encountered in the groundwater. The occurrence of these high levels is ascribed to oxidation-reduction reactions, particularly to the oxidation of pyrites occurring in the geological material, e.g. in the confining shales. Oxidation of pyrites would seem to occur widely throughout the aquifer. In a previous study (Tredoux & Kirchner, 1981) it was shown that sulphate was increasing in the Auob aquifer to the south of Stampriet due to oxidation of pyrites. In the Nossob aquifer (see Figure 7.4c) sulphate concentrations are low in the north and in the northwest, but reach very high levels in the Salt-Block.

Significant nitrate levels are known to occur widely in the Kalahari. The leguminous vegetation that occurs abundantly in the area could potentially fix the nitrogen which leads to the generation of the nitrates. This phenomenon occurs both in the areas underlain by basalt and by Kalahari sand. Figure 7.5a shows that nitrate concentrations between 10 and 100 mg/L occur over virtually the whole basin. Low nitrate concentrations are noticeable in the eastern part of the basin and along the lower reaches of the Nossob River. This is expected to relate to the recharge process along the riverbed, as a similar phenomenon is noticeable to a lesser extent along the lower reaches of the Auob River.

High nitrate concentrations at individual boreholes may indicate pollution, particularly in the unconfined aquifer system. On-site sanitation systems may be the main cause of pollution. For identifying pollution, certain samples were also analysed for the nitrogen isotope ratio ($^{15}N/^{14}N$). This data is being reported on, in the section on isotopes below.

In the Auob aquifer nitrate concentrations are low over most of the northeastern part of the basin (see Figure 7.5b). On the contrary, low but persistent nitrate concentrations are present in the Auob aquifer in the western half of the basin. The natural denitrification processs noticed previously (Tredoux & Kirchner, 1981) along the Auob River between Stampriet and Gochas is not visible due to a decrease in data points in this area.

Nitrate is virtually absent from the Nossob aquifer (see Figure 7.5c) and where boreholes drilled into the Nossob aquifer seem to have nitrates it is highly likely that the borehole casing is leaking and the groundwater from the Nossob aquifer is contaminated by water leaking from the overlying Kalahari sediments.

Generally the potassium concentration in groundwater is very low, however, in groundwater from the Kalahari sediments it is often slightly elevated (Kirchner & Tredoux, 1975). On the other hand, basalt has low potassium concentrations with much lower potassium to sodium ratios. Potassium is also a very useful indicator of pollution derived from on-site sanitation, from waste disposal sites, and similar pollution sources. However, potassium itself is not a pollutant.

The potassium concentration in the unconfined aquifer system is low around the edge of the basin, particularly in the area underlain by basalt (see Figure 7.6a). In the central part of the basin concentrations are slightly higher but the concentration gradient towards the southeast, i.e. the area of the Salt-Block does not show any significant increase. One anomalous borehole occurs near Aranos. This borehole (WW32888) has a totally anomalous chemical composition with high sodium, potassium, bicarbonate and nitrate concentrations, but a low chloride concentration. The high potassium and nitrate concentrations could indicate pollution, but the low chloride concentration does not support such a conclusion.

Potassium undergoes fixation if illite is present. Therefore, the potassium concentration in solution can be reduced along the flow path. In the case of the Auob aquifer (see Figure 7.6b) potassium concentrations are low in the northern and western parts of the basin in areas where the aquifer could be recharged. The groundwater in the Auob aquifer along the Nossob River in the area near Leonardville also has a very low potassium concentration despite its higher salinity. Potassium concentrations are also very low in the southeast and parts of the aquifer along the Botswana border. Mineral analysis of the Karoo sandstones confirmed the presence of illite (Tredoux, 1981).

The potassium concentration in the Nossob aquifer (see Figure 7.6c) is generally very low except for the three boreholes in the southeast. All these boreholes have very high sodium concentrations, which means that the potassium to sodium ratio is still very low. At such high sodium concentrations the exchange of the relatively small potassium concentration may not be possible.

The silica concentration is the highest in the groundwater originating from the Kalkrand Basalt in the northwestern part of the basin (see Figure 7.7a). The silica concentration in the northern and western part of the basin generally exceeds 50 mg per litre. In the basalt and the Kalahari sediments the silica concentration in the water is mostly in equilibrium with amorphous silica. The free silica in the weathered basalt causes the elevated silica concentration in the groundwater in the basalt.

Silica concentrations in the Auob aquifer are relatively high in the area adjacent to the basalt outcrop in the west (see Figure 7.7b). The higher salinity water in the Auob aquifer near Leonardville has a low silica concentration, similar to the groundwater in the Nossob aquifer in that area. The lower salinity water generally has a higher silica concentration. In general, the silica concentration decreases as the pH increases. The silica concentration decreases towards the southeast alongside the Botswana border.

In the Nossob aquifer the silica concentrations are generally very low (see Figure 7.7c). One borehole, originally classified as “Nossob” (WW 4140), has a silica concentration of 27 mg per litre but it is assumed that this borehole does not produce water from the Nossob aquifer although it is deep enough. It is highly likely that the borehole either does not have sufficient casing or that the casing is corroded.

The hydrochemical evolution of groundwater generally starts from a calcium magnesium bicarbonate water and ends as a sodium chloride water. Between these end members a whole series of possible combinations exists.

During this hydrochemical evolution, the sodium concentration expressed as a percentage of the total cation concentration, increases from a low value of 20 to nearly 100 percent. The reasons for these changes are ion exchange on clays and other materials, the dissolution of salts from the rock matrix, precipitation of salts, redox reactions, and other processes. Not all these processes operate in each aquifer but the general principle of evolution into sodium-chloride type water, takes place in most aquifers. This evolution is clearly evident in all three aquifer systems in the artesian basin.

In the case of the unconfined aquifer system the water in the northern, north-western and western part of the basin is of a calcium-magnesium type but changes in the southerly, south-easterly, and easterly direction into a sodium type water with more than 95 percent sodium (see Figure 7.8a). Water with a high sodium concentration also occur in other saline areas, e.g. in the basalt in the west, and in the eastern part of Aminuis.

In the Auob aquifer, water with a low sodium percentage occurs only in the north, northwest and southwest of the basin (see Figure 7.8b). Groundwater with a high sodium percentage is found along the Nossob River near Leonardville and over the southeastern part of the basin. In the case of the Nossob aquifer, the groundwater generally has a sodium percentage in excess of 90 and mostly in excess of 95 percent. Only one borehole on the Weissrand has a slightly lower sodium percentage (see Figure 7.8c).

Whereas the relative sodium concentration increases during the hydrochemical evolution of groundwater the relative bicarbonate concentration decreases. Therefore, the initial bicarbonate concentration can exceed 70 percent while the final concentration could be below 25 percent.

In the unconfined aquifer system the bicarbonate percentage is the highest in two areas in the north and northwest and decreases in a southeasterly direction (see Figure 7.9a). A relatively high bicarbonate percentage also occurs on the Weissrand. It decreases in an easterly direction. Low bicarbonate percentages occur in the Kalkrand Basalt.

In the Auob aquifer the highest bicarbonate percentage occurs in the north, and this area extends southwards towards the centre of the basin (see Figure 7.9b). The lowest bicarbonate percentages occur in the south and near the southern end of the basalt outcrop. Generally the absolute bicarbonate concentration increases with hydrochemical evolution but decreases relatively because of the rapid increase in salinity (i.e. chloride).

The bicarbonate percentage varies considerably in the Nossob aquifer, reaching nearly 90 percent at borehole WW39847 (J4N) while decreasing to less than 25 percent in the southeast (see Figure 7.9c).

7.4.2 Water Quality Trends with time

A preliminary comparison of data from the earlier surveys with data from the present study indicated that the water quality may be changing with time. Accordingly, the DWA data were scrutinised for earlier analyses pertaining to boreholes included in the PCI hydrochemical surveys. Ten such boreholes were found and the chemical analytical data for these boreholes are summarised in Table 7.2. The relative composition of the groundwater seems to be fairly consistent although inexplicable changes are evident. As the electrical conductivity (EC) is generally a reliable analytical parameter, the EC values were compared for each borehole (see Table 7.3).

It is of significance to note that large differences were found varying from a 0.6 percent increase to 37.6 percent. All examples indicated a significant increase of more than 10 percent, but only in one case it was marginal (0.6 percent). All aquifers (except the basalt for which no analytical data were found) showed an increase in salinity, including the Nossob. The locations of these boreholes and the relevant percentages are shown in Figure 7.10.

