The Geohydrology of the Swartkops River Basin - Uitenhage Region, Eastern Cape

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No Water ...... No Nothing !

National Water Conservation Campaign caption
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ABSTRACT

A hydrocensus of all groundwater users in the Swartkops River Basin was conducted in 1992 and 1993 to assess the occurrence and quality of groundwater in the Basin, as well as the characteristics of the various aquifers in the Basin. The extent of pollution of the groundwater reserves was noted. This specialist study was carried out to assist the Department of Water Affairs and Forestry in formulating a water quality management plan for the river basin, and was prompted by concern regarding the deteriorating water quality of the region. It was determined that the only aquifer in the river basin which was severely polluted in places was the Swartkops River Alluvial Aquifer. Following recommendations arising from the initial survey, a groundwater monitoring network of shallow boreholes was installed in the alluvial aquifer in 1994 and groundwater sampling runs commenced in 1995.

Groundwater occurs in the region in a shallow alluvial aquifer and a deeper fractured secondary aquifer. These aquifers are separated from one another by an impermeable, confining layer of Cretaceous sediments in the central and eastern parts of the study area, causing artesian conditions in places. The groundwater of the aquifers in the study area has a sodium-chloride character of low salinity in the western high-lying portion of the study area, with mineralisation increasing eastward, as aquifer lithology and distance from recharge sources change. The hydrochemical character of the groundwater is a function of the proximity of the basin to the sea, as well as connate conditions existing in the sediments of marine origin. It is shown that pollution of both the surface and shallow sub-surface water bodies is occurring, mainly in the industrial and residential areas of Uitenhage and Despatch. These polluted zones are not extensive when compared with the whole catchment area but have a definite effect on local conditions. Estimations of pollution load volumes are made based on hydraulic parameters derived from aquifer tests.

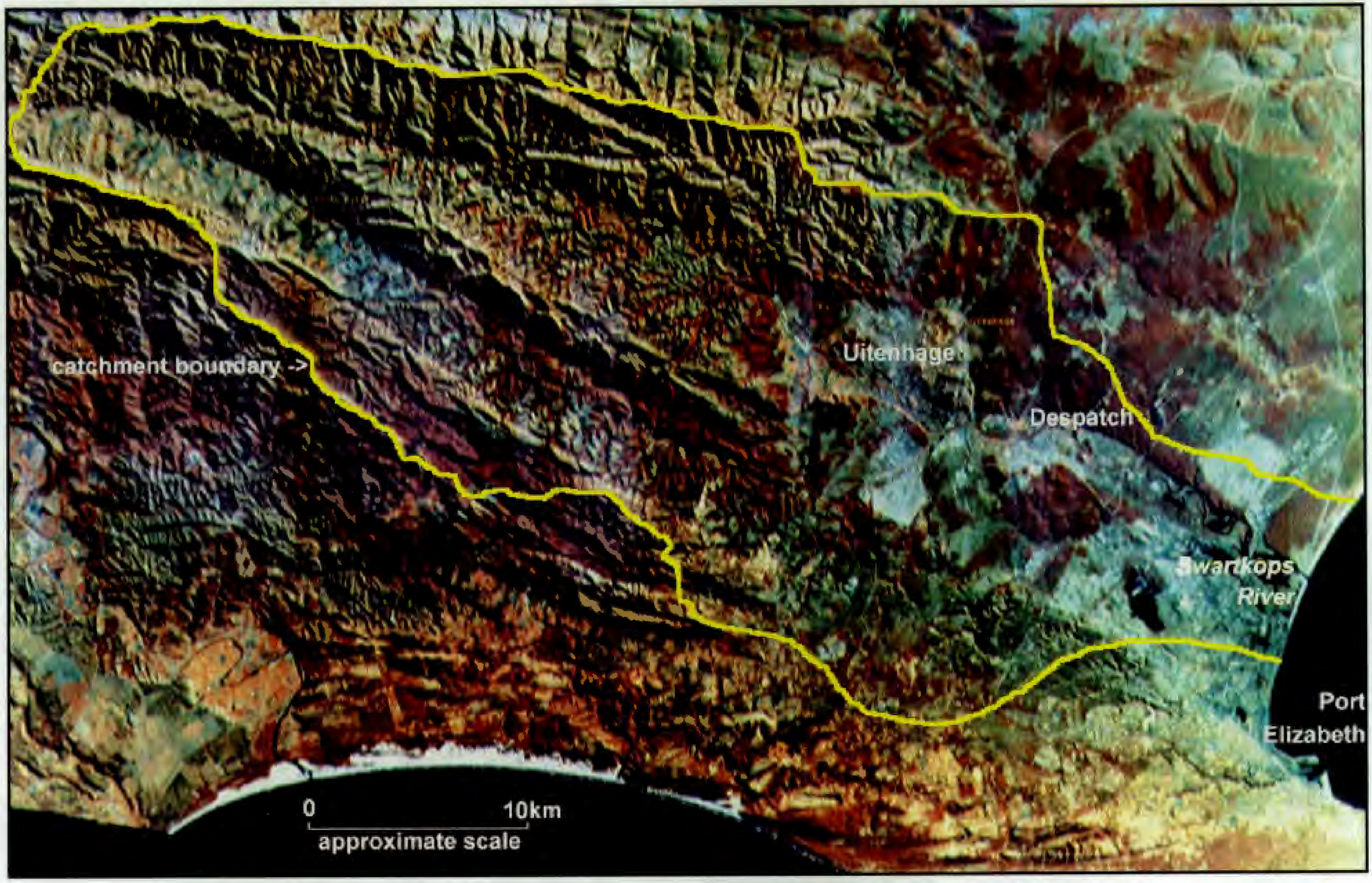
This study represents an overview of the geohydrology of the Swartkops River Basin, thereby providing a reference tool for water-resource management purposes in the region. It includes a unique study on the geohydrology of the Swartkops River Alluvial Aquifer and the extent of pollution of this aquifer, as well as a detailed account and discussion on the historical and present factors affecting variations in groundwater flow and artesian conditions in the area. A summary of suggested aquifer management practices is given to ensure the long-term sustainability of the groundwater resources of the river basin.

SAMEVATTING

'n Hidrosensus van al die grondwater-verbruikers in die Swartkopsrivieropvangsgebied is in 1992 en 1993 uitgevoer om die bestaande grondwatergehalte en -voorkoms in die gebied, sowel as die eienskappe van die veskillende waterdraers te bepaal. Die omvang van besoedeling van die grondwaterbronne is aangeteken. Dié spesialiteitstudie, uitgevoer om die Departement Waterwese en Bosbou met die opstel van 'n watergehalte bestuursplan vir die rivierkom behulpsaam te wees, is deur kommer rakende afnemende watergehalte in die gebied gemotiveer. Dit is vasgestel dat alleenlik die alluvialewaterdraer noemenswaardig by plekke besoedel is. 'n Grondwatermoniteringsnetwerk van vlak boorgate is in 1994 geïnstalleer, na aanleiding van aanbevelings afkomstig van die oorspronklike hidrosensus, en monitering is in 1995 begin.

Grondwater kom in die gebied voor in 'n vlak riviergruisafsetting en 'n dieper genate sekondêre waterdraer. Hierdie waterdraers word deur 'n ondeurlaatbare laag Kryt afsettings van mekaar geskei, met gevolglike artesiese toestande. Die grondwater van die waterdraers is 'n natriumchloried tipe, van goeie gehalte in die westelike hoërliggende gedeelte van die studiegebied, terwyl 'n toename in mineralisasie ooswaarts merkbaar is. Die hidrochemiese eienskappe kan gekoppel word aan veranderings in die waterdraende formasies asook die konnaatwater wat in die afsettings voorkom. Dit is bewys dat plaaslike besoedeling van oppervlak- en grondwater hoofsaaklik in die industriële en residensiële gebiede van Uitenhage en Despatch voorkom. Hierdie besoedelingsones is in vergelyking met die totale opvangsgebied nie groot nie, maar het 'n merkbare uitwerking op plaaslike toestande. Beramings van besoedelingsladings, gebaseer op hidrouliese parameters afkomstig van waterdraertoetse is gemaak.

Hierdie studie verteenwoordig 'n oorsig van die geohidrologie van die Swartkopsrivieropvangsgebied en vorm 'n waardevolle basis vir waterbronbestuur in die gebied. Dit sluit 'n unieke studie van die geohidrologie van die Swartkopsrivier alluviale waterdraer en besoedeling hiervan in. 'n Volledige beskrywing van die faktore wat grondwatervloei en artesiese toestande in die gebied beïnvloed is ingesluit. 'n Opsomming van waterdraerbestuursstrategië om die grondwaterbronne van die rivierkom te beveilig is gegee.



Frontispiece: Landsat thematic image of the Swartkops River Basin (bands 4-R 5-G 3-B, June 1990)

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GLOSSARY

aquifer : (<L aqua = water, ferre = to carry) permeable geological formation that is capable of storing or yielding economic quantities of groundwater of a quality suitable for a required use, e.g. unconsolidated coarse sands and gravels.

aquitard : (<L aqua, tardus = to slow down) geological formation capable of transmitting significant quantities of water on a regional scale over long time periods, but where the low permeability is not sufficient to locally justify economical extraction, e.g. clays and shales.

aquiclude : (<L aqua, claudere = to close) impermeable geological formation that does not transmit water, e.g. dense unfractured igneous rocks.

* *Note : the above three terms are relative and depend on the hydraulic characteristics of the formations overlying and underlying the unit being defined.*

artesian : confined groundwater where the pressure is usually higher than that of atmospheric pressure, and therefore sufficient to cause groundwater, e.g. in a borehole, to rise above the confined aquifer where it is termed *sub-artesian*, or ground surface in which case it is termed *free-flowing artesian.*

assimilative capacity : capacity of a water body or aquifer to absorb - through processes of dilution, dispersion and degradation - waste or contaminants disposed to the water body, without impairing its fitness for use.

attenuation capacity : capacity of a water body or aquifer to reduce the concentrations of leachate in the water body, by processes such as dilution, oxidation and ion-exchange; natural systems have a limited attenuation capacity - pollution results when the attenuation capacity is exceeded.

confined aquifer : aquifer bounded above and below by an *aquiclude*.

connate water : groundwater of marine origin trapped in sediments with sea-level retreat and subsequent diagenesis of the sediments.

DRASTIC : aquifer vulnerability classification system where DRASTIC is an acronym for:- D - depth to water table, R - recharge, A - aquifer material, S - soil material, T - topography, I - impact of vadose zone and C - conductivity.

