

**THE CHEMICAL GROUNDWATER
CHARACTERISTICS OF THE SUTHERLAND AREA,
NORTHERN CAPE.**

By

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DECLARATION

I declare that The Chemical Groundwater Characteristics of the Sutherland Area, Northern Cape is my own work and that all the sources I have used or quoted, have been indicated and acknowledged by means of complete references.

ETHICAL CONSIDERATION

The results of this study would be made available to the Sutherland municipality and farmers of the region. All the farmers who allowed me access to their boreholes can utilise the results and data contained in this thesis. The author hopes that the results of this study be used to develop and manage the groundwater resources more effectively for generations to come.



.....
Shafick Adams
November 1998

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I dedicate this work to all my family and friends.

ABSTRACT

The objectives of the project were to establish, identify, interpret and map the chemical groundwater composition of the area surrounding the town of Sutherland. Processes that govern the groundwater chemistry of the area are identified and interpreted.

The study area is underlain by the fractured rocks of the Abrahamskraal formation of the Beaufort Sequence, Jurassic dolerites and intrusives associated with the Salpeterkop Carbonatite Complex. The groundwaters naturally evolve from a Ca-HCO₃ to a Na-Cl type water with Na-HCO₃, Ca-SO₄, Na-SO₄ and Ca-Cl being the intermediate water types formed. Statistical, graphical and hydrochemical techniques are used to characterise the groundwater composition of the fractured aquifers in the Sutherland region.

The statistical techniques, specifically descriptive, Pearson's correlation matrices and varimax rotated factor analyses were used on the hydrochemical data set. The statistical analyses aided in reducing the rather large data set to the more significant variables that impact on the groundwater composition. The results of the statistical analyses coupled with graphical methods and the stable isotopes (¹⁸O and ²H) suggested that topography, evapotranspiration, geology and anthropogenic influences are the major factors responsible for the groundwater composition of the area. A number of processes were identified that occur within the subsurface.

Rainwater charged with biogenic CO₂, infiltrates into the subsurface where it dissolves carbonate-containing minerals, mostly CaCO₃. In flatter areas, where infiltration is slow, the infiltrating water leaches evaporitic salts to the subsurface. Thus, in higher lying areas where salt leaching is absent, Ca-HCO₃ type waters would form. Where salt leaching is predominant, Na-Cl type water may form. Na-Cl type waters also form because of natural hydrogeochemical evolution. Through the mechanism of cation exchange Na-HCO₃ waters are formed where Ca is exchanged mainly by bound Na. Precipitation of calcite out of a solution results in the dissolution of gypsum

($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), fluorite (CaF_2) and carbonate minerals (i.e. strontianite). Formation of Ca-SO_4 waters is formed in this manner. Exchangeable Na is released and Ca is taken up by the geological matrix forming a Na-SO_4 type water. At higher salinities, the process of reverse cation exchange results in the Ca-Cl type water from Na-Cl water, whereby Na is replaced by bound Ca. The presence of Ca-Cl type water is indicative of mixing or dilution of a more saline and older water by a fresher, younger water dominated by Ca ions. Elements that do not contribute significantly to the groundwater salinity such as Mg, K, Sr and Ba participate in cation exchange processes but are masked by the major ions Ca, Na, Cl, HCO_3 and SO_4 .

The processes of dissolution, precipitation and cation exchange coupled with the physical environment, result in the hydrogeochemical groundwater evolution of the area. Superimposed on the processes occurring in the subsurface are the effects of concentration by means of evapotranspiration and land use practices. Irrigation return flows together with the high evaporation rates increases the formation of the already high natural soluble salts in the unsaturated zone. Nitrate pollution from animal wastes causes isolated instances of pollution of the fractured rock aquifers.

In order to supply potable groundwater to the area it is recommended that boreholes, if possible, be situated away from topographical flat areas. Monitoring programs should also be initiated to determine the changes of the groundwater over time.

ABBREVIATIONS

AEC	-	Atomic Energy Corporation
DWAF	-	Department of Water Affairs and Forestry
GMWL	-	Global Meteoric Water Line
pers. comm.	-	personal communication

Name	Abbreviation	Unit
Correlation coefficient	r	
Deuterium	^2H or D	per mil
Electrical conductivity	EC	mS/m
Metres	m	m
Milligrams per litre	mg/l	mg/l
Oxygen-18	^{18}O	per mil
Partial pressure of <i>carbon dioxide</i>	pCO ₂	atm
Parts per million	ppm	ppm
Redox potential	Eh	mV
Saturation index	SI	
Total dissolved solids	TDS	ppm or mg/l