Attempts were made to obtain long-term chemical data for the town supply boreholes in the Stampriet Artesian Basin. Records were accessible for the late 1960s and early 1970s but no continuous records were found until the 1980s and 1990s. The later data were inaccessible at this stage. In view of the findings above, further attempts should be made to set up such records, especially for those areas that are being heavily pumped.

7.4.3 Hydrochemical Profiles

A total of 18 hydrochemical profiles were measured in the artesian basin. This included repeating the profile in borehole WW39840 (J2A) after five weeks. Table 7.4 provides a complete list of boreholes logged hydrochemically. The locations of these boreholes are shown in Figure 7.11a. The boreholes are widely distributed over the basin and include newly drilled holes, JICA boreholes, recorder boreholes and others. The hydrochemical profiles for these boreholes are shown in Figures 7.11b to 7.11s.

Hydrochemical profiling of a borehole requires removal of the pumping equipment. As can be understood, few farmers are willing to remove the equipment and generally unused boreholes are the only ones available for this purpose. This limits the choice of boreholes and often old, unused boreholes, which may be partly filled with sand or stones, have a corroded casing, or similar problems, are offered for logging. Another aspect is that the profiling should preferably take place in an uncased borehole for obtaining the actual hydrochemical data relating to the aquifer itself.

Borehole WW10120 on Boomplaas, R386, is fitted with a recorder and is located to the south of Stampriet. Unfortunately no details are available on the well screen and only limited geological information. Nevertheless, the hydrochemical profile can be used to infer what the situation may be. This borehole is connected to the Auob aquifer, although it is not clear from the geological borehole logs. This borehole is further down gradient in the basin than the others at Olifantswater West and it is noticeable that the dissolved oxygen at this point in the Auob aquifer is very low (see Fig 7.11b). It is also evident that the Eh (oxidation-reduction potential) reaches negative values, indicating reducing conditions. This is confirmed by previous observations of natural denitrification in this part of the Auob aquifer (Tredoux & Kirchner, 1981). The pH of the water is high, indicating that cation exchange has taken place with associated changes in the carbonate equilibria. Nevertheless, the salinity of the water is low and it has an EC of only 70 mS/m. In this case, the temperature gradient in the upper part of the borehole is exceptionally high as the temperature increases by two degrees over 30 m. This anomaly seems to indicate the upward flow of warmer water from the deeper parts of the borehole. Considering the Eh, pH and EC graphs, it could imply that water enters the borehole at approximately 108 m and exits at approximately 65 m below surface. This would suggest that the borehole casing is leaking and water from the confined Auob aquifer is finding its way into the Kalahari overburden. It may be worthwhile to inspect the casing with a borehole camera.

The hydrochemical profile for borehole WW10185 is shown in Figure 7.11c. This borehole is located in the roads camp at Blumfelde. The geological description for this borehole is incomplete and it does not mention any Kalahari sediments although calcrete is visible at the surface. It is interesting to note that the water quality does not change significantly with depth. Even the temperature gradient is low as the temperature increases by only one degree over 80 m. No information is available on the casing and whether it is perforated at any depth. This borehole had not been used for many years and the slightly lower dissolved oxygen near the surface could be related to material that dropped down the borehole but remained suspended near the surface. Similarly, the low dissolved oxygen at depth is described to foreign material that dropped down the hole and sank to the bottom. This hydrochemical profile is considered to be representative of the unconfined aquifer system overlying the confined Auob aquifer. The salinity (EC) of 106 mS/m is also higher than in the Auob aquifer.

The DWA recorder borehole WW22544 is located further south along the Olifants River on the farm Olifantswater West, M102. Figure 7.11d shows that the solid casing extends downwards as far as the Lower Rietmond shale. It is typical for groundwater in contact with the carbonaceous shale to have very low dissolved oxygen and a low Eh. Except for the upper part of the water column within the casing, the pH and EC remain constant with depth. The slight anomaly in the temperature curve at approximately 88 m could theoretically relate to the upward leakage of water from the Auob aquifer.

Borehole WW22837 is located southeast of Mariental on the farm Tugela, R212 (see Figure 7.10). It is now equipped for water level recording and is called observation borehole JO-4A. The hydrochemical profile for this borehole is shown in Figure 7.11e. No information is available regarding the presence of any perforations in the borehole casing. It is noteworthy that the dissolved oxygen increases towards the lower part of the Auob (A5) sandstone and remains at a relatively high level up to the end of the hole. In contrast the Eh decreases opposite the interbedded shale (A4) and increases opposite the A3-sandstone. Due to the fact that no information is available on the perforations in the casing it is difficult to interpret the various response curves. However, the Eh curve seems to indicate that the casing was perforated opposite the two sandstone members as well as the interbedded shale. The pH increases opposite the upper Auob member (A5), decreases opposite the shale (A4), and then remains constant down the hole. Similar to the dissolved oxygen the EC also increases opposite the lower part of the Auob A5 sandstone and then remains at this higher level up to the bottom of the hole. On the other hand, the temperature gradient is low up to the bottom of the A3 sandstone where after the gradient increases. Particularly the information provided by the dissolved oxygen, the EC and temperature would seem to indicate that groundwater enters the borehole through the (bottom part of the) A5 sandstone, flows down the borehole, and leaves the borehole through the A3 sandstone.

The DWA recorder borehole WW32457 is located on the farm Spes Bona at Stampriet. This borehole was drilled into the Auob sandstone and the piezometric level at this point is generally above ground level. The borehole casing is extended above ground and the recorder is mounted 12.5 m above ground level to allow for the periodic rise in the water level. No information is available on the borehole construction below ground. Investigation by borehole camera may provide important answers. Hydrochemical logging of this borehole showed that the groundwater at this point in the Auob aquifer has a high dissolved oxygen level (see Figure 7.11f) and accordingly also a high Eh value. The pH of approximately 7.8 and the EC of 72 mS/m agree well Auob aquifer water quality in other areas. The Eh and pH show anomalies at approximately 7 m below surface. When the logger was lowered it met with resistance at this point and it was established that the roots had entered the borehole at this depth. The variations in Eh and pH at this depth are ascribed to the presence of the roots. The temperature anomaly is ascribed to the heating of the exposed casing above ground level. The depth where the roots penetrated the casing, water may be seeping into the surrounding soil leading to evaporation and cooling of the immediate environment.

Borehole WW33038 is located on the farm Donnersberg, L29, along the upper reaches of the Nossob River at the edge of the Stampriet Artesian Basin. This unused borehole was drilled through the Kalahari formation into red quartzite of the Kamtsas formation (see Figure 7.11g). Water was struck in gravels at the base of the Kalahari. In the hydrochemical logging anomalous responses were found for several parameters. These included a low Eh at the top of the gravel, a high pH at the top of the borehole high salinity in bottom part of the borehole and a decreasing temperature from top bottom. The borehole had an "anaerobic" smell and although the borehole was properly sealed it may contain polluted water.

Generally, deeper boreholes are cased through the Kalahari beds for preventing losses of artesian water, or for reasons of instability of the geological material. In an attempt to obtain information on groundwater in the Kalahari beds borehole WW33468 was logged while it was still being drilled and only had a short length of casing at the top (see Figure 7.11h). It was evident that the Kalahari groundwater had relatively high dissolved oxygen and Eh values. The pH value increased somewhat with depth. The anomalous EC and temperature curves could possibly be due to the effect of the drilling operations. It is concluded that a newly drilled borehole should be allowed to equilibrate with the natural groundwater for a month or longer before chemical logging is attempted.

Borehole WW35769 was drilled through thick Kalahari sediments and Karoo dolerite into the Auob aquifer (see Figure 7.11i). The borehole was cased through the Kalahari beds and the casing cemented into the dolerite. The deep groundwater was found to contain little dissolved oxygen. The Eh reached its lowest level some distance below the top of the dolerite but then increased with depth. The pH had its highest level some metres into the dolerite but this may be due to the effect of the cement grouting of the casing. This may also have affected the electrical conductivity in the upper part of the borehole. However, considering the temperature curve, there may be a natural reason for the deviation in the EC, the pH and Eh curves.

The next four boreholes are all located on the Weissrand. The Rietmond shale cover at observation borehole WW37225 (also called observation borehole J0-7A), is relatively thick, while at borehole WW37226 the Auob aquifer occurs at much shallower depth. The borehole also extends beyond the Nossob aquifer (see Figures 7.11j and 7.11k). The hydrochemical profiles at the two boreholes differ widely. Borehole WW37225 is relatively saline which may be due to the fact that the large part of the Rietmond shale is not cased. In contrast, borehole WW37226 is much less saline and even the Nossob aquifer has a low salinity.