DAS Index : simplified version of the DRASTIC system and is an acronym for:- D - depth to water table, A - aquifer material and S - soil material.

electrical conductivity : (EC in mS/m at 25°C) indirect measurement of the concentration of dissolved solids in a water body by measuring the ability of the water to conduct an electrical current. As the concentration of ions in solution increases, the EC increases. (1mS/m ≅ 6.5mg/ℓ TDS :- see also *TDS*)

equivalents per million : (epm) unit of ionic concentration - calculated by dividing the ionic concentration in ppm by the equivalent weight of the ion (also referred to as *meq/ℓ*)

hydraulic conductivity : (*K* in m/day) measure of the ability of a formation to transmit groundwater, dependent primarily on the nature of the openings in the formation and defined by the Darcy equation. Also referred to as *permeability.*

juvenile water : mineral water of magmatic origin derived from the earth's interior and not from atmospheric or surface water.

leachate : highly contaminated liquid containing chemical, biological and bacteriological constituents, which is formed when water passes through waste piles or from liquid effluent retention structures.

leaky aquifer : aquifer bounded above and below by aquitards, or where one boundary is an aquitard and the other is an aquiclude; if a leaky aquifer is in hydrological equilibrium the water level in the borehole tapping the aquifer may coincide with the water table. Also referred to as a *semi-confined aquifer*.

meteoric : water derived from recent precipitation recharge, as opposed to *connate* water.

mineral groundwater : groundwater containing >1000mg/ℓ TDS.

permeability : see *hydraulic conductivity.*

phreatic water : subsurface water occurring below the water table in an unconfined aquifer, i.e. groundwater, as opposed to *vadose* water.

piezometric surface : pressure surface to which groundwater rises when a confined aquifer is penetrated by a borehole; this rise is in the borehole either above the contact between the aquifer and the overlying confining layer, or above the surface of the earth, in which case the borehole is referred to as free-flowing *artesian* (also referred to as *potentiometric surface*).

porosity : (η in %) index of how much groundwater can be stored in the saturated material of an aquifer, expressed as a percentage of the bulk volume of the material.

potentiometric surface : see *piezometric surface.*

primary aquifer : aquifer in which the groundwater is stored and transmitted in the open pore spaces between the clasts comprising the formation (hence primary porosity).

recharge : the portion of water (usually rainfall) which reaches an aquifer, irrespective of which path it follows, resulting in a change in aquifer storage.

secondary aquifer : aquifer in which the groundwater is stored and transmitted in secondary openings/structures in the formation, e.g. fractures, joints, faults and bedding planes (hence secondary porosity).

semi-confined aquifer : see *leaky aquifer.*

specific yield : (Sy - dimensionless) volume of groundwater which will drain under gravity from a unit volume of an unconfined aquifer.

storage coefficient : (S - dimensionless) volume of water yielded per aquifer area per drop of water table (unconfined aquifer) or piezometric surface (confined aquifer), equivalent to Sy in unconfined aquifers. Also referred to as *storativity.*

thermal groundwater : naturally heated groundwater; in South African conditions this is groundwater with a temperature >25°C - or in hot tropical areas groundwater that is >5°C hotter than neighbouring shallow aquifer groundwater.

total dissolved salts : (TDS in mg/ℓ) indicator of the salinity of a water body; measurement of the total concentration of dissolved salts in the water. As TDS increases, the salinity increases. Also referred to as *total dissolved solids* (see also *EC*).

transmissivity : (T in m²/day) rate at which groundwater can be transmitted through a unit strip of aquifer under a given gradient; equivalent to *K* multiplied by the aquifer thickness.

unconfined aquifer : groundwater in an aquifer which is bounded below by an aquiclude but with no confining layer above it; and where the upper boundary is the water table which is free to rise and fall as a function of atmospheric pressure. Also referred to as a *water-table or phreatic aquifer.*

vadose : the unsaturated zone occurring beneath the land surface and overlying the water-table.

LIST OF ABBREVIATIONS

ARSC : Algoa Regional Services Council

CGH : Cape of Good Hope

CR : constant rate (aquifer test)

CRAU : Coega Ridge Aquifer Unit

CRD : cumulative rainfall departure

CSIR : Council for Scientific and Industrial Research

DOC : dissolved organic carbon

DSW : Despatch sewage works

DWA&F : Department of Water Affairs and Forestry

EC : electrical conductivity (mS/m)

ECT : East Cape Tanning

EM : electromagnetic

epm : equivalents per million

G&I : Gubb & Inggs wool-washers

GIS : geographical information system

GPR : ground penetrating radar

IWQS : Institute for Water Quality Studies (DWA&F)

K : hydraulic conductivity (m/day)
Kv : vertical conductivity
Kh : horizontal conductivity

ℓ/s : litres per second (yield)

m AMSL : metres above mean sea level

m BMSL : metres below mean sea level

mbc : metres below (borehole) collar
mbs : metres below surface

meq/ℓ : milli-equivalents per litre

mg/ℓ: milligrams per litre (≡ ppm)

mS/m : milli-Siemens per metre (1mS/m ≡ 10μmhos/cm)

M : million (in, e.g. Mm^3/yr)

OA : oxygen absorbed

ppm : parts per million (≡ mg/ℓ)

PWP : Perseverance wool pullery

RSA : Republic of South Africa

RWQO : receiving water quality objectives

SABS : South African Bureau of Standards

SAR : sodium adsorption ratio

SAU : Swartkops Aquifer Unit

SGWCA : subterranean government water control area

SPL : specific pollution load

SRAA : Swartkops River Alluvial Aquifer

SRWRMP : Swartkops River Water Resources Management Plan.

Sy : specific yield (dimensionless)

T : transmissivity (m^2/day)

TAL : total alkalinity

TDS :	total dissolved solids
TMG :	Table Mountain Group
TMS :	Table Mountain sandstone
UAB :	Uitenhage artesian basin
USGS :	United States Geological Survey
USW :	Uitenhage sewage works
WASP :	Waste-Aquifer Separation principle
WQM :	Water Quality Management Directorate
WRC :	Water Research Commission

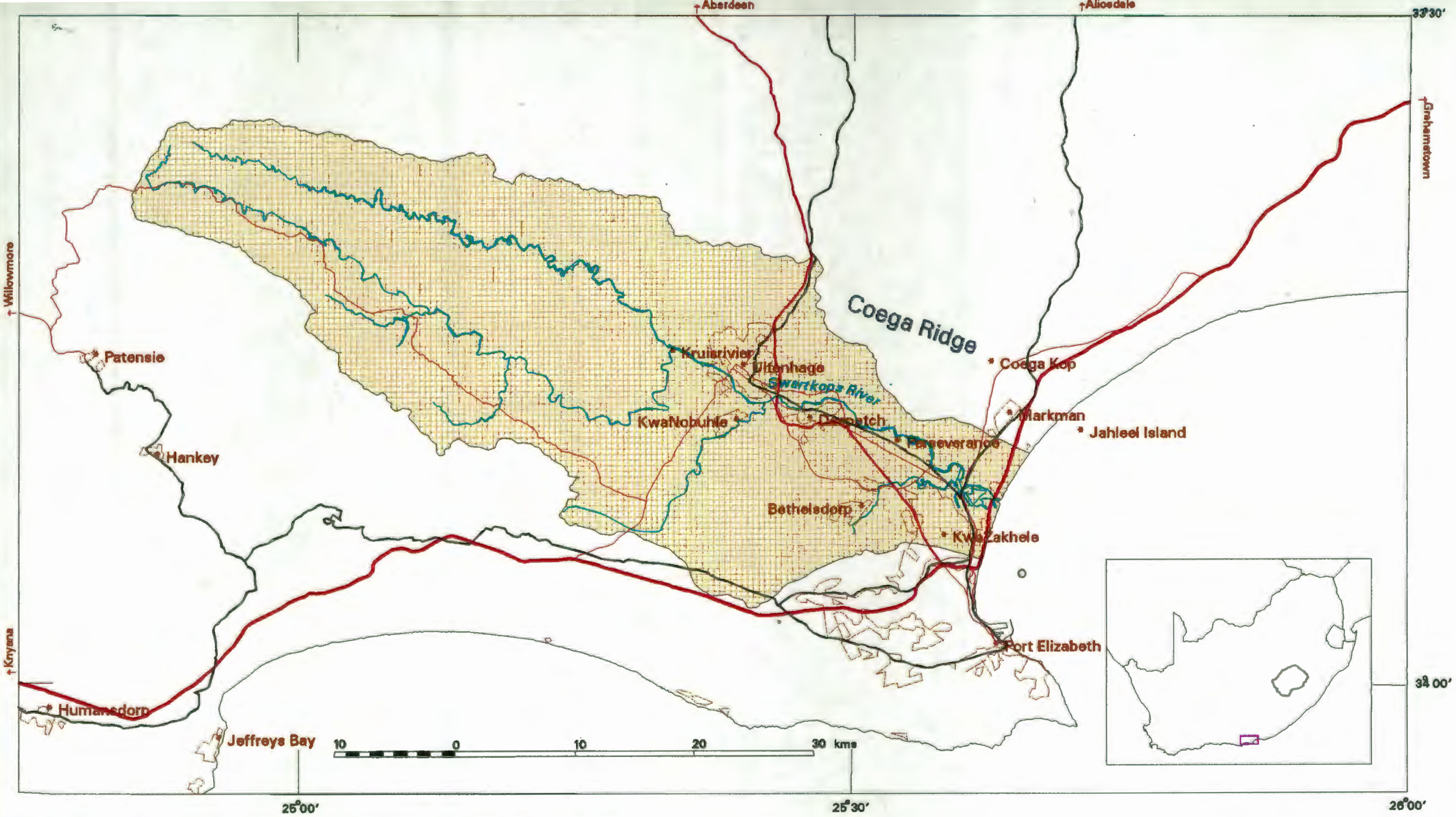
1. INTRODUCTION

The Swartkops River Basin (Map 1) falls within South Africa's largest and geohydrologically most important artesian groundwater basin - the Uitenhage Artesian Basin - and supplies surface-water and groundwater for farming, domestic, commercial and industrial uses. One of the Eastern Cape's largest industrial areas, and one of South Africa's major car-manufacturing plants, is enclosed and supported within this basin, *viz.* the Port Elizabeth-Uitenhage metropolitan region. As a result of this development within the basin, the natural water resources which the basin supplies are of strategic importance to the whole of the Eastern Cape. By the same token, as a result of this development, the water resources within the basin are vulnerable to contamination and over-exploitation by increasing demand being placed on the water resources, which have only limited supply potential.

There has been increasing concern regarding the amount and extent of pollution of both surface and sub-surface water in the Swartkops River Basin, as growing development pressures have been placed on the basin. The Swartkops River estuary - a sensitive area used for recreation, conservation and mariculture purposes - is also under threat from the deteriorating quality of the river water draining into it. The increased pollution loading of the river is due in part to industrialisation in the Uitenhage - Despatch - Port Elizabeth area, increases in farming activities west of the Swartkops - Brak River confluence and increased informal settlement in the area.

Recent requests to the Department of Water Affairs and Forestry (DWA&F) from industries in the Uitenhage area for an increase in the quantity of effluent allowed to be discharged into the Swartkops River, has highlighted the need for a thorough water quality investigation and the development of a water quality management plan for the basin. Such a management plan can only be effectively achieved once the hydrological system is fully understood and the present water quality status is documented. A number of situation analyses have therefore been initiated and carried out in recent years to evaluate the *status quo* of the occurrence, quality and movement of water - both surface and sub-surface - in the Swartkops River Basin. Once the separate studies are complete and the results compiled, assessed and interpreted, management objectives can be set and a monitoring network designed to ensure the long-term viability of the strategic water resources of the basin.

This study represents a compilation - in a single document - of all available information on the relevant characteristics of the geohydrology of the Swartkops River Basin. Aspects of aquifer delineation, groundwater occurrence, hydraulic parameters, quality, present abstraction, exploitation potential, and pollution are discussed. The results of a recent catchment-scale hydrocensus, monitoring network design and installation in the primary alluvial aquifer, and a study of the factors affecting spring-flow variations in the artesian basin - all carried out by the Geohydrology Directorate of the DWA&F - are also presented. Finally, recommendations on management strategies for the water resources within the basin are suggested.



MAP 1 : STUDY AREA LOCATION

COMMUNICATIONS NETWORK	STUDY AREA	SURFACE WATER	URBAN AREAS
National Road : N2	▨ Swartrkops River Catchment	Rivers	Outline of Towns
Arterial : R75			
Main and Secondary			
Railway			

DEPARTMENT OF WATER AFFAIRS AND FORESTRY
Directorate Geohydrology
Southern Region
Cape Town

1.1. Background

In 1992 the Council for Scientific and Industrial Research (CSIR) was commissioned by the Algoa Regional Services Council (ARSC) to carry out a study concentrating on the surface water quality of the Swartkops River Basin. The study was conducted in response to the historical as well as increasing concern expressed by numerous interested and affected parties regarding the deteriorating water quality in the basin.

Following on from this study, the DWA&F initiated a Water Resource Management Plan for the Swartkops River basin in 1992, based on the Receiving Water Quality Objectives (RWQO) approach. It became apparent that more information was required on the groundwater regime - an integral component of the hydrological system of the basin - in order to effectively implement the water quality management plan. The primary alluvial aquifer was of special interest, since it was vulnerable to pollution due to its shallow and generally unconfined to semi-confined nature.