C A T I O N S	Aluminium	Al ³⁺	C A T I O N S	Strontium	Sr ²⁺
	Barium	Ba ²⁺		Uranium	U ⁶⁺
	Boron	B ³⁺		Zinc	Zn ²⁺
	Calcium	Ca ²⁺		Hydrogen	H ⁺
	Copper	Cu ²⁺	A N I O N S	Bicarbonate	HCO ₃ ⁻
	Iron	Fe ²⁺ /Fe ³⁺		Carbonate	CO ₃ ²⁻
	Magnesium	Mg ²⁺		Chloride	Cl ⁻
	Manganese	Mn ²⁺		Fluoride	F ⁻
	Nickel	Ni ²⁺		Nitrate	NO ₃ ⁻
	Potassium	K ⁺		Phosphorus	P ³⁻
	Sodium	Na ⁺		Sulphate	SO ₄ ²⁻

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CHAPTER 1

GENERAL INTRODUCTION

1.1 INTRODUCTION

Groundwater, an important natural resource, in the Sutherland area is highly variable in its chemical character. The region depends entirely on groundwater for domestic and agricultural usage as no adequate surface waters or piped water exists. The variability in the quality of the groundwater is the result of the various processes and activities occurring at the surface and the subsurface.

The groundwater mainly occurs in fractured aquifers and is exploited by means of boreholes. Siting of these boreholes is too often based on unscientific procedures, resulting in boreholes with various yields and qualities. An understanding of the region's hydrogeological/geomorphological conditions, which in turn influences the chemical quality of the water, is thus important to understand the groundwater characteristics of the area. The chemical composition of the groundwater can be used to describe the interaction of the subsurface water with its environment.

It is postulated that groundwater chemistry can elucidate the characteristics of the aquifers found in the study area, the factors and processes that determine its constituents and how these differ in space and time. Thus, by deciphering the main factors and processes that determine the variability in the groundwater chemistry, areas can be delineated that is favourable or unfavourable for the occurrence of groundwater of a suitable quality for domestic and agricultural usage.

1.2 BACKGROUND TO THE STUDY

This study forms part of a five-year project entitled: "A groundwater supply assessment and strategy for the Western Karoo, Namaqualand and Bushmanland". The Water Research Commission funds this project.

Groundwater is gaining increasing importance in the supply of water to rural communities in the drier regions of South Africa where surface waters are very scarce or absent. Assessing the groundwater characteristics was thus important, mainly in terms of quality. Assessing the quantity that the aquifers yield falls beyond the scope of this project.

Understanding the area's potable groundwater resources is important, as it is the only source of water for the local communities and farmers. As the importation of surface water over very long distances is very costly.

No serious attempt has previously been made to assess the water quality, and thus the groundwater chemistry of the area. Management and monitoring systems are absent. The need for adequate groundwater management and monitoring is increasing and can only be achieved if enough data are available on the existing water resources like boreholes and wells. Two sets of data are required to formulate these management strategies, namely quantity and quality data.

This study focuses mainly on the groundwater chemistry/quality, to evaluate and define the aquifers of the Sutherland area. However, this study will try to prevent a data-rich and information-poor situation, by analysing and interpreting the data and try to correlate the results obtained with the physical and human environment.

1.3 OBJECTIVES OF THE STUDY

The objectives of the study were to:

- (1) Establish the chemical composition of groundwater.
- (2) Identify and interpret the different water qualities.
- (3) Map the groundwater in terms of distribution and chemistry in the areas surrounding Sutherland.

- (4) Identify the hydrogeologic and geomorphological conditions that influence the chemical composition of the groundwater.

1.4 RESEARCH REQUIREMENTS

To achieve the above objectives, the following research requirements were identified:

- (1) Sampling of individual boreholes for chemical and isotopic analyses (for selected boreholes) and recording its physical parameters (e.g. pH, alkalinity, temperature, geological and geomorphological setting and depth to water).
- (2) Developing conceptual models for a fractured rock aquifer.

1.5 ORGANISATION OF THE STUDY

The first four chapters mainly concentrate on the descriptive and observational characteristics of the area. The remaining chapters focus on the presentation and interpretation of the chemical data.

Theoretical considerations are reviewed in Chapter 2.

Chapter 3 describes the study area.

Methodologies and presentation of conceptual models are outlined in Chapter 4.

The geohydrochemistry is discussed in Chapter 5 in terms of the hydrogeochemical processes, its distribution and its relation to the physical environment.

Conclusions and recommendations are made in Chapter 6.

CHAPTER 2

THEORETICAL CONSIDERATIONS

2.1 INTRODUCTION

Existing literature, comprising of both local and international literature, is reviewed in this chapter. Literature surveyed and reviewed was of areas experiencing similar or nearly similar conditions to that found in the specific study area (i.e. arid to semi-arid climate and similar geological conditions). The literature study significantly contributed to the formulation of the conceptual models outlined in Chapter 4. Relevant literature will also be incorporated in subsequent chapters to aid interpretation.