In the case of boreholes WW37227 and WW37228 the formations are similar, the boreholes are of similar depth, and both derive water from the Auob aquifer (see Figures 7.11l and 7.11m). For this reason the hydrochemical profiles for these two boreholes are also similar but the numeric values differ significantly in many cases.

Figure 7.11n shows the hydrochemical logs for borehole WW39839 (J1A) from the water level at 59.07 m to the end of the hole. The various screens located opposite the sandstone subunits of the Auob formation are the only open areas in this borehole. It is noteworthy that nearly all the graphs show a change just above or below the first screen in the upper Auob sandstone. Just below the water level a trace of dissolved oxygen (DO) can be noticed, but the groundwater entering the borehole from the Auob sandstone seems to be virtually devoid of oxygen. The Eh decreases from the water level to the bottom of the borehole. The pH decreases slightly, while the electrical conductivity increases slightly at the first screen. The temperature profile gives the most interesting response. It would seem that the temperature gradient in the borehole is virtually zero up to the last screen, but then a sharp increase is evident. The interpretation is that cooler groundwater in equilibrium with the environment at the top screen enters the borehole, flows down the borehole, and then leaves the borehole through the bottom screen. This is only possible if the pressure head is higher in the upper sandstone (A5) than in the lower one (A1). It is unknown whether this is actually the case but it may be possible to determine it using suitable packers. A sensitive device for measuring vertical flow may give a direct indication of such a situation.

At borehole WW39840 (J2A), the dissolved oxygen concentration is also low and decreases with depth (see Figure 7.11o). The oxidation-reduction potential at the top of the borehole is lower than that of borehole WW39839 at depth. The pH of the water is relatively high and higher than at WW39839. This is plausible, as the Auob water has evolved further at this point than at borehole WW39839. This means that ion exchange has progressed and the alkalinity of the water has increased. The electrical conductivity is relatively stable throughout but increases in the sump of the borehole below the screened section at the bottom. It is only marginally higher than at borehole WW39839 (J1A). The Eh, pH, EC and temperature borehole WW39841 are all affected to some extent at the screened sections. Particularly the temperature curve shows an anomalous pattern. This was thought to relate to the test pumping of the borehole during preceding days and it was decided to repeat the logging at a later stage.

However, the hydrochemical log carried out five weeks later produced a nearly identical temperature graph (see Figure 7.11p) and the cause of the anomaly is still unknown.

In the case of the Nossob aquifer at Olifantswater West, M102, borehole WW39841 (J2N), it is evident that the dissolved oxygen was very low (see Figure 7.11q). The Eh was also much lower than at the adjacent Auob aquifer borehole and reaches very low negative values, confirming that the Nossob water is more reducing. The pH was unusually high and showed its highest values opposite the well screen. At the time the borehole was logged, it was already much more than a month after completion of the pumping tests. However, it may be that the cement used for grouting the borehole still affected the water by increasing the pH. The EC also shows a deviation at the top of the well screen. The temperature has a relatively constant gradient and reaches a higher temperature than in the Auob borehole nearby (WW39840). A small temperature anomaly is also visible at the screened section. It may be that in this case upward flow takes place from the bottom section of the Nossob sandstone to the top, which would imply that the pressure in the bottom section might be the higher.

Borehole WW39873 was drilled for the IAEA project as part of the investigation into the natural recharge of the Stampriet Artesian Basin. It is situated along the Olifants River at the edge of the basin on the farm Gumuchab Ost, M94. In this case basalt of the Kalkrand formation overlies the Auob aquifer. The borehole was logged more than a month after drilling had been interrupted and before the borehole was developed and casing installed. Only a short length of casing had been installed for protection of the borehole at the time of logging (see Figure 7.11r). It is interesting to note that the dissolved oxygen concentration in the groundwater in contact with the basalt is low while it increases opposite the Auob aquifer. The Eh remains relatively high throughout the borehole. It is, however, important to note that the salinity (EC) in the borehole is relatively high, much higher than could be expected for water in the Auob aquifer near the recharge area. In the meantime casing has been installed in the basalt and now pure Auob water should be procurable. The borehole was also equipped as an observation borehole and numbered JO-2A.

Figure 7.11s shows the hydrochemical profile for borehole WW6921. It is located on the farm Old Dempster, R356, adjacent to Cobra, R349 and, therefore, at the edge of the so-called Salt-Block area. According to the borehole record, plain casing was installed to a depth of 155.5 m, i.e. to the top of the *Upper* Rietmond formation. Only the first water strike at a depth of 103.6 m (in the Kalahari) is indicated. The borehole was completed in June 1960 and also sampled in 1969 during the CSIR Salt-Block survey. At that stage the EC of the water (*mainly* (?) from the Auob aquifer) was 380 mS/m.

At the time of hydrochemical profiling, the borehole was not in use any more as the quality had deteriorated. It was established that the borehole casing was badly corroded and the borehole depth had decreased from 265.2 m to 190 m, i.e. it was filled to a point above the Auob aquifer. The hydrochemical profile confirms the deterioration of the water quality to a pH of 10 and an EC of 3000 mS/m.

It is important to note that the point at which the water shows the significant deterioration is below the bottom of the installed casing. It would be important to know whether the main reason of the deterioration in water quality was that the borehole had been filled with sand and other material to a point above the Auob sandstone or whether the deterioration was due to saline water derived from the Rietmond formation. The poor water quality does not seem to arise from the Kalahari beds because the salinity in that part of the borehole (assuming that the borehole casing is corroded, i.e. allowing the Kalahari water to enter the borehole) only reaches 500 mS/m.

Despite the obvious shortcomings of the process, there are many benefits of hydrochemical profiling down a borehole. The identification of leaky borehole casings is one such benefit that can be derived from an interpretation of the combination of the temperature and other anomalies recorded through logging.

7.4.4 Environmental Radioisotope Determination and the “Age “of the Groundwater

As explained above, it is essential at any particular point to know how long it took the groundwater to reach that point, calculated from the time it was recharged. The ^{14}C ages in the unconfined aquifer system are shown in Figure 7.12a. Overall, the ages are high, despite the fact that the aquifer system can be recharged virtually everywhere in the basin. Nevertheless, it is important to note that younger water occurs in the northwestern part of the basin in or near the Kalkrand basalt. Younger water (< 2000 a) also occurs along the lower reaches of the Nossob River, which confirms recharge from the riverbed during periods of flood. Younger water (< 5000 a) of good quality also occurs along the lower reaches of the Auob River at borehole WW39854 (J8K), confirming the importance of floodwater recharge in the basin.

On the other hand, the groundwater in the Auob aquifer is generally old, even close to the northern and western edge of the basin (see Figure 7.12b). 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)) the ages are very high. These high ages are inconsistent as far as the relative distance to any potential recharge area is concerned. Also in the Nossob aquifer the ages are very high, already in the northeastern part of the basin (see Figure 7.12c). The younger age 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.

Considering the high ^{14}C ages, the very low tritium values can be expected both in the unconfined aquifer (see Figure 7.13a) and in the confined Auob aquifer (see Figure 7.13b). 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 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 could be overestimated due to chemical reactions.

7.4.5 Stable Environmental Isotope results

Both the deuterium and ^{18}O stable isotope results (in ‰) are negative numbers as these waters are depleted in these isotopes. However, the programme that was used for plotting the values could not handle negative data and the results were multiplied with –1 before plotting. When multiplied by –1, the deuterium values in the unconfined aquifer system decrease from the northwest to the southeast (see Figure 7.14a). 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 ‰ 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 conspicuous as they are lower than expected for that area and must be related to the recharge processes, which will be discussed further below. The large number of data points is due to the parallel IAEA project under which two-thirds of the stable isotope analyses (^{2}H and ^{18}O) were carried out.

Except for the extreme south, deuterium values in the Auob aquifer do not vary significantly over the basin (see Figure 7.14b). This would indicate that once the groundwater has reached the aquifer, no evaporation or other process can significantly affect the stable isotope concentrations. Only mixing with water from another source can change the stable isotope composition. The higher values in the far south agree with the values in the unconfined aquifer system, indicating that the two aquifers are in hydraulic contact. Figure 7.14c shows a similar consistent pattern for the Nossob aquifer. The extremely high value (-20 ‰) at borehole WW36986 on the Weissrand contradicts with the nearby borehole WW39853 (J7N) with a more realistic value of –50 ‰.