The Geohydrology Directorate of the DWA&F was subsequently requested to carry out a groundwater survey of the area as a specialist study which would provide input for overall water resources management recommendations for the Swartkops River Basin. In response to this request, a hydrocensus of all groundwater abstraction points in the Swartkops River Basin was carried out in the period August 1992 to June 1993. The evaluation of this data provided an initial overview of the occurrence and quality of groundwater in the river basin, and indicated that significant pollution of at least the alluvial aquifer had occurred on a localized scale, as a result of leaching of contaminated water from surface impoundments.

Based on the findings of the hydrocensus report, the installation of a network of monitoring boreholes was recommended to ascertain the extent and spread of this pollution, in order to provide a management tool for future pollution control. A monitoring network was then designed by the author and constructed in late 1994, aquifer tests were conducted in early 1995 and initial hydro-chemical sampling runs were carried out during 1995.

All groundwater abstraction points in the Swartkops River Basin are about to be re-surveyed by the DWA&F for the purposes of issuing abstraction permits, as well as to enable more effective control of the use of groundwater within the artesian basin. An essential requirement for this survey has been identified, *viz.* the compilation of the fragmented data on the geohydrology of the river basin into a single document for reference purposes.

1.2. Aims and Objectives

A literature review showed that most of the existing data for the study area is limited, site-specific and relatively out of date. The primary intention of this study is, therefore, the collation into a single document of all old and new relevant information, which reports on and assesses the geohydrological conditions existing in the study area on a catchment-scale. In so doing, it is hoped that this document will provide a useful reference for groundwater-management strategies and any future geohydrological research conducted within the basin.

Specific objectives are the following:

1. To divide the basin into logical geohydrological units for improved understanding of a complex system; aquifer nomenclature is suggested for purposes of standardisation;
2. To report on the present status of groundwater occurrence and quality in the catchment, a product of a three year project, and especially the groundwater quality in the shallow alluvial aquifer;
3. To characterise of the geohydrology of the Swartkops River Basin for assistance in
    a) the DWA&F's Swartkops River Water Resources Management Plan and,
    b) the re-survey of the Uitenhage Artesian Basin by the DWA&F for purposes of controlling abstraction from the Uitenhage Subterranean Government Water Control Area (SGWCA);
4. To assess the *status quo* of the surface water quality relevant to the study, with emphasis on identifying interflow relationships, if any, between the river water and the alluvial aquifer, and between the alluvial aquifer and the underlying aquitard;
5. To identify pollution sources in the river basin - both point and non-point - and identify whether the pollution occurs "naturally" as a result of the mineralogy of the host rock, the occurrence of connate water, or due to man's influences. Results obtained from the recently installed alluvial aquifer groundwater monitoring network and subsequent sampling runs will be used extensively to assess the degree of pollution of the alluvial aquifer;
6. To highlight areas of concern with respect to groundwater pollution in order that remedial measures can be taken by the local controlling authorities. Estimation of the volume of contaminated groundwater entering the Swartkops River system will also be made;
7. To assess the requirements for and make recommendations on additional work to be carried out in the Swartkops River Basin;
8. To identify project short-falls and make recommendations for additional studies, to improve the knowledge-base on the geohydrology of the Swartkops River Basin. Water-resource management strategies are outlined to ensure the sustainability of the groundwater resources of the Basin.

1.3. Field Work and Methodology

1. An intensive literature survey and desk study of all geological, geohydrological and hydrochemical data from technical reports, scientific papers and literature covering the study area was conducted and all the relevant data summarised.
2. A hydrocensus of all groundwater users and groundwater abstraction points (including boreholes, dug-wells and springs) within the Swartkops River catchment was carried out and the information analysed and presented. The hydrocensus data collected included relevant variables such as water point (site) type and location, water-levels and piezometry, quality, pump type and borehole yields, abstraction volumes and water use, field measurement of salinity and borehole geology, where available. The information obtained was summarised and tabulated for purposes of discussion and reference.
3. Samples of selected borehole water, river water, drain water and seepages as well as identified pollution sources were taken and analysed for major dissolved inorganic ions. The sampling of known and potential pollution sources was carried out, where possible, in the vicinity of surveyed groundwater sites. This was done for purposes of "finger-printing" the source of the contaminated groundwater, and to attempt correlations between observed hydro-chemistries. Recent emphasis was placed on the shallow primary alluvial aquifer due to its unconfined to semi-confined nature and relatively high permeabilities, which makes it vulnerable to pollution.
4. The primary purpose of a water analysis is to determine the suitability of the water for a proposed use. The "end-users" of the Swartkops River water are recreational users in the estuary as well as shellfish aquaculture. The results of the surface and groundwater quality analyses obtained from the hydrocensus were therefore related to SABS (1984) and DWA&F (1993a) allowable limits for water used for domestic purposes. The processing and presentation of the analytical data in tabular form and interpretation with respect to hydro-chemical assemblages and cation-anion ratios, as well as a discussion of possible factors causing any anomalous values encountered, was then undertaken.
5. Hydraulic parameters such as aquifer conductivities were derived from the drilling project carried out to install a monitoring network of boreholes in the alluvial aquifer. These characteristics were then interpreted with respect to interflow relationships between surface and groundwater bodies.
6. Spatial information in the form of data coverages of the study area were produced on a GIS by digitising maps and combining relevant data obtained from the hydrocensus. This information was input into the GIS for data query purposes, map editing and geohydrological map production. Geological data presented on the Geological Survey maps for the study area were assumed to be correct. If, however, anomalies were recognised during the hydrocensus in, e.g. an unexpected groundwater quality from a specific host-rock, then field checks were done to confirm the expected geology.

1.4. Previous Geohydrological Investigations

Previous investigations in the area have been site specific or concentrated on the artesian aquifer conditions in the Uitenhage SGWCA only. With the exception of this study, no catchment-scale studies have been carried out to date. The previous studies are, however, considered of relevance to the present investigation since they describe the geohydrological conditions occurring in specific areas within the catchment. They are summarised below, in chronological order.

Bosazza (1947) reported on the locality of springs in the Bethelsdorp area and targeted drilling sites to intersect artesian aquifer conditions. Observations were made on the successful utilisation of dug-wells in the region to abstract shallow groundwater from the rudaceous alluvial and conglomerate beds in the local valley floors.

Van Eeden (1952) reported on the quantity and quality of artesian water in the Uitenhage and Port Elizabeth Regions. Geophysical work determined that the Cretaceous layers underlying the "Zwartkops" River thicken and widen in an easterly direction towards the sea and thicken in a northerly direction normal to the strike of the infilled basin. Sites for drilling artesian boreholes were targeted in areas where minimal Cretaceous sediment penetration was required before intersecting Table Mountain Sandstone (TMS).

Enslin (1962) described events leading up to the proclamation of the Uitenhage SGWCA and outlined procedures to be followed with the issuing of drilling and groundwater abstraction permits. The geological and geophysical surveys, carried out as a result of various requests from affected parties that the artesian groundwater resources in the region be better understood and developed in the national interest, were discussed. The requests stemmed from increasing concern regarding noticeable decreases in flow at existing springs, as a result of the drilling of strong artesian boreholes. The dewatering of the area with time was described and reasons for the lowering of the groundwater levels and decreasing artesian pressures discussed. A short summary is given of the occurrence, as well as the possibilities of intersecting artesian groundwater in places. The loss of the artesian groundwater to especially the calcareous Alexandria Formation due to leaky aquifer conditions, caused by the corrosion of borehole casing by the acidic groundwater, was noted with concern. Recommendations were made to seal the leaking boreholes as well as install pressure meters in order to determine the total groundwater loss.

Marais (1964 & 1965) carried out detailed geohydrological mapping and an investigation of the Uitenhage Artesian Basin to determine the configuration of the basin. He reported on groundwater occurrence in the geological formations present in the area, including data on abstraction volumes. The pre-1965 changes from artesian to sub-artesian conditions, as a result of the rapid and uncontrolled drilling of boreholes for irrigation purposes in sections of the area, were noted.

Marais strongly recommended stricter control within of the Uitenhage SGWCA in order to protect and preserve the groundwater asset from over-exploitation due to uncontrolled abstraction. Urgent recommendations were also made to either seal or re-case those artesian boreholes in the area that had corroded casing.

Marais and Saayman (1965) gave a detailed report on the geological and geophysical investigation of the Uitenhage Artesian Basin. Geological mapping was complemented with geophysics in "blank" areas of no data using seismic, magnetic and gravimetric methods. The study was principally initiated by the growing concern of groundwater users in the area of reductions in borehole and spring yields as a result of increasing rates of groundwater abstraction since the 1950's.

McCallum (1974) conducted a general environmental study of the Swartkops River basin (for Hill Kaplan and Scott Inc., consulting engineers) as a pre-requisite to preparation of a development plan east of Despatch. The technical report includes information on generalised geology, soil profiles and groundwater level monitoring from shallow augered holes in the Lower Swartkops River basin.

Talma et al. (1982) carried out a detailed geochemical investigation of groundwater in the recharge area of the Uitenhage artesian aquifer and found this water to have a very low pH and alkalinity as a result of groundwater movement through the silicic TMS host-rock to the aquifer. Inorganic carbon concentrations in the groundwater were proposed to derive from solution of gaseous carbon dioxide in the soil.

Johnstone (1982) studied the geochemical origins of the groundwater in the Kruisrivier area and the possible causes of mineralization. It was proved experimentally that groundwater abstracted from the Kirkwood Formation will have a higher percentage TDS than the Enon Formation or the TMS, assuming equal contact time of the groundwater with the aquifer host rock. It was also shown that with increasing distance from the recharge area, and thus greater contact time between the rock and the groundwater, the TDS content of the groundwater increased.

Parsons (1983) recognised three major types of water in a study of the Coega Kop area, *viz.* water derived solely from the TMS, water derived solely from the Cretaceous formations and water of mixed origin caused by artificial leaky aquifer conditions as a result of borehole casing corrosion. It was proposed that this mixing was important only in weakly artesian boreholes, since the pressure of the strongly artesian TMS water would not allow entry of the Cretaceous water into the corroded casing.

Bush (1985) reported on geological mapping, drilling, resistivity surveys and hydrochemical analyses to delineate the hydrogeological parameters of the aquifers and aquicludes in the

Kruisrivier / Bethelsdorp areas. He found that the major aquifer in the Kruisrivier area is formed by the Kirkwood sandstone and Enon conglomerate acting as a single unit, while in the Bethelsdorp area the major aquifer comprises the highly fractured Table Mountain quartzites, artesian in places, yielding good quality water. The Kirkwood Formation mudstones were considered to form an aquiclude and contribute only small quantities of highly saline groundwater. The Kruisrivier area showed a decline in piezometric levels as abstraction in the region exceeded recharge, whereas a general recovery of groundwater levels in the Bethelsdorp area was occurring.

Venables (1985) studied the northern portion of the Uitenhage SGWCA, i.e. the Coega Ridge area, to quantitatively evaluate the TMS aquifer which formed the principal aquifer of the artesian system. The study involved a hydrocensus, geological and geophysical work and included borehole drilling, aquifer testing and hydrochemical sampling. The study results formed the basis for decisions on the easing of drilling and abstraction restrictions in the other geohydrologically less important parts of the Uitenhage SGWCA. Recommendations were made to re-define the boundaries and decrease the size of the control area.

Reynders (1987) provided a hydrogeological and water utilisation background in the area for the purpose of redefining the boundaries of the Uitenhage SGWCA, as proposed by Venables in 1985. Appropriate policy regarding the management of the control area to ensure its optimal use was suggested. A further recommendation was made to seal all boreholes with corroded casings in the Coega Kop area.

SRK (1991) sub-contracted to the CSIR on contract to the ARSC to carry out a geohydrological investigation of the groundwater quality in the Swartkops River catchment. This study was essentially a précis of existing, relatively outdated, data provided mainly by the DWA&F, and no new conclusions were reached. Two aquifer types were listed as occurring in the region, i.e. a shallow primary aquifer and a deeper secondary aquifer. Pollution to the primary aquifer as well as surface water in the area of Uitenhage was found to be occurring but secondary aquifer pollution was considered to be minimal. The origin, extent and nature of pollution to the primary alluvial aquifer was uncertain. A close relationship was proposed to exist between the river and shallow sub-surface flow conditions. It was postulated that sub-surface preferential flow paths existed in the form of "palaeo-channels" within the alluvium.