2.2 PREVIOUS WORK

No previous water quality studies have been done or published for the study area. One report on the geohydrology of the Sutherland area could be found (DWAF, 1946). This two-page report only dealt with the siting of a few boreholes on the farm Kruisrivier. The Department of Water Affairs and Forestry (DWAF) did several geohydrological surveys around Williston (Seward, 1983, 1986). Hydrogeological investigations in the vicinity of Merweville (Diettrich, 1973) and Fraserburg (Wilke, 1962) provided the only real information found for the Western Karoo in the immediate vicinity of the study area. To date most of the geological work done in the area was centred on Salpeterkop, a carbonatite extrusive structure (De Wet, 1975; Newton, 1987; Verwoerd, 1990; Verwoerd et al., 1995).

The Geological Survey of South Africa mapped the structures (dykes, major joints and fractures) in the study area (Chevallier, pers. comm.). The Geological Survey has interpreted the geology of the area on 1:250 000 (Theron, 1983) and 1:50 000 scale geological maps, the latter unpublished.

2.3 LITERATURE REVIEW

2.3.1 Fractured rock aquifers/formations

It is well recognised that the quality of groundwater varies considerably over short distances in many of South Africa's fractured aquifers (Parsons and Tredoux, 1993). More than 90% of the aquifers in South Africa are fractured aquifers (Kirchner and Van Tonder, 1995). Except for some localised occurrences of permeable porous Cretaceous and Karoo sandstones, pre-Tertiary formations do not feature as primary aquifers (Vegter, 1995) in the study area.

Kirchner and Van Tonder (1995) defined the term fracture as cracks, fissures, joints and faults, which are caused mainly by:

- (1) Tectonic movement, secondary stresses, release fractures, shrinkage cracks, weathering, chemical action and thermal action.
- (2) Petrological factors like the compositions of minerals, internal pressures and grain sizes.

A fractured rock mass can be considered a multi-porous medium, consisting of two main components, namely matrix rock blocks and fractures (Kirchner and Van Tonder, 1995). Fractures are conductivity conduits for flow whilst the matrix blocks may be permeable or impermeable, with most of the storage contained within the permeable matrices (Kirchner and Van Tonder, 1995). The density of fractures may also be a factor in storing significant amounts of water and depends on the lithology and structural components of the geological setting. Thinner sedimentary rocks can be more susceptible to fracturing than thicker sedimentary rocks units (Domenico and Schwartz, 1990). Hughes and Sami (1991) found that the sandstones of the Bedford catchment have undergone a high degree of lithification and assumed that they deform in a brittle fashion and fracture in response to stresses. The mudstones

behave in a more ductile fashion (due to their high clay content) within this catchment. Fractures may close at depth, due to the weight of the overlying material. The openings develop typically in the upper part of the earth's crust, being generally restricted to the upper 100 m (Wright, 1994).

Dolerite intrusions are common in Karoo aquifers and experience has proven that their location is often associated with high yielding boreholes due to the fracturing they have caused in the adjacent country rocks (Enslin, 1950). Jointing is common along these intrusive contacts and they are particularly valuable on the upslope side of the hydraulic gradient in the Karoo sediment (Robins, 1980). Major joint directions in the Karoo sediments near Sutherland are north and east-north-east (Theron, 1983). Karoo sediments have a poor primary permeability but the intrusive contacts form high-permeability conduits that can draw from a wide area of the sediments and support sustained yields of up to 6 l/s, as found by Robins (1980) in Swaziland. Increased yields could also be associated with fracturing and other deformational features such as fold axes and faults. Weaver et al. (1993) found in the Strydenberg region that not all dolerite contacts yield water.

2.3.2 Recharge

It could be stated that the groundwater quality (salinity) depends on the amount of rainfall infiltration that contributes to recharge (AEC, 1990). There is a general correlation between mean annual rainfall and groundwater quality with poorer quality water being associated with areas receiving a low average rainfall. It is noticeable that areas receiving less than 2250 mm/annum tend to exhibit the poorest water quality (AEC, 1990). De Beer and Blume (1985) suggest that the water in the Karoo sequence is generally of a poor quality. The higher the rainfall the better the quality of groundwater, although superimposed on this is more local specific factors depicting the quality of groundwater (AEC, 1990).