Initially it would seem that the ^{18}O distribution in the unconfined aquifer system differs from that of deuterium, but it seems to be largely related to the choice of contour intervals (see Figure 7.15a). Also in this case the values increase in a southeasterly direction along with the topographic gradient and the groundwater flow direction. In the unconfined aquifer system evaporation or evapotranspiration is possible over most of the basin. In this case the low values (up to –9.0 ‰) along the lower reaches of the Nossob River are also clearly evident. In the Auob aquifer the 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 7.15b). In the extreme south, the values are comparable with those of the unconfined aquifer system.

In the Nossob aquifer (see Figure 7.15c) the same two boreholes, WW36986 and WW39853 (J7N), with high deuterium values, also have anomalously high d^{18}O values.

In Figure 7.16a 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 approximately 5, which agrees with a typical evaporation line. Thus virtually all the groundwater in the basin has been subjected to evaporation. The isotope data for the unconfined aquifer system of the Kalahari, basalt (Kalkrand Formation) and the Rietmond Formation are plotted separately in Figure 7.16b. 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 subjected to evaporation or evapotranspiration. This is of significance, as it would indicate that the floodwater soaked away quickly before the water had a chance to evaporate at the surface. The outliers at the higher end of the scale have already been identified on the maps.

The graph for the Auob aquifer (Figure 7.16c) shows that the deviation from the meteoric water line is generally less for the Auob groundwater, except for a few outliers, which have already been identified on the maps. Most of the Nossob groundwater also plots in this part of the graph (see Figure 7.16d).

The nitrogen isotope ratio (^{15}N/^{14}N), expressed as d^{15}N ‰, has been determined for fifty samples in the unconfined aquifer system and the Auob aquifer in areas where nitrate occurs. The results were plotted on maps for providing an overview of the situation (see Figures 7.17a and 7.17b). Generally, a d^{15}N value of +5 to +8 ‰ indicates that the nitrate is from a natural soil/plant origin, while a d^{15}N value higher than +10 ‰ may indicate nitrogen from an animal source or on-site sanitation. Although most of the isotopic ratios are low, some of them are high enough to indicate a potential pollution source. These values confirm observations in the field where 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 case of the unconfined aquifer system, a total of eight boreholes sampled for ^{15}N showed potential signs of pollution, while at four of these it could be more likely. Two, or potentially three of the boreholes sampled in the Auob aquifer may be affected. The identified boreholes should be inspected for further follow-up actions.

7.4.6 Discussion of Hydrochemical Evolution

For the purpose of this discussion, the relative composition of the groundwater in the various aquifers was calculated and the data plotted on trilinear diagrams. These diagrams can show the hydrochemical evolution of the groundwater in the aquifer as it is subjected to various processes, such as salinisation by dissolution, softening by ion exchange, and other phenomena.

Figure 7.18a shows the graph representing the combined aquifer system including the Kalahari, basalt and Rietmond groundwater. In order to test the premise that the three unconfined aquifers are similar enough to be combined for the purpose of the evaluation of the data, separate graphs were compiled for each aquifer, i.e. Kalahari groundwater in Figure 7.18b, basalt groundwater in Figure 7.18c and Rietmond groundwater in Figure 7.18d. In these three graphs the points are subdivided according to the EC intervals, giving an indication of the salinity of the water. The number of sampling points in each of the aquifers differs greatly, but in all of them the hydrochemical evolution starts as a calcium-magnesium-bicarbonate water, which plots in the left-hand corner of the diamond shaped field. In the Kalahari groundwater both cation exchange and salinisation processes are prominent and high salinities are attained. The high nitrate in the Kalahari groundwater affects the plotting positions in the diamond shaped field, which then obscures the other processes. It is not evident whether cation exchange plays a role in the evolution process in all of the aquifers. In the basalt it seems to be of minor importance while other salinisation processes may be more important. In the Rietmond cation exchange seems to be more prominent, while salinisation by dissolution of salts or through concentration by evaporation plays a minor role. The diagram shows that the final water in this formation is a sodium-bicarbonate water. The high salinities in the Kalahari groundwater are mainly a feature of the area in and near the Salt-Block. No Rietmond samples are available from that area. It is concluded that for the purpose of the depiction of the water quality in the artesian basin, the combination of the three types of groundwater is a practical approach. Only when much greater detail is needed in any specific area, it may be wise to follow a different approach.

In the Auob aquifer the complete process of cation exchange and salinisation by dissolution can be followed (see Figure 7.18e). This is also aided by the subdivision according to the EC intervals. It is important to note that the salinity of the water is relatively low compared to that of the Kalahari (or the Nossob) groundwater. The two saline boreholes included in the graph are those located in the extreme southern part where Auob groundwater is affected by the high salinity water in the Kalahari sediments.

In an earlier study, a detailed investigation was made of the Auob aquifer in the area to the south of Stampriet along the Auob River (Tredoux & Kirchner, 1981). Then it was found that bacterial denitrification was a natural feature in the aquifer to the south of Stampriet. At the same time, the sulphate concentration increased through the oxidation of pyrites. Cation exchange removed calcium and magnesium from solution while the sodium concentration increased. The disturbance of the carbonate-calcite equilibrium allowed further dissolution of calcium carbonate, continued ion exchange and an increase in the alkalinity and pH. Potassium also decreased and this was ascribed to fixation by illite, which is present in the rock matrix (Tredoux, 1981).

In the case of the Nossob aquifer the graph starts well beyond the cation exchange stage and continue with the dissolution and salinisation process (see Figure 7.18f). As the Nossob aquifer does not extend to the northern rim of the basin, it can only be recharged indirectly in that area, and it would seem that the groundwater has already undergone cation exchange by the time it reaches the Nossob aquifer. The only remaining process in the Nossob aquifer is salinisation by dissolution during the long residence time of the groundwater.

A characteristic of the Nossob water is its corrosiveness. This is a feature of the artesian waters in the basin once it has undergone cation exchange, regardless of the aquifer. The total alkalinity and the pH of the water is very high. Furthermore, the water is unsuitable for irrigation due to its high sodium adsorption ratio and bicarbonate character.

In the vicinity of the Salt-Block area all the water is corrosive, regardless of whether it is in the confined aquifer or in the overlying Kalahari sediments. For this reason virtually all boreholes in that area will be leaking unless they are constructed with stainless steel or plastic casings. This is a problem that needs to be addressed.

7.4.7 Extent of Area with Suitable Water Quality for Various Purposes

Based on the present study and earlier detailed studies, usable groundwater is procurable over most of the basin, except in the so-called Salt-Block area in the southeast. The high salinity in this area precludes groundwater use for most purposes. Nevertheless, the drilling of the JICA boreholes has proved that near this area usable water can still be obtained if the necessary care is taken to design the borehole correctly. This is not expected to be feasible over the whole of the Salt-Block area. Thus, in that area, groundwater of usable quality will not be procurable.

High salinity groundwater also occurs near Kalkrand and in part of the area underlain by basalt only saline groundwater is available.

High nitrate concentrations occur in many areas, notably at Kalkrand and in the

Salt-Block. Also in other areas, mainly underlain by basalt, high nitrate concentrations prevail. It is known that it entails a serious risk for infants, but also for livestock. In general opting for drinking water with a low nitrate concentration can reduce this risk. It is, however, necessary to alert the general population to the dangers involved.

7.4.8 Borehole Leakage and Quality Deterioration

Leakage of groundwater from the confined aquifers causes pressure loss, the loss of good quality water, and contamination of usable aquifers. Water quality problems in the Stampriet Artesian Basin can often be related to incorrect borehole design, borehole casing deterioration and leakages. The importance of this problem, particularly at the edge of the Salt-Block, is illustrated below by means of a few examples. In this area it could also be called the ***unconfined aquifer system groundwater salinity threat.*** This is of special consequence in the southern part of the study area, closer to the so-called Salt-Block. To the south and southeast of the high-pressure area, the possibilities increase for groundwater from the overlying unconfined sediments to leak into the artesian sandstones. The quality of the water in the overlying aquifer(s) deteriorates in a southward direction. The closer to the Salt-block, the more disastrous the effects of (even a small) leakage will be. The absence of confining shales overlying the Auob sandstone in parts of the area approaching the Salt-Block constitutes a serious problem. In Table 7.5 a set of four examples are given of water qualities in the various aquifers at each particular point.