Pitts and Raath (1993) were contracted by the DWA&F to conduct a geophysical investigation for this study in order to determine the geometry of the primary alluvial aquifer present in the Swartkops River valley, as well as to attempt to delineate zones of pollution. The frequency domain electromagnetic (EM) profiling and sounding technique was used as well as the relatively new technique of ground penetrating radar (GPR). Initial investigations with the EM technique yielded little correlation between interpreted results and known geology. The GPR technique was ineffective over much of the study area due to high electrical conductivities of the shallow groundwater. Where the technique could be applied, e.g. in the lower reaches of the Kwa-Zunga River, no accurate depth interpretations could be made. It was suggested that the more expensive seismic refraction and direct current sounding and profiling techniques should be investigated for defining the aquifer size.

Maclear (1993) reported on a hydrocensus of over 120 groundwater users in the Swartkops River basin to assess the occurrence and quality of the groundwater; carried out as a specialist investigation for the SRWRMP. Hydrochemical facies were outlined and discussed for various regions of the aquifer of similar water quality. The survey showed that pollution of the groundwater was occurring in the alluvial aquifer, mainly in the industrialised areas around Uitenhage and Despatch. The various sources of pollution were identified and discussed with respect to observed borehole water quality down-drainage of the pollution sources. Numerous dug-wells were identified, mostly in the Despatch area, where groundwater contained in fluvial terrace gravels was abstracted for small-scale garden and orchard irrigation. It was concluded and strongly recommended that the installation of a groundwater monitoring network was necessary to determine the origin and extent of pollution of the alluvial aquifer, and to provide geohydrological data for the little understood alluvial aquifer.

Parsons (1994) carried out a site-specific geohydrological study for Waste-Tech (Pty.) Ltd. at the Aloes waste disposal site near Motherwell, north of the Swartkops River. It was determined that the Uitenhage Group mudstones and shales were highly impermeable and acted as a very effective natural barrier to leachate migration. The seepage groundwater contained in the rock formations below the site was further found to be highly saline and unfit for any use. It was concluded that the waste disposal site did not pose a pollution threat to any groundwater resources in the area.

Maclear (1995) reported on the installation of a network of shallow boreholes designed to monitor the groundwater quality and fluctuations in water levels with time in the Swartkops River Alluvial Aquifer. The report summarised all the relevant project details, including borehole logs, difficulties experienced during drilling in the unconsolidated alluvium, aquifer testing results for derivation of hydraulic parameters, and project cost.

A conceptual aquifer model for the Swartkops River Alluvial Aquifer was proposed, *viz.* a relatively thin, conductive, coarse saturated alluvial package, overlain by a semi-confining layer of sandy soil and clayey silt, and underlain by impermeable Kirkwood Formation mudstones. Derived transmissivities and estimated hydraulic conductivities for the alluvial aquifer were presented. Because of the variable nature of the geohydrology of the alluvial aquifer over the study area, it was suggested that the aquifer parameters obtained should not be extrapolated to apply to the aquifer on a regional scale. These data, however, provide a useful first assessment and are the only practically derived estimates of aquifer hydraulics available for the study area to date.

Maclear and Woodford (1995) presented the findings on a study of the factors affecting spring-flow variations at the Uitenhage Springs. A substantial database of spring-flow records spanning almost a century was analysed and associated with rainfall, drilling and abstraction history, and seismic events within a set radius of the Springs. It was determined that exploitation of the aquifer had the greatest effect on spring-flow, while only a few seismic events were considered to have had a definite - albeit temporary - influence on flow. No significant correlation was found between spring-flow and rainfall over the whole study period, as a result of the over-riding influence of drilling and pumping activities. During periods of lowered abstraction from the Coega Ridge Aquifer, however, the cumulative rainfall departure method illustrated the natural relationship between spring-flow and recharge.

2. STUDY AREA

The study area (Map 1) comprises the catchment of the Swartkops River and is approximately 1 400km² in extent (Maclear, 1993). It is located in the Southeast Cape Province immediately north of Port Elizabeth and is oriented approximately northwest-southeast. A large proportion of the river catchment lies within the Uitenhage SGWCA boundaries, as outlined in Bekker (1989) and detailed further in Section 4.

2.1. Relief and Terrain

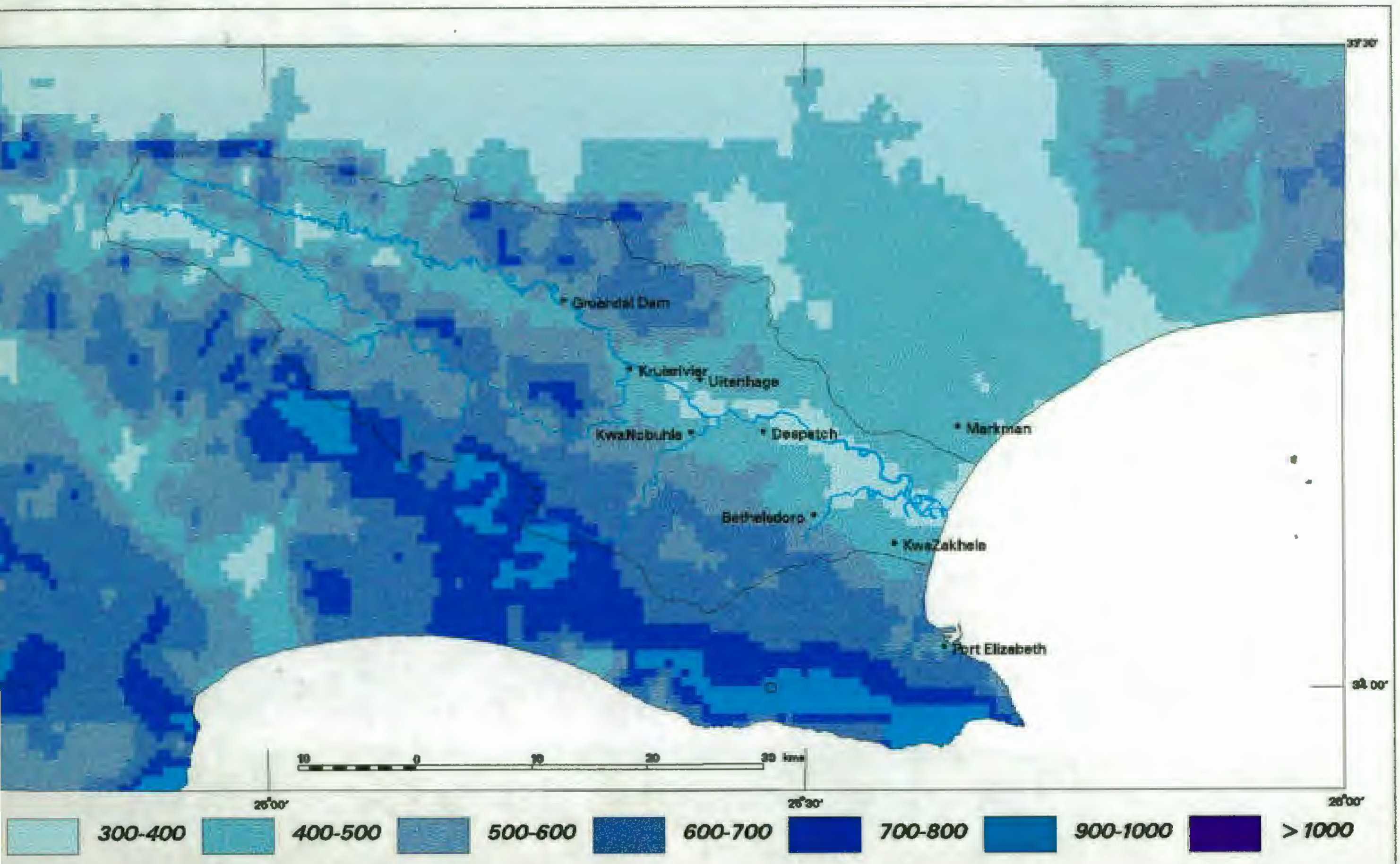
The western part of the region consists of high west-northwest striking mountain ranges namely the Groot Winterhoek, the Elands and the Zunga Berge comprising the main catchment area - with the lower-lying Van Stadens Berg to the south (Map 2). Towards the coast in the east, the mountain ranges are fringed by low-lying terraced coastal plains (detailed in Section 3.2). The coastal plains slope gently seawards at approximately 1° and surround an extensive alluvial floodplain and estuary. Isolated koppies formed by inliers of resistant Table Mountain Sandstone (TMS) project through the soft Cretaceous strata in the coastal area and along Coega Ridge. To the south, undulating hills occur.

Areas underlain by TMS, or a thin veneer of Tertiary formations, are mostly covered by grass; whereas impenetrable thorny False Macchia bush covers the high lying areas underlain by Cretaceous strata, and Karoo and Karroid valley bushveld occurs in the low-lying areas. The Bokkeveld Group rocks weather to form fertile soil mostly vegetated by thick bush (Acocks, 1951).

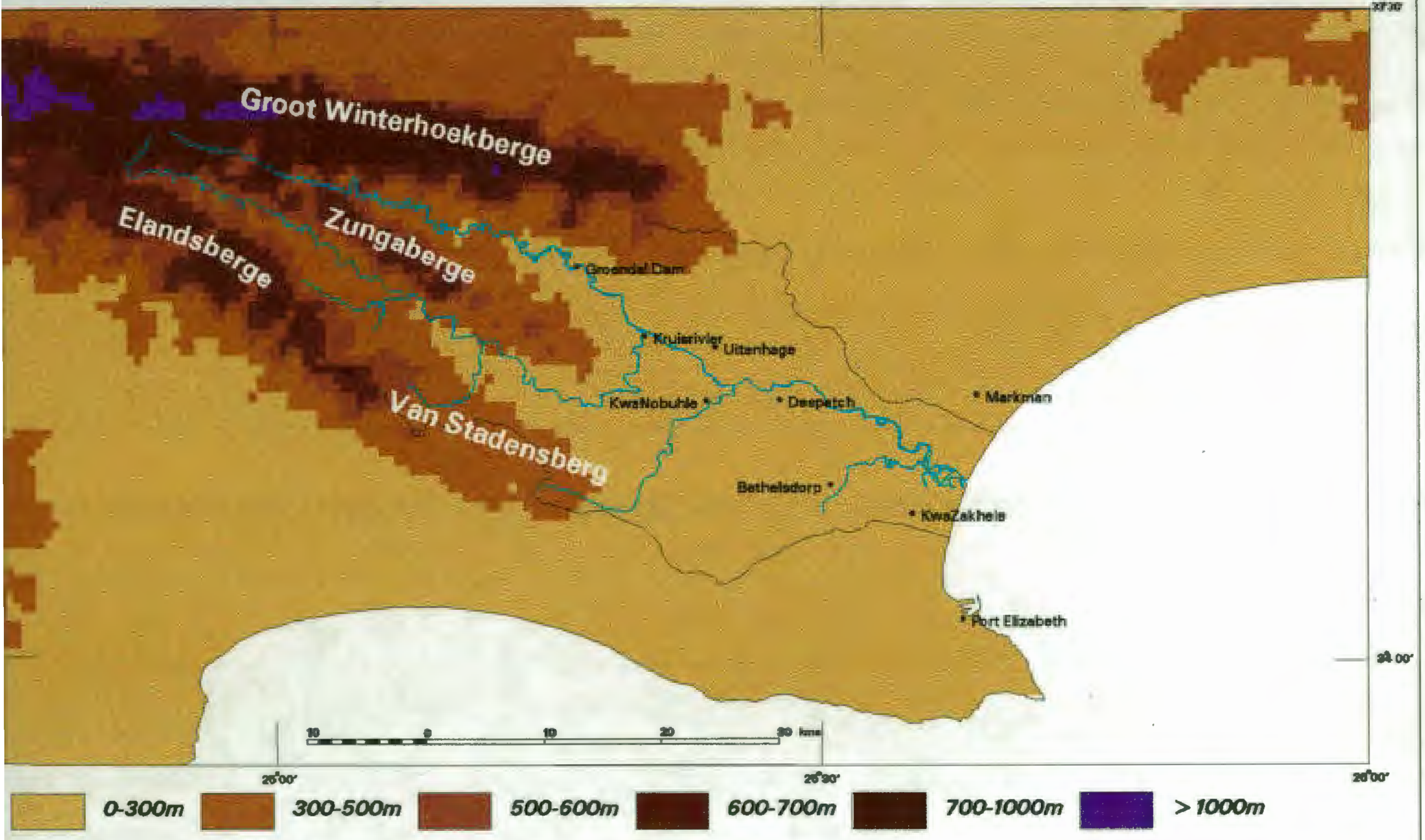
2.2. Climate

The study area falls into climatic region A of Schulze (1986), i.e. Southern Cape coastal belt with rain during all seasons. The highest rainfall occurs as heavy downpours - due mainly to orographic as well as cyclonic influences - during the last four and first three months of the year. The influence of topography on rainfall occurrence is clearly illustrated on Map 2. No proof of long-term climatic changes have been found in recent geological history (Marais, 1965).