The water bearing formations of South Africa are recharged by rain infiltration, which

can amount to 3% of mean annual recharge in the west, with an average annual rainfall of 250 mm, to 23% in the east, with an average rainfall of 1200 mm (Simonis and Kok, 1989). The secondary Karoo aquifers have limited storage (S) ($S = 0.004$) and recharge rates of between 2-5 % of annual precipitation (Bredenkamp et al., 1995; Van Tonder and Kirchner, 1990). Annual recharge may also be erratic because of the variability of rainfall. The amount of recharge depends on the head differential and the hydraulic properties of the aquifers. Recharge from natural sources includes the following (US Dept. of the Interior, 1981):

- (1) Deep percolation of precipitation as a major source of groundwater recharge.
- (2) Seepage from surface water bodies is another important source of recharge. In arid regions where the entire flow of streams may be lost to an aquifer, seepage may be of major significance.
- (3) Recharge by means of underflow from a nearby, hydraulically connected aquifer.

The amount of recharge is influenced by vegetative cover, topography and nature of soils and the type, intensity and frequency of precipitation (US Dept. of the Interior, 1981). Groundwater levels tend to rise during rainy periods or after a heavy storm. This is due to the fact that the joints penetrated by the boreholes are in hydraulic continuity with the joints that are open to recharge (Robins, 1980). The favoured recharge mechanism in Karoo aquifers is flow along preferred pathways (Van Tonder and Kirchner, 1990). In general, shallow water levels occur in areas of outcrop and recharge, whereas deep water levels coincide with basement depressions having thickened beds and a lack of recharge (Levin, 1981). Groundwater generally moves from levels of higher potential energy to levels of lower potential energy. The energy is essentially the result of elevation and pressure (Davis and De Wiest, 1966).

2.3.3 Natural hydrogeochemistry

Katz and Choquette (1991) state that the chemical composition of groundwater that is unaffected by human activities, is determined by a series of complex physical, chemical and biological processes occurring as the water derived from precipitation moves through soil, the unsaturated zone and the saturated zone. The hydrogeochemistry of groundwater reflects the source of the water, the lithology of the aquifer and the local chemical conditions such as temperature, pressure and redox potential (Henderson, 1986). Hydrochemical analysis of groundwater is thus not only useful for determining the potability of groundwater, but also in understanding the geology and movement of groundwater (Ophori and Toth, 1988). The chemical constituents of groundwater commonly reflect the environment of occurrence including, geological, biospherical and human influence (Malomo et al., 1990). According to Tredoux and Kirchner (1981), an intimate knowledge of the chemical evolution of the water in an aquifer is required in order to classify the water sources and to identify the groundwater mixture.

Water naturally contains a number of different inorganic constituents. The major cations are calcium, magnesium, sodium and potassium, the major anions are chloride, sulphate, carbonate and bicarbonate. Although not in ionic form, silica can also be a major constituent. In addition, there may be minor constituents present such as iron, manganese, fluoride, nitrate, strontium and boron (Fetter, 1988).

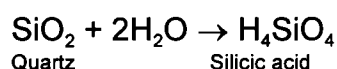
2.3.3.1 Weathering and dissolution

The weathering of rocks is both a chemical and mechanical process (Henderson, 1986). The weathering process entails the interaction of an aqueous solution with rock material to produce a solution of different composition from the reactant one, a residue of insoluble solids of the initial rock and other solids that are secondary mineral phases (Henderson, 1986). On encountering soil and rock, water incorporates major and trace elements by decomposing and dissolving rock minerals. For the most part this is

accomplished by reaction of the H⁺ ion with carbonate and aluminosilicate minerals to liberate cations and silica into solution and leave behind clay minerals (Rose et al., 1979). Chemical weathering is thus an important process that can neutralise incoming acidity. Weathering of minerals generally exhibits two types of reactions (Henderson, 1986):

- (1) Congruently whereby all minerals dissolve completely.

Example:



- (2) Incongruently whereby some minerals dissolve and others recombine to form a new solid phase.

Example:



The amount of carbonates, bicarbonates and dissolved carbon dioxide (CO₂) largely controls the pH of water (El Ghandour et al., 1985). The type of contamination bases, degree of ionisation, extent of hydrolysis and buffering actions governs the pH of water (El Ghandour et al., 1985). Strong acids from precipitation, together with carbonic acid from biological processes in the soil, attack minerals and release dissolved components to the water (Katz and Choquette, 1991). If the aggressive weathering agent is a strong acid from precipitation, the accompanying anion (SO₄²⁻, NO₃⁻ or Cl⁻) will balance the base cation released (Katz and Choquette, 1991). If carbonic acid is the principal weathering agent the bicarbonate anion will balance the cations released (Katz and Choquette, 1991).

The carbonate ions are mainly derived from calcium carbonate rocks, which generally have low solubilities, however, in the presence of dissolved CO₂ the rocks become highly soluble forming bicarbonates (El Ghandour et al., 1985). This suggests that the content of bicarbonate in solution is dependent on the amount of CO₂ in water. Carbon dioxide can be present in soil gas and will react with precipitation percolating through