The first example shows the water quality in the Kalahari and Auob aquifers at the JICA boreholes on Cobra, R349, east of Gochas. Whereas the water in the overlying Kalahari aquifer (borehole WW39849) is totally unusable, even for stock watering, the water from the Auob aquifer (borehole WW39850) is of potable quality. These boreholes were properly designed and constructed with the perforated casing at the correct depth and proper grout seals preventing leakage. However, if any such borehole were to begin leaking in such an area the potable groundwater will be at risk. The extreme corrosiveness of the water increases the risk as very few steel borehole casings could withstand the effect of the water for any length of time.

Details of a second example were recorded on the same farm. Borehole WW9919 was drilled in 1969. At that stage the CSIR was carrying out the survey in the Salt-Block and the initial water struck in the Kalahari beds was sampled and analysed (see Table 7.5). This water had a similar quality to that of borehole WW39849. Subsequently the borehole was grouted and completed in the Auob aquifer and water of excellent quality was obtained, similar to (or even slightly better than) that of borehole WW39850.

On the farm Rooikop, R503, further to the southeast, the water in the Kalahari aquifer was struck at 82 m depth. This was of extremely poor quality and the brine was several times as saline as seawater. Yet, the water found in the Auob aquifer at 177 m, was still of potable quality. It is evident that a very small leak from the Kalahari aquifer would render the Auob water unusable. It is also apparent that the brine will be exceptionally corrosive.

The final example is from Ou Dempster, R356, neighbouring farm to the south of Cobra. Borehole WW6921 was drilled in 1960 and sampled in 1969. At that stage the water was just outside the limits for potable water but still usable for stock watering. However, in 1999 it was found that the borehole had been abandoned. The EC had increased from 380 mS/m to 2910 mS/m and was also unsuitable for stock watering. Had the borehole been correctly designed (see par. 7.4.3) it may have lasted longer, but the casing had also been corroded.

These examples demonstrate that in certain areas potable water or at least water suitable for stock watering can be procured when the necessary care is exercised and the boreholes correctly designed and constructed.

Although groundwater movement is slow, the saline water contamination via a borehole may be significant. The general rate of groundwater movement in the subsurface may be of the order of one metre per annum under natural gradients and assuming that the water flows through the matrix. But under increased gradients (vastly different hydraulic heads in different aquifers), and fracture flow conditions, the situation will be totally different. Thus it is important to identify and rectify leaking boreholes for the longer term protection of the water resource.

7.5 Isotope and Chemical Evaluation of Aquifer Recharge

7.5.1 Conceptual Hydrogeological Model

The unconfined aquifers in the Kalahari sediments, the Kalkrand basalt and the Rietmond formation can be recharged at any location in the basin where these formations occur. However, considering the rainfall distribution pattern it is more likely that recharge will take place in the northern part of the basin where the average rainfall is higher. In the area south of Aminuis and east of the Nossob River towards the Botswana border the water levels are very deep, and in this area direct rain recharge may be impossible.

From the hydrochemistry and isotopes it was concluded that floodwater recharge of the unconfined aquifer was taking place at least along certain sections of the three main rivers crossing the basin. Examples are the area along the Nossob River to the southeast of Aranos, along the Auob River south of Gochas, along the Auob River near Tweerivier, and possibly also elsewhere.

Based on the general southerly to south-easterly water level gradient over the Stampriet Artesian Basin it is evident that recharge of the artesian sandstones has to occur in the northern, north-western and western parts of the Basin. The rainfall distribution over the Stampriet Artesian Basin confirms the importance of the northern areas for accepting recharge in the somewhat higher rainfall area.

However, no outcrops of the artesian sandstones are known in the north and recharge has to take place through the overlying Kalahari sediments or basalt. The high salinity and high nitrate concentrations in many parts of the basalt outcrop preclude recharge of water of appropriate quality through the basalt itself. Considering the excellent quality and particularly the low salinity of the water in the Auob sandstone near the recharge area and even at Stampriet it requires a mechanism, which will allow the water to bypass the basalt itself on its route to the Auob aquifer. Based on the isotope composition, the transport of water to the Auob aquifer has to take place quickly enough to limit evaporation. This can only happen through suitable and highly permeable structures. Thus the search should be for such structures.

Dr K Schalk of the Geological Survey carefully recorded the details of the Uhlenhorst cloudburst of 1960 (Schalk, 1961). The notes on this event provide important clues as to the recharge mechanisms of the artesian sandstones. This would seem to indicate that certain pans in the vicinity of Uhlenhorst responded differently and some were found to be relatively permeable and the ponded rainwater quickly soaked away. Other pans were impermeable and the water only evaporated or seeped horizontally through the dunes into the next depression. The water levels in the artesian basin responded within weeks and the nearest artesian boreholes that had stopped flowing started flowing three weeks after the cloudburst.

Provided the water can rapidly seep into the subsurface such an event can provide most of the answers to the questions regarding the excellent water quality and non-evaporated water in the artesian sandstones. It may very well be that significant recharge can only take place during such events. Finding the permeable structures and faults should provide at least some of the answers.

According to the recently compiled Auob formation isopach maps, the Nossob River crosses a thick section of the Auob formation where it enters the basin to the north of Leonardville. In view of the high groundwater age in this area, it is doubtful whether the floodwater actually enters the formation at this place, but it is worth investigating.

Recharge of both the Auob and Nossob sandstone outcrops and suboutcrops take place on the Weissrand. Both the hydrochemistry and the isotope results confirm the situation. However, the average annual precipitation is significantly lower than in the north and therefore recharge will also be less. Both the hydrochemical trends and the isotopes support such a conclusion.

The hydrochemical data and the groundwater ages for the Nossob aquifer indicate that aquifer recharge is a long-term process. By the time the water reaches the Nossob sandstone, it has already undergone virtually complete ion exchange and has reached an age of at least 20 000 years. The exact recharge process is, however, still unclear, but the present thinking is that the water can only reach the sandstone via faults penetrating the overlying Mukorob shale. It is highly likely that the groundwater has passed through at least a part of the Auob aquifer on its way to the Nossob aquifer. In the Auob aquifer it probably underwent cation exchange and other processes and by the time the water reaches the Nossob aquifer it already has a sodium bicarbonate character. Subsequently the only remaining process is salinisation by dissolution during the long residence time of the groundwater in the Nossob aquifer.

7.6 Conclusions

7.6.1 Insights Gained into Hydrogeology

The Southeast Kalahari (Stampriet) Artesian Basin has a complex geology and it would seem that the hydrogeology should also be complex. However, it would seem that despite the many faults, dolerite intrusions and other complicating factors, the groundwater in the confined aquifers form a few relatively contiguous water bodies with particular characteristics.

The specially drilled JICA boreholes have yielded valuable information regarding the characteristics of the various formations in different parts of the basin.

The recharge mechanisms are not yet fully understood, but it would seem that progress is being made to get to clarify the recharge of the various aquifers. The hydrochemistry and isotope data have confirmed a number of earlier conclusions regarding floodwater recharge of the unconfined aquifers along the river valleys.

Hydrochemical evolution is evident in all the aquifers and it can be linked to the isotope results and the groundwater age.

Hydrochemical logging of the boreholes is a useful tool for identifying leaky borehole casings and other problematic situations. It needs to be complemented with down the hole camera follow-up of identified problem boreholes as well as vertical flow measurements in such boreholes.

Local pollution of the groundwater at stock-watering points and through inappropriate on-site sanitation systems seems to be happening. This is not noticeable everywhere, but the frequency is sufficient to warrant action in this regard.

Much of the water is extremely corrosive as a result of the cation exchange and proper precautions are needed for maintaining borehole casings and other equipment. It is also concluded that many, if not all, boreholes are leaking. It should be considered what steps have to be taken in this regard.

7.6.2 Increasing Groundwater Salinity with Time

At ten boreholes representing the main aquifers, the groundwater salinity had increased significantly over two to three decades. In two cases increases exceeded 30 percent. The reason(s) for the increase in salinity is unknown but it is potentially possible that leaky borehole casings may be playing an important role, e.g. allowing poorer quality water from the overlying aquifer to affect the underlying aquifers. Further investigation is needed to establish the extent of the problem, to find the reason(s) for this phenomenon and to derive possible solutions.

7.6.3 Adequacy of Existing Information

The JICA study has yielded very important additional information and provides a solid baseline for further study. However, linking of the new data with the wealth of earlier data was not possible within this project and too much of the important earlier data is still presently inaccessible. The coverage of hydrochemistry, isotopes and also other aspects can be extended significantly by linking the earlier data with the new information. Making full use of the earlier data will eventually also benefit the groundwater modelling exercise.