Precipitation over the study area varies from 760mm/yr in the Groot Winterhoekberge to 610mm/yr at Groendal Dam, 435mm/yr at Uitenhage and 660mm/yr at the Port Elizabeth airport (WB 40, 1986). Reddering and Esterhuysen (1981) estimate the catchment's mean annual precipitation (MAP) at 636mm.



RAINFALL mm/yr



ELEVATION

MAP 2 : RAINFALL AND TOPOGRAPHY

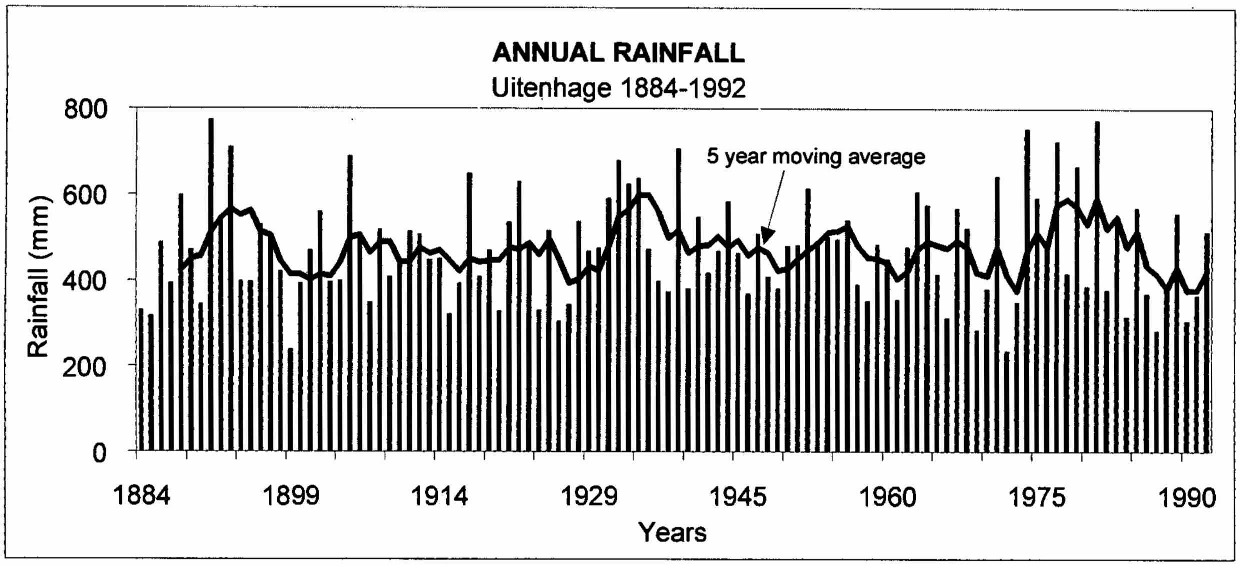


Figure 1: Annual rainfall - Uitenhage (private records, Mr. Inggs, Kruisrivier).

Figure 1 shows the annual rainfall measured at Inggsville farm near Bullmer Drift, Kruisrivier (Uitenhage) over a 108 year period. The average annual rainfall for this region - roughly central to the study area - is 470mm. Average monthly rainfall, evaporation and temperature data for Port Elizabeth are shown in Figure 2. Annual A-pan evaporation figures vary from 1 790mm/yr at H.F. Verwoerd airport to 1 500mm/yr in the Groendal Dam area at the base of the Groot Winterhoekberge (Directorate Hydrology, DWA&F, Pretoria).

The region enjoys a temperate climate with warm humid summers and mild to cool winters. The prevailing wind varies from southeast in summer to southwest in winter, frequently reaching strong gale force along the coast.

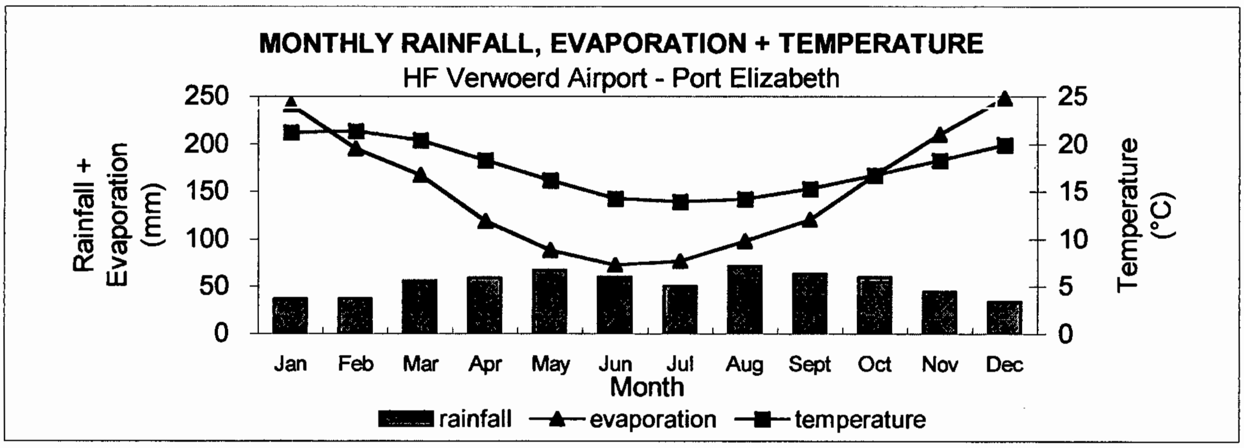


Figure 2: Average monthly weather characteristics - Port Elizabeth (Weather Bureau Station 34/7677).

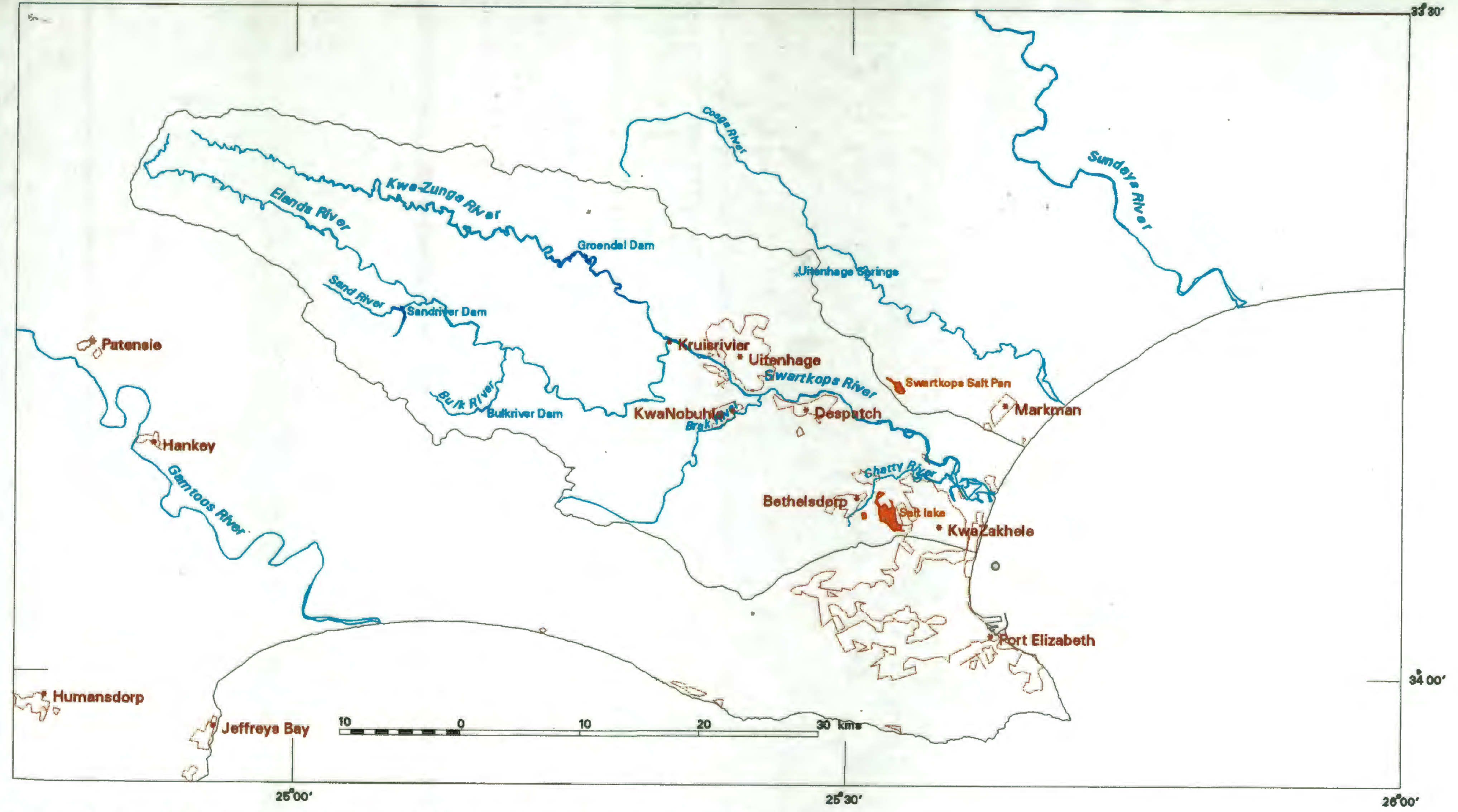
2.3. Geomorphology and Drainage

The easterly flowing Swartkops River is the major drainage feature of the catchment (Map 3), which has a mean annual runoff (MAR) of 84.2Mm³ (Reddering and Esterhuysen, 1981). The Swartkops River's two main tributaries are the northern Kwa-Zunga and the southern Elands Rivers which confluence at the Kruisrivier cadastral farm region. Other minor ephemeral drainage features, *viz.*. the Sand, Bulk, Brak and Chatty Rivers, drain the southern catchment area.

The western mountainous areas of the drainage basin are the source of the Swartkops River. The drainage follows structural weaknesses and a shale filled syncline in the Kwa-Zunga and Elands River valleys respectively. The main drainage follows a youthful trellis pattern in the mountainous regions composed of highly jointed TMS, and a dendritic pattern in the tracts occupied by Enon conglomerate. Eastward, where the river drains the broad, mature, open-valley floodplain and estuary, the flow pattern assumes a multi-channel braided system eroding into the semi-consolidated sediments of the Uitenhage Group. From Kruisrivier to the sea the Swartkops River occupies a 2km wide flood-plain on which the river intermittently changes course. Extensive meandering of the lower Swartkops River on the floodplain area occurred over time - major direction changes being noted in living memory as far upriver as Uitenhage. Lateral migration 1 to 2.5km north and south of the river's present channel position is documented in McCallum (1974). Periodic flooding of the Swartkops and Elands Rivers and major tributaries occurs during the wet winter months.

In the upper regions of the Swartkops River, the river channel is filled with a dominantly coarse-grained sedimentary assemblage with boulder beds, becoming increasingly finer grained with fewer boulders as distance down-stream increases. The sediment in the Kruisrivier area is arenaceous and proximal becoming argillaceous and distal from the Bethelsdorp area eastward, and older and flatter in the central and eastern portions of the study area.