7.7 Recomendations

7.7.1 Further Information Needs

Particularly in the northern part of the Stampriet Artesian Basin the recharge areas and the recharge mechanisms need further clarification and delineation. The detailed geological description of the various members of the Karoo Sequence has indicated areas where recharge of the artesian sandstones would be possible. It has also identified structures, mainly faults, which will allow groundwater to reach the sandstones in areas where it is overlain by basalt, shale or other formations. This has contributed to the delineation of the recharge areas but further drilling will be necessary (as part of the IAEA project) for full identification and confirmation of these areas and the particular recharge mechanisms.

All hydrochemical data-points from previous surveys, which presently still exist, should be linked with the boreholes recorded during the hydrocensus. The present survey included a total of 265 hydrochemical samples and the eventual value of the present studies will be significantly enhanced when the previous 4 000 high quality chemical analyses are combined with the latest data. Although several of the analyses have been linked with hydrocensus boreholes, it was not possible to complete the task within this project. The task should, nevertheless, be undertaken for future use.

7.7.2 Increase in Groundwater Salinity

Comparing the hydrochemistry of ten boreholes over a period of several decades has shown that a gradual salinisation is taking place. All of the boreholes had an increased salinity ranging from 0.6 to 37.6 percent. All aquifers seem to be affected and the phenomenon needs following-up.

7.7.3 Down-the-Hole Hydrochemical Logging of Boreholes

Further hydrochemical logging of boreholes is needed for more detailed analysis of rock-water interactions, identifying leaky borehole casings, and other problems. It will also aid the following of trends at the newly drilled boreholes, specifically those with a low yield. In these cases, the cement used for grouting the borehole casing may have significantly influenced the hydrochemistry. It may take years for the hydrochemical equilibria to be re-established.

7.7.4 Safeguarding of Collected Information

The electronic data gained through this project, should be safeguarded for future use, preferably in different ways. This should ensure future accessibility and will prevent the need for recapturing of valuable data as was experienced when electronic data from previous surveys were destroyed.

Table 7.1 Results of Duplicate Samples Submitted to NamWater for Analysis

Sample No	Borehole No	Date sample taken	Date Received	Date analysed	pH	Con-ductivity mS/m	TDS	Na	K	Ca as $CaCO_3$	Mg as $CaCO_3$	SO_4	NO_3 as N	NO_2 as N	SiO_2	F	Cl	Total Alkalinity as $CaCO_3$	Phenol-phtalein Alkalinity as $CaCO_3$
DS5947	WW1543	18-03-2000	07-04-2000	19-04-2000	8.1	64.3	431.0	61	7	112.5	100.0	26	2.3	-	35	0.3	23	282	-
DS7631	WW1543	19-10-2000	26-10-2000	03-11-2000	7.9	66.3	444.2	58	14	112.5	108.3	26	3.1	-	37	0.3	28	282	-
DS5925	WW1843	25-03-2000	07-04-2000	19-04-2000	7.9	73.5	493.0	75	12	110	100.0	39	2.4	-	25	0.3	52	274	-
DS7505	WW1843	06-10-2000	19-10-2000	25-10-2000	8.5	75.3	504.5	75	11	100	91.7	23	3.4	<0.1	25	0.3	54	264	6
DS5857	WW4942	18-03-2000	07-04-2000	18-04-2000	8.3	66.8	447.0	125	5	42.5	79.2	24	<0.5	-	21	0.2	39	334	-
DS7638	WW4942	21-10-2000	26-10-2000	03-11-2000	8.1	68.7	460.3	120	7	40	66.7	28	<0.5	-	23	0.2	41	276	-
DS5935	WW10595	29-03-2000	07-04-2000	19-04-2000	8.6	717	4804.0	1820	12	2.5	12.5	1140	50	-	36	5	960	1100	40
DS7788	WW10595	03-11-2000	20-11-2000	05-12-2000	8.6	704	4716.8	1740	12	7.5	8.3	1060	57.4	<0.1	36	4.9	1040	1026	44
DS7797	WW15119	08-11-2000	20-11-2000	05-12-2000	8.6	195.4	1309.2	455	2	15	8.3	126	<0.5	<0.1	14	0.5	290	440	10
DS7810	WW15119	-	20-11-2000	05-12-2000	8.6	196.7	1317.9	475	1	10	4.2	230	<0.5	<0.1	13	0.5	285	434	22
DS6839	WW39847	31-05-2000	02-08-2000	02-10-2000	8.5	99.2	664.6	230	4	2.5	4.2	31	<0.5	<0.1	15	0.7	29	448	10
DS6840	WW39847	28-05-2000	02-08-2000	02-10-2000	8.5	99.5	666.7	240	4	2.5	4.2	35	<0.5	<0.1	16	0.8	27	454	10

Table 7.2 PCI Groundwater Chemistry Survey Boreholes also Previously Sampled and Analysed by DWA

Laboratory No.	Sampling Date	Borehole No.	pH	Electrical Conductivity	TDS	Sodium	Potassium	Sulphate	Nitrate as N	Nitrite as N	Silica as SiO_2	Fluoride	Chloride	Total Alkalinity	Calcium Hardness	Magnesium Hardness
C1142	13-05-1965	874	7.7	72	550	129	11.0	34	19.9	0.1	34	0.7	43	300	93	87
DS5928	25-03-2000	874	7.8	89	595	127	9.0	40	21.0	-	43	1.0	32	294	90	88
C1211	09-06-1965	1100	7.5	73	524	134	10.2	36	15.0	0.0	8	0.8	50	315	65	105
DS7525	10-10-2000	1100	8.8	93	625	210	5.0	53	8.0	<0.1	21	1.0	45	354	25	29
C3804	18-03-1968	2302	9.0	205	1590	595	7.0	118	35.0	0.0	25	1.6	145	850	5	5
DS7902	15-11-2000	2302	9.0	258	1729	655	7.0	166	34.0	2.0	25	3.0	171	892	8	8
C5258	21-07-1969	5943	7.2	55	465	40	8.6	12	13.0	Trace	25	0.8	20	295	126	149
DS8184	04-11-2000	5943	8.3	61	407	45	6.0	18	18.0	<0.1	57	1.0	20	282	135	154
C2797	03-04-1967	9105	8.0	202	1390	512	3.0	182	4.0	Trace	25	1.0	410	385	15	30
DS7808	06-11-2000	9105	8.6	239	1601	540	1.0	195	5.0	<0.1	14	1.0	420	394	13	8
C4322	04-09-1968	9658	7.0	69	483	84	13.0	22	9.8	0.0	22	0.3	25	337	120	117
DS5957	21-03-2000	9658	8.0	76	506	87	14.0	22	5.0	-	50	0.0	25	348	143	83
C8254	03-08-1971	11314	7.7	155	950	360	5.0	82	3.0	0.0	25	0.4	193	455	21	9
DS7790	06-11-2000	11314	8.4	156	1044	360	3.0	92	1.0	<0.1	14	1.0	177	438	15	8
C8504	16-10-1971	12914	7.5	130	775	249	11.0	70	0.0	0.0	25	0.6	170	350	68	62
DS5860	18-03-2000	12914	8.6	175	1175	390	5.0	124	1.0	-	15	1.0	230	468	15	21
C18734	17-08-1978	23169	8.7	109	874	264	36.0	44	11.0	0.0	10	0.4	105	470	51	64
DS5847	17-03-2000	23169	8.3	150	1008	300	15.0	70	12.0	-	36	0.0	160	470	55	67
C18830	29-08-1978	23334	8.1	54	360	17	9.0	13	8.0	Trace	25	0.4	20	250	140	125
DS5851	17-03-2000	23334	8.2	64	426	25	6.0	14	8.0	-	75	0.0	16	288	160	121

Table 7.3 Water Quality Changes Over a Period of Two to Three Decades in the Artesian Basin

Borehole No. WW	Farm No	Latitude	Longitude	Aquifer	Sampling Dates	Electrical Conductivity mS/m	Percentage change
874	R202	-24.36940	18.68330	A	13-05-1965	72	23.6
					25-03-2000	89	
1100	R118	-24.57100	18.33810	A	09-06-1965	73	27.4
					10-10-2000	93	
2302	R346	-24.97435	19.10679	K	18-03-1968	205	25.9
					15-11-2000	258	
5943	R128	-24.14992	18.47790	A	21-07-1969	55	10.9
					04-11-2000	61	
9105	R499	-25.01740	19.93333	A	03-04-1967	202	18.3
					06-11-2000	239	
9658	L618	-23.56300	18.96990	R	04-09-1968	69	10.1
					21-03-2000	76	
11314	R533	-24.67171	19.56467	A	03-08-1971	155	0.6
					06-11-2000	156	
12914	L957	-23.32820	19.91860	N	16-10-1971	130	34.6
					18-03-2000	175	
23169	L330	-23.37930	19.58720	K	17-08-1978	109	37.6
					17-03-2000	150	
23334	L330	-23.14550	19.55690	R	29-08-1978	54	18.5
					17-03-2000	64	