The estuary - comprising supratidal mudflats and intertidal and subtidal sediment bodies in the lower reaches - is underlain by older Holocene estuarine deposits (Reddering and Esterhuysen, 1981). The estuary was formed during marine transgression in the late Pleistocene when the Swartkops River valley was inundated and filled with sediment.



MAP 3 : MAJOR DRAINAGE FEATURES

3. GEOLOGY

The geology of the study area is illustrated on Map 4 and summarised in Table 1.

3.1. Stratigraphy

The west and southern portion of the study area comprising the Groot Winterhoekberge, the Kwa-Zunga River valley and the Elands- and Van Stadensberge are formed by quartzitic sandstones of the Ordovician to Silurian Table Mountain Group (TMG). The Table Mountain sandstone (TMS) is the main provenance rock for the quartzite clasts that dominate the river bedload in the upper reaches of the Swartkops River and its tributaries. Pockets of raised terrace gravel and silcrete of Tertiary age occur as outliers forming ridge deposits.

A large part of the Elands River catchment is underlain by Bokkeveld Group (Ceres Subgroup) black shales, metamorphosed to slate in places, and subordinate siltstone (Toerien and Hill, 1989). The river alluvium in this region consists of oligomictic, clast-supported deposits of gravel and boulders (Plate 1), comprising 98% quartzite, 2% sandstone and <1% fault breccia and phyllite (Hattingh and Rust, 1991).

The central study area consists mainly of Cretaceous to Jurassic Uitenhage Group deposits with river alluvium in the valley and floodplain areas. Kent (1980) considered the three major units of the Uitenhage Group to be lateral facies of a single sedimentary succession with the conglomerates of the Enon Formation grading laterally and vertically into the over-lying variegated reddish-brown Kirkwood Formation sandstones and mudstones (Plate 2) which in turn may penetrate the Sundays River Formation.

Despatch and Uitenhage lie on alluvium and Kirkwood and Sundays River Formations of the Uitenhage Group. Inliers of Peninsula Formation sandstones (such as Searle Hill outcropping southeast of Kruisrivier) occur in the central, as well as north-central portion of the study area where they outcrop and sub-outcrop along the Coega Ridge. The south-central region is composed of Nanaga Formation aeolianites of the Algoa Group.

Quaternary floodplain and Cretaceous terrace deposits of the Algoa and Uitenhage Groups comprise the eastern part of the study area, with the mudstones and sandstones of the Kirkwood Formation forming the rolling hills along the R75 southeast of Uitenhage. The low-lying, west-northwest striking terrace scarp immediately north of the Swartkops River is formed by resistant, well-indurated Alexandria Formation deposits (Le Roux, 1989) of the Algoa Group (Plate 3).

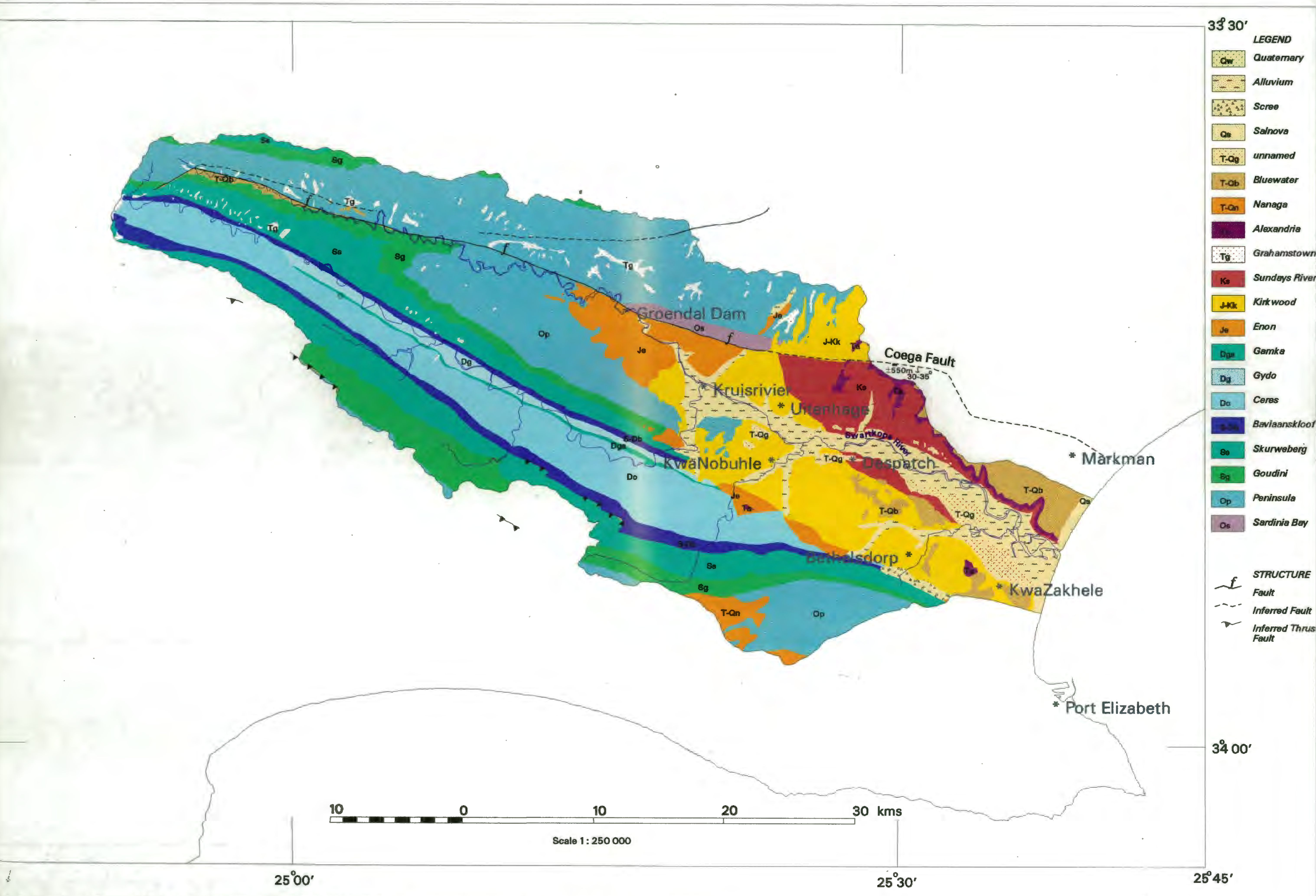
3.2. Landscape Evolution

The geologically dominant feature in the study area is the WNW-ESE striking and plunging depositional trough as delineated by Van Eeden (1952). The nomenclature of the Uitenhage Artesian Basin (UAB) is derived from this trough. This depositional basin was infilled during the Jurassic to Cretaceous periods by an assemblage of shallow marine to fluvial sediments (refer to Section 4 for detail).

Evidence exists for at least three major marine transgressions and regressions during the Tertiary and Quaternary periods with an overall regression of the shoreline to its present form (Ruddock, 1968). In the early to middle Pliocene crustal subsidence followed by tectonic uplift of the Algoa Basin occurred. This caused bevelling of the Cretaceous Uitenhage Group sediments during the marine transgression, and deposition of dune cordons and lagoonal sediments associated with the marine regression, to form the Grassridge Platform (north of the present-day Perseverance siding).

Late Pliocene marine transgression shifted the shoreline up to the present Swartkops Salt Pan escarpment causing denudation of the Alexandria Formation to form the Coega Platform (west of Coega Kop). Late Pleistocene marine transgression moved the shoreline inland, depositing the Alexandria Formation sediments and forming the Ingleside Terrace (comprising Sutton Vallance and Mormons Vlakte).

A major late Pleistocene regression took the shoreline well below the modern coastline, resulting in extensive river rejuvenation and downcutting of the Swartkops, Coega and Sundays Rivers to form the noticeable elevated river terraces of today (Plate 4). The Holocene epoch was characterised by minimal tectonic activity with minor sea-level fluctuations only, forming localised raised palaeo-beaches (Stear, 1987).



AP 4 : STUDY AREA GEOLOGY (from SA 1:250 000 geological series sheet 3324)

Table 1: Stratigraphy of prominent geological formations in the study area (from Maclear, 1993).

Group	Formation	Depositional Environment	Age	Description
-	-	Fluvial / estuarine	Recent	Alluvial and colluvial clastic deposits of quartzite and sandstone material
Algoa	Salnova	Beach to near-shore / estuarine	Pleistocene to Holocene (Q)	Calcareous sandstone and clastic limestone / coquinite deposits on wave-cut platforms. Often overlain by recent wind-blown sands, soil layers and calcrete (Le Roux, 1989)
	Bluewater Bay	Fluvial	Pliocene to Pleistocene	Intermediate to low-lying plateau deposits of alluvial sheet gravel and sand, e.g. Motherwell, Mormon's Vlakte and Stillwell (Le Roux, 1989)
	Nanaga	Aeolian	Pliocene to Pleistocene	Semi-consolidated calcareous aeolian sandstone formation related to regressive events with abundant cross-bedding (Toerien and Hill, 1989)
	Alexandria	Foreshore to lagoonal / estuarine veneer deposit on seaward sloping terraces	Miocene to Pliocene (T)	Well-indurated alternating layers of calcareous sandstone, coquinite (shelly limestone), conglomerate and sandstone with a rich assemblage of marine invertebrates (Le Roux, 1989)
Uitenhage	Sundays River	Cyclic marine and estuarine	Cretaceous	Succession of greenish-grey mudstone and silty sandstone with subordinate pebble washes and a few thin bentonitic beds in places. Formation is rich in marine fossils (Kent, 1980)
	Kirkwood	Fluvial to basin entry point / estuarine deposits (distal)	Jurassic	Brightly coloured reddish to purplish mudstone, sandstone and siltstone containing a wealth of plant fossils and reptile and invertebrate remains. Basal sandstone unit commonly displaying a transitional inter-tonguing contact with the Enon formation (Kent, 1980)
	Enon	Alluvial fan conglomerate (proximal fanglomerate)	Jurassic	Poorly sorted moderate to well-rounded massively-bedded conglomerate (commonly containing extremely large boulders) with subordinate lenticular sandstones and mudstones (Kent, 1980)
Bokkeveld	Ceres Subgroup	Shallow marine	Devonian	Dark-grey to black thick carbonaceous shale units containing marine invertebrate fossils with intervening thinner fine grained feldspathic sandstones (Toerien and Hill, 1989)
Table Mountain	Baviaanskloof	Beach and off-shore shelf	Upper Silurian	"Dirty" fine grained massive sandstone and subordinate grey-black carbonaceous and micaceous shale. Prominent light grey, medium grained, feldspathic sandstone unit (Kareedouw Member) occurs roughly in the middle of the Formation (Toerien and Hill, 1989)
	Skurweberg	Along-shore to shallow marine	Upper Silurian	Medium to coarse grained, thick to very thick-bedded, profusely cross-bedded quartzose sandstone forming prominent white weathering precipitous cliffs (Theron et al., 1989)
	Goudini	Shoreline to fluvial in the eastern area	Lower Silurian	Fine to medium grained medium-bedded quartzose sandstone containing thin shale and siltstone lenses, weathering to shades of red and brown due to Fe and Mn content (Malan et al., 1989)
	Peninsula	Deltaic to shallow marine, long-shore	Upper Ordovician	Areally prominent medium to coarse-grained supermature generally massively bedded sandstone becoming quartzitic in places; scattered vein quartz pebbles and subordinate lenticular shale layers (Toerien and Hill, 1989)

3.3. Structure

Post-Cape lateral compression during the Cape Fold Belt orogeny produced zones of intense folding with southward dipping axial planes and fold intensity decreasing northwards. This compression produced the dominant, regional east-southeast trending folds in the Cape Supergroup rocks, forming the mountain chains in the study area (Section 2.1). Two large ESE-striking regional folds form the Elands River syncline in the south and the Swartkops River anticline in the north (Toerien and Hill, 1989). The Van Stadens and Elands Berge form the southern and northern limbs respectively of the Elands River syncline which plunges eastward below the Cretaceous sediments, from approximately the Brak River to the coast (Marais, 1965). Further to the north, the Kwa-Zunga River flows through the Swartkops River anticline, where valley erosion occurred as a result of structural weaknesses and faulting in the tensional regime along the anticlinal fold axis. The northern limb of the Swartkops River anticline forms the Groot Winterhoekberge. Figure 3 and Figure 4 show simplified geological profiles through the study area and illustrate the geometry of the aquifer units.