Table 7.4 List of Boreholes Logged Hydrochemically Down the Hole

Borehole No. WW	Latitude °S	Longitude °E	Farm Name	Farm No	Date Drilled	Depth, m	Date Logged	Water Level, m	Logged Depth, m	Casing, m	Geology (below casing)
10120	24.54940°	18.56250°	Boomplaas	R386	12-12-1969	141.4	20-10-1999	30.42	126.6	123.8	Sh?, A
10185	23.57136°	18.31741°	Neu Loore	M097	27-11-1969	91.7	19-07-2000	8.05	87.0	unknown	R, Shale
22544	23.68440°	18.39420°	Olifantwater West	M102	19-11-1977	134.0	20-10-1999	23.38	144.2	57.0	Sh, N
22837	24.82069°	18.25369°	Tugela	R212	30-10-1978	126.0	19-10-1999	34.15	122.9	18.0	Sh?, N
32457	24.32810°	18.39440°	Spes Bona	R132	11-08-1973	>79.2	06-11-1999	-1.48	79.2	unknown	Sh?, A
33038	23.18618°	18.67985°	Donnersberg	L029	10-04-1992	40.0	06-11-1999	13.63	33.4	18.0	K, ?
33468	23.50077°	18.78707°	Erf 33 Leonardville	L015	abandoned	(88.0)	06-11-1999	17.31	88.0	(6.0)	K, Shale
35769	24.34573°	19.89709°	Naomi	R455	03-05-1999	341.0	05-11-1999	110.71	307.5	128.0	Dol, Sh, A
37225	25.07258°	18.10842°	Glencoe	R078	18-03-1999	120.0	04-11-1999	29.42	120.6	42.0	Sh, A, Sh
37226	25.13287°	18.18740°	Goamus	R070	14-04-1999	174.0	04-11-1999	51.68	171.0	54.0	Sh, A, Sh, N, Sh
37227	25.32167°	18.34262°	Nooitgedacht	R164	26-07-1999	138.0	04-11-1999	14.19	137.5	72.0	Sh, A, Sh
37228	25.30103°	18.35473°	Nooitgedacht	R164	20-07-1999	138.0	04-11-1999	13.86	137.4	72.0	Sh, A, Sh
39839	23.25415°	18.98668°	Christiana	L727	29-04-2000	198.6	14-06-2000	59.07	196.8	84.0	A
39840	23.64747°	18.38873°	Olifantwater West	M102	27-06-2000	130.5	14-06-2000	15.53	129.1	95.0	A
39840	23.64747°	18.38873°	Olifantwater West	M102	27-06-2000	130.5	20-07-2000	16.50	128.7	95.0	A
39841	23.64808°	18.38871°	Olifantwater West	M102	18-05-2000	208.2	19-07-2000	40.65	203.8	181.1	N
39873	23.52892°	18.29247°	Gumuchab West	M094	29-06-2000	132.0	20-07-2000	9.75	104.8	(6.0)	Basalt, A
6921	24.92220°	19.36807°	Ou Dempster	R356	02-06-1960	265.2	05-11-1999	100.27	190.0	155.5	(K), A, Sh, (N)

Table 7.5 The Threat Leaky Boreholes Pose to Groundwater Quality

Farm Name & No		Cobra, R349		Cobra, R349		Rooikop, R503		Ou Dempster, R356	
Borehole No WW		39849	39850	9919	9919	9852	9852	6921	6921
Depth, m		158	264	<< 237	237	82	177	265	190
Aquifer		K	A	K	A	K	A	K?	A
Date sampled/analysed		27-08-2000	04-08-2000	13-06-1969	1969	1969	1969	05-11-1999	1969
Analysis No		DS7177	DS7174	V1519	A2982	V1306A	V1306B	-	V1320
pH		9.2	8.4	8.4	7.9	9.4	8.0	10.2	8.0
Electrical conductivity	mS/m	2220	186	1725	181	20800	248	2910	380
Total dissolved solids	mg/L	14874	1248	11776	1068	139235	1756	-	2745
Sodium as Na	mg/L	7400	495	4450	415	54000	621	-	1082
Potassium as K	mg/L	39	5	58	3	832	20	-	8
Calcium as $CaCO_3$	mg/L	3	3	11	3	5	85	-	24
Magnesium as $CaCO_3$	mg/L	4	4	31	8	7	12	-	5
Chloride as Cl	mg/L	4100	220	3179	172	21395	451	-	526
Sulphate as SO_4	mg/L	1850	125	1494	98	21400	231	-	360
Total Alkalinity as $CaCO_3$	mg/L	6520	592	3302	528	61400	514	-	1214
Nitrate as N	mg/L	60.0	<0.5	106.7	0.0	0.0	8	-	0.3
Fluoride as F	mg/L	19.0	1.2	10.6	0.9	260	0.8	-	5.6
Silica as SiO_2	mg/L	30	15	30	12	4	5	-	15

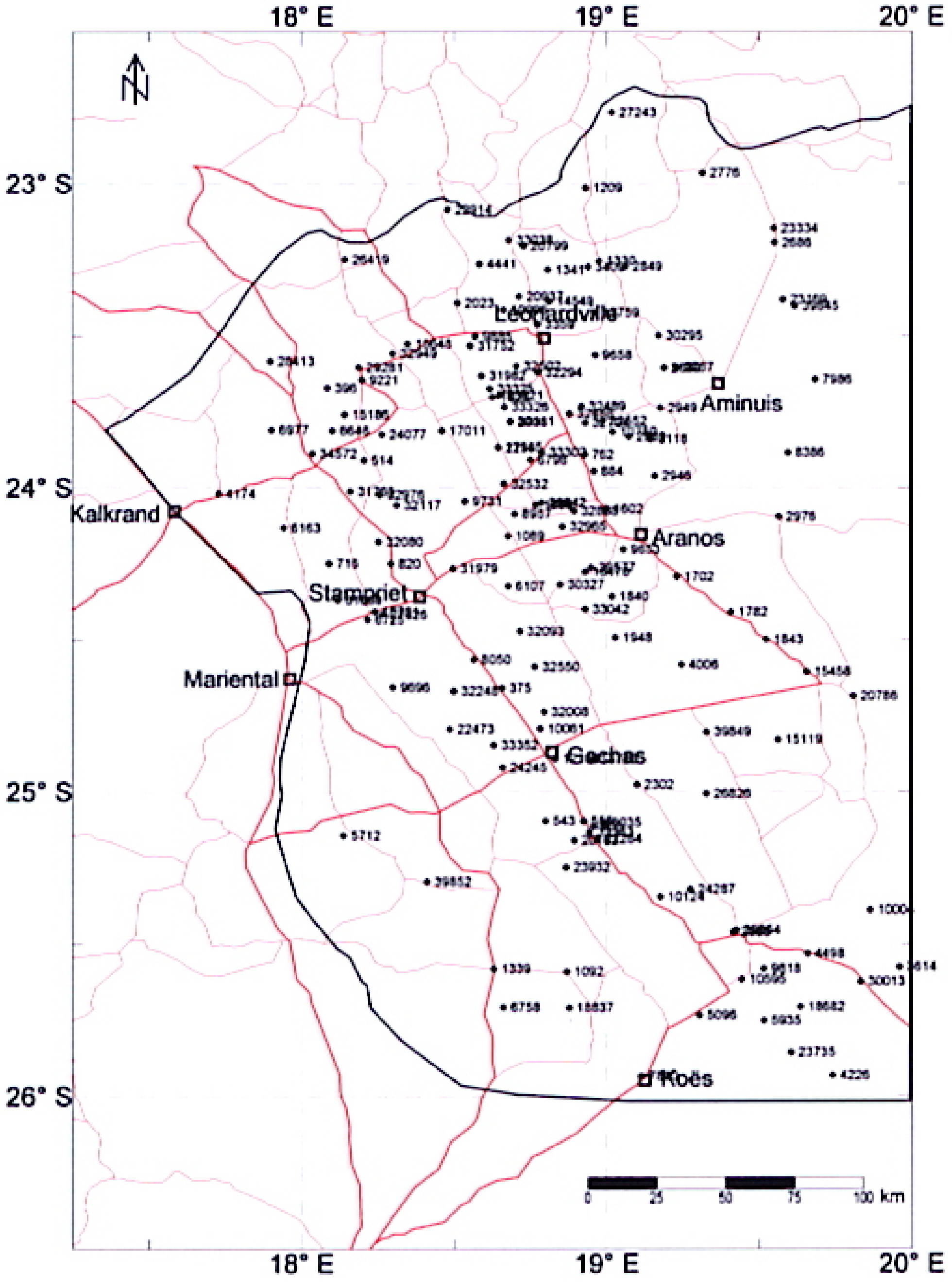

Figure 7.1a Sampling Points in the Unconfined Aquifer System (Kalahari, Basalt & Rietmond).

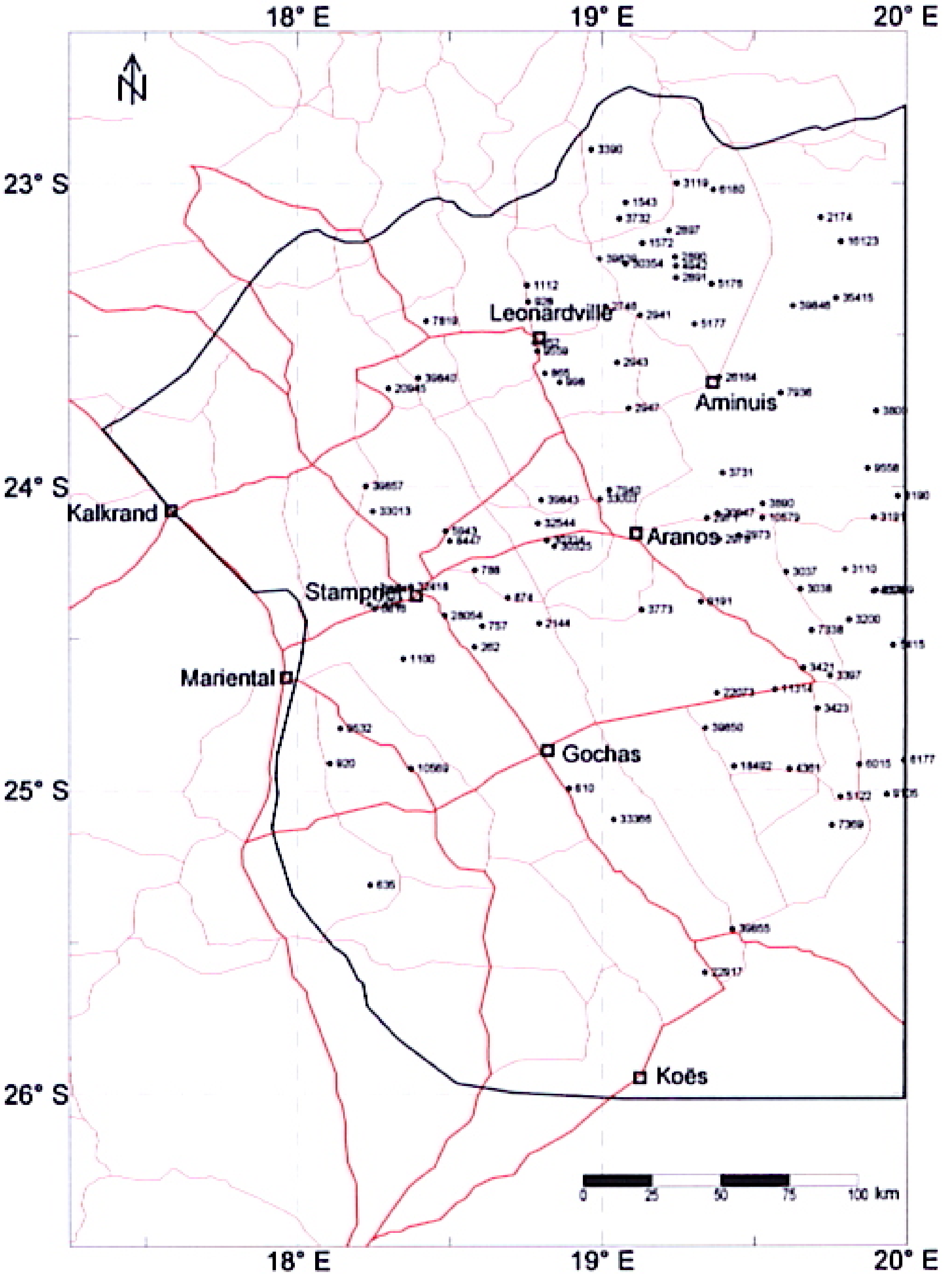

Figure 7.1b Sampling Points in the Auob Aquifer

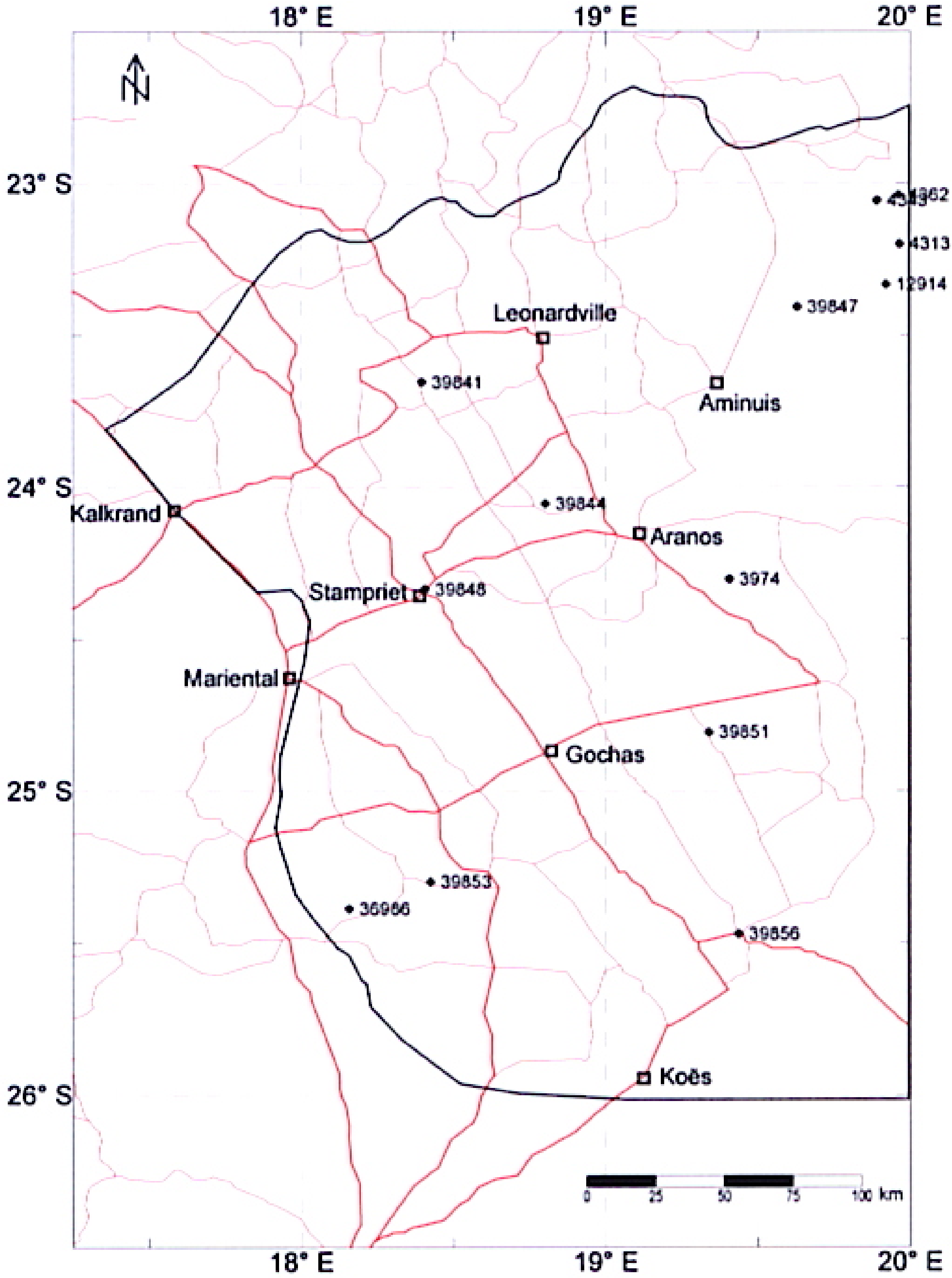

Figure 7.1c Sampling Points in the Nossob Aquifer