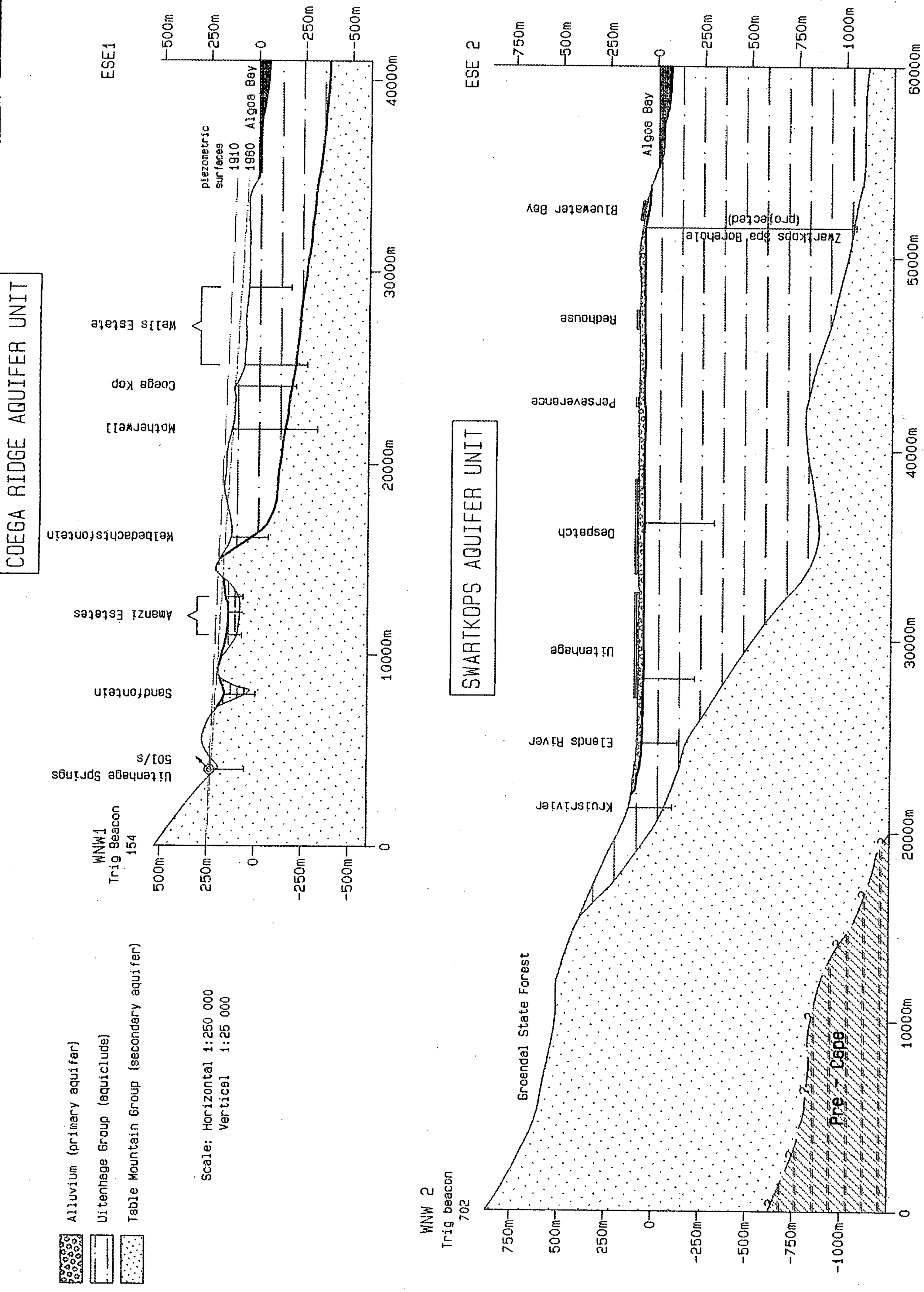
The southern Cape Province sediments are confined to a series of fault-controlled basins extending along the Cape Fold Belt (Kent, 1980). The Algoa Basin (related to the break-up of Gondwanaland) consists of an assemblage of sub-basins infilled primarily with clastic sediments. Two major sub-basins are recognised onshore, viz. the Sundays River and the Uitenhage Basins (Toerien and Hill, 1989).

3.3.1. Coega Fault

The Coega Fault is the major structural feature in the region and is the eastern extension of the regional scale Coega-Baviaanskloof Fault Zone, which was reactivated in the Quaternary near present-day Uniondale and Port Elizabeth (Hill, 1988). The Coega Fault is a normal tensional fault with an average vertical southward displacement of the Cretaceous sediments of 550m (calculated from geophysical data in Marais and Saayman, 1965). The downthrow on the fault is geohydrologically significant since, a) it makes aquifer penetration logistically and economically unfeasible for small-scale drill rigs on the southern side of the fault, in the central regions of the study area; and b) the aquiclude of the Swartkops Aquifer Unit (Section 11) is juxtaposed against the artesian aquifer of the Coega Ridge Aquifer Unit (Section 10).

The Coega Fault is traceable from west of the Groendal Dam eastward to the coast, either by field observation or inferred from stratigraphic borehole information and geophysical surveys. The exact position of the Coega Fault in the eastern part of the study area is controversial with geophysical profiling identifying step-faulting, which results in a southward displacement of the fault as shown on Map 4.

Figure 3: Longitudinal sections through the Swartkops River Basin.
Refer to Figure 6 for section locations.



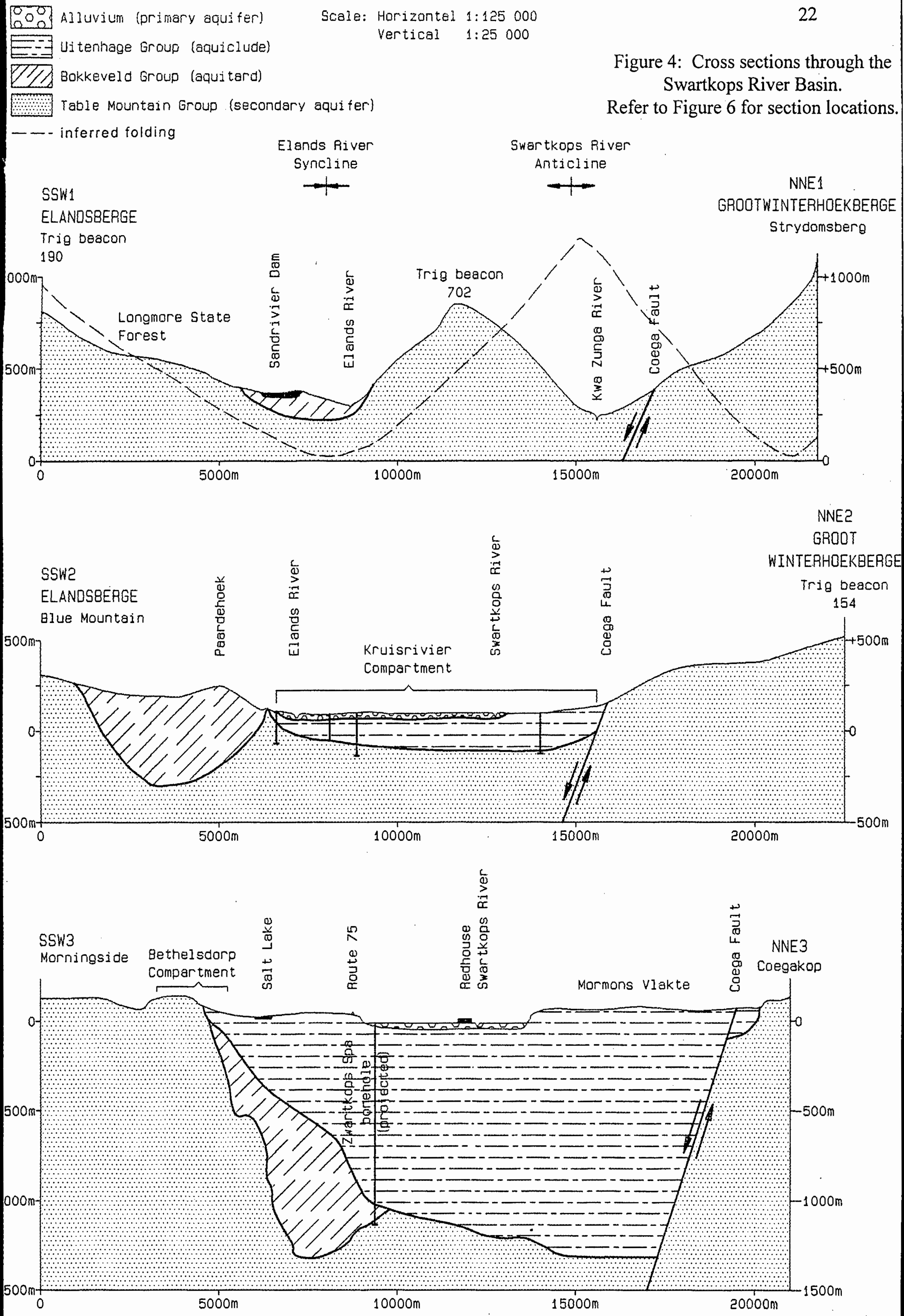


Figure 4: Cross sections through the Swartkops River Basin. Refer to Figure 6 for section locations.

Field observation of the side-wall of the Coega Kop quarry shows large blocks of highly brecciated and faulted quartzite of the Peninsula Formation (Plate 5). According to the geological map (Port Elizabeth sheet 3324), the quarry lies more than 300m north of the indicated fault trace, which implies that faulting has occurred over a zone more than 300m wide. Field mapping (carried out for this study) along the northern banks of the Groendal Dam - the only area in which the fault plane is exposed - identified the fault zone in two tributary valleys of the dam (Plate 6). In these valleys it was observed that the faulting occurs over a zone of at least 50m. Due to the intensely sheared nature of the TMS no dominant fault plane dip or strike could be mapped. Core logging of a borehole drilled in the vicinity of the Coega Fault, as reported in Venables (1985), confirmed that there are a number of smaller faults within a zone associated with the major fault, rather than a simple planar feature. These observations are of geohydrological significance as detailed in Sections 6 and 10.

3.4. Table Mountain Group

The catchment area to the UAB consists of mountains of highly folded, faulted and jointed quartzitic sandstone (TMG) in the west, comprising the Elandsrivier and Groot Winterhoekberg ranges. The TMG sandstone is characteristically fractured to such an extent that the original bedding is obscured. In fault zones the quartzite has a sugary texture. The TMG has a minimum thickness of 500m.

3.5. Bokkeveld Group

The Bokkeveld Group shales, deposited during the Devonian period, form the unconformity surface on which sediments of the Uitenhage Group were deposited. These shales are exposed in the Elands River valley. Eastward toward Algoa Bay they occur as a sub-outcrop below the Uitenhage Group.

Sediments of the Bokkeveld Group occur in the southwest and south of the study area from the Elands River valley to the Chatty River near Bethelsdorp, and immediately north of the study area where they form a steeply north-dipping contact with the TMG. The Bokkeveld Group deposits have a folded thickness of 500-1000m.

3.6. Uitenhage Group

The Uitenhage Group deposits accumulated in the graben-like Uitenhage Trough of the Algoa Basin, with the Coega Fault plane forming the northern scarp to the depositional basin. The Middle to Upper Cretaceous clayey mudstones and siltstones of the Uitenhage Group overly the TMG in the east of the study area, and produce more subdued topography compared with the mountainous TMG landscape. The Cretaceous sediments dip northward at 5-10°, with a steepening in dip towards the Coega Fault.

The Uitenhage Group is represented in the study area by the Enon, Kirkwood and Sundays River Formations from west to east respectively. The Enon Formation deposits usually occur in the pre-Cretaceous landscape, often as infill to the palaeo-valleys. The formation consists of generally structureless conglomerate units interbedded with semi-consolidated sandstone beds. The conglomerate is comprised of a polymictic assemblage of cobbles and boulders of TMG provenance cemented by a sandy matrix. The Enon Formation typically forms steep red cliffs in the central and northwest portions of the study area, with the thickest deposits (200m) on the immediate downthrown side of the Coega Fault.

The occurrence of the Kirkwood Formation is restricted to the lower-lying valleys of the Swartkops River in the study area and consists of interbedded siltstones and mudstones with minor thin (1.5-3m) sandstone layers. The Kirkwood Formation (Plate 2) typically weathers to form reddish-purple outcrops of blocky desiccated clay, and reaches thicknesses of 600-1000m in the central and eastern portions of the UAB.

The Sundays River Formation occurs in the north-central part of the study area between the Coega Fault and the Swartkops River valley and consists primarily of khaki-grey mudstone with thin interbedded sandstone units, reaching thicknesses of 400m.

3.7. Algoa Group and Recent

The Tertiary and Recent deposits are confined to the eastern portion of the study area and consist predominantly of calcareous sandstones and coquinites laid down in aeolian to near-shore environments (Plates 7 and 3).

Alluvial and colluvial clastic deposits occur as a thin veneer within the central and eastern reaches of the Swartkops River flood-plain and as raised terrace gravel deposits around Despatch (Plate 4 and Section 13).

4. UITENHAGE ARTESIAN BASIN

The study area of the Swartkops River Basin falls mainly within the Uitenhage Artesian Basin (UAB) and a discussion on the geohydrology of the UAB is therefore relevant.

The UAB is a complex, fractured rock aquifer covering an area of about 3 700km^2, and is recharged by rainfall on the Groot Winterhoek and Zunga mountain ranges to the west. It occurs mostly within the Port Elizabeth and Uitenhage Districts and is the only extensive aquifer with free-flowing artesian conditions of its type in RSA, representing the country's largest and only economically important artesian basin. Over the last century, groundwater resources have been extensively exploited in the UAB, mostly for agricultural use along the Coega Ridge.

The present-day UAB was an open basin in the Jurassic period (120M years ago), ringed by mountains to the north, south and west. Pebble and boulder alluvial deposits were washed from these mountains under a high energy environment of deposition and accumulated mainly along the western margin of the basin to form the Enon Formation conglomerate and sandstone. Clays were then deposited unconformably on the Enon Formation - under a basin-entry depositional environment to form the mudstones and siltstones of the Kirkwood Formation. Fossil plant remains in these sediments indicate a fresh to brackish environment of deposition (Mountain, 1955). Subsequent invasion of the basin by the sea deposited marine to estuarine clays to form the Sundays River Formation, with a rich variety of marine fossils. During the Tertiary, numerous periods of marine transgression and regression (Section 3.2) formed terraces in the Cretaceous sediments of the Uitenhage Artesian Basin and deposited a veneer of calcareous sandstones (Algoa Group) with sea-level retreat.

4.1. Uitenhage Artesian Basin - Aquifer Delineation

The artesian basin configuration is controlled by post-depositional faulting in the north (Coega Fault, Section 3.3.1) and folding in the south (Section 3.3). The UAB's natural boundaries are the Indian Ocean to the east, the TMG-Bokkeveld Group contact in the vicinity of the Coega River to the north, the Groot Winterhoekberge to the west and the St. Albans Flats (west of Port Elizabeth) to the south. The total yield of the UAB aquifer is estimated at 80ℓ/s (Venables, 1985; Maclear and Woodford, 1995).

The Swartkops River Basin - which forms the major part of the UAB - is sub-divided geologically and hydrologically by the Coega Fault into two major aquifer units, *viz.* the relatively shallow *Coega Ridge Aquifer Unit* (CRAU) north of the Coega Fault and the deeper *Swartkops Aquifer Unit* (SAU) to the south of the Fault (Figure 5 and Figure 6). The two units function independently from one another, i.e. abstraction from a borehole in one unit only affects the yield of boreholes or springs in the unit from which abstraction is occurring, and not in the neighbouring unit.

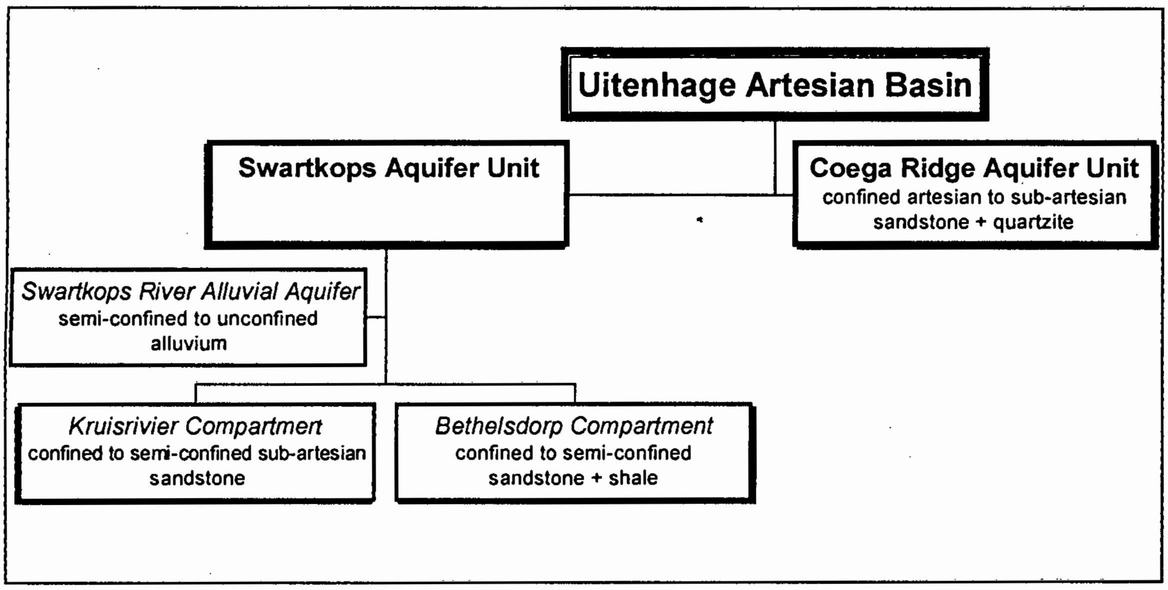


Figure 5: Sub-division of the Uitenhage Artesian Basin.

The Swartkops Aquifer Unit is further sub-divided into the *Kruisrivier Compartment* and *Bethelsdorp Compartment* by the low-permeable to impermeable Bokkeveld Group infill of the Elands River Syncline; and the *Swartkops River Alluvial Aquifer* (SRAA) which occurs as a thin narrow unit over most of the Swartkops Aquifer Unit.

4.2. Declaration of a Control Area

Geohydrological conditions in the study area changed after 1908 from free-flowing artesian to sub-artesian along the CRAU and Kruisrivier Compartment. This was a result of the arrival of drilling machines in the area and the resultant rapid increase in the number of boreholes drilled to augment the yield from the artesian basin for irrigation.

In 1950 the Hall Commission heard evidence regarding the weakening flow conditions in the UAB and as a result of substantial pressure from the farmers in the region, the basin was declared a Subterranean Government Water Control Area (SGWCA) in 1957, by means of Government Proclamations No. 260 of 1957 and No. 958 of 1958. These proclamations announced and stated regulations with regard to the control area, respectively. The Uitenhage SGWCA is shown in Figure 6 and covers an area of 1 125km^2.

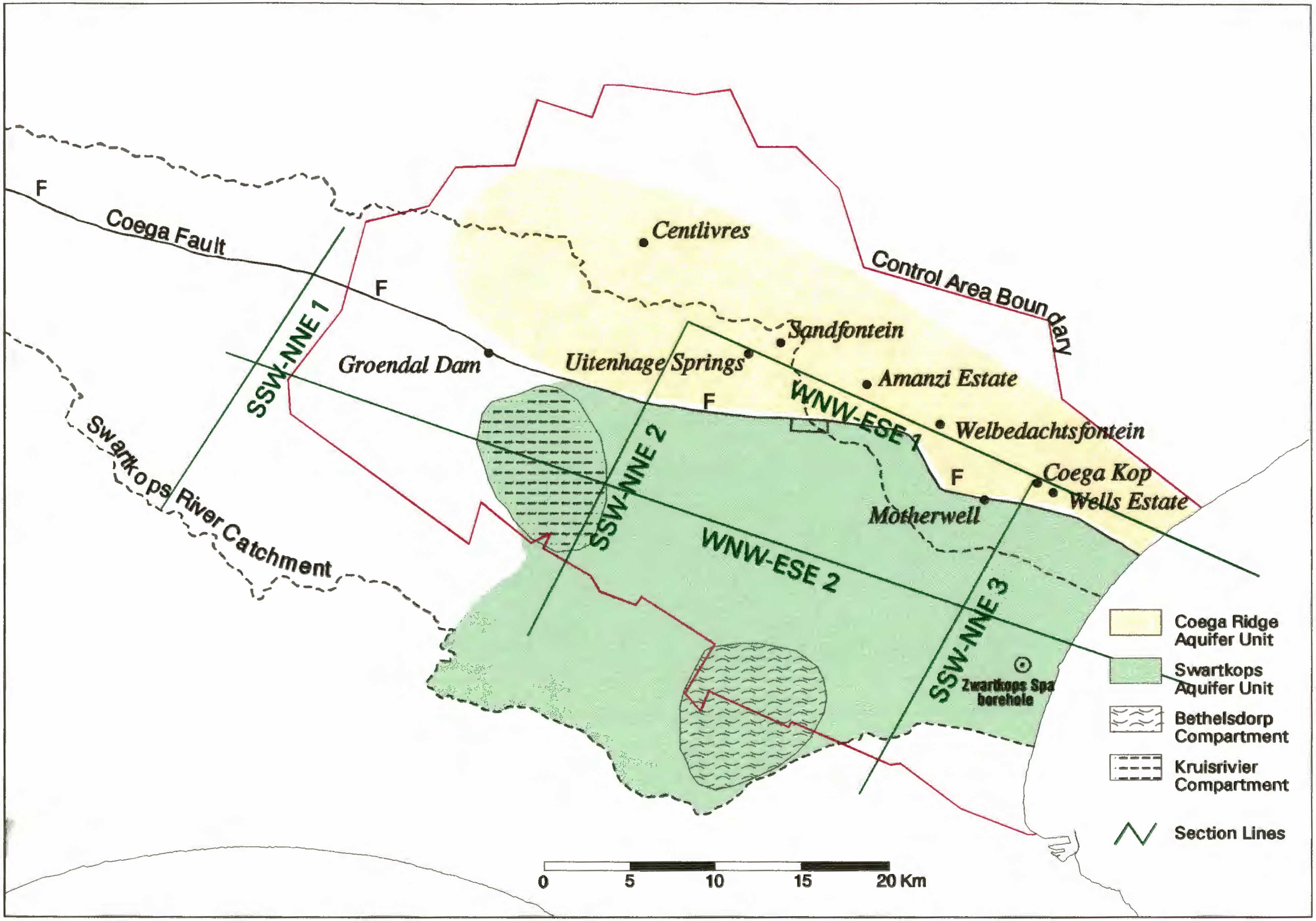


Figure 6 : AQUIFER GEOMETRY - SWARTKOPS RIVER BASIN

5. GENERAL GEOHYDROLOGY

Two main aquifer types occur in the Swartkops River Basin, *viz.* a minor, shallow semi-confined to unconfined, unconsolidated primary alluvial aquifer; and a deeper major artesian to sub-artesian, fractured secondary aquifer, in quartzites of the TMG, and basal sandstone and conglomerate layers of the Enon Formation. Most of the artesian groundwater within the secondary aquifer is restricted to relatively narrow, well-defined zones of intense fracturing.

The two main aquifer types are separated vertically from one another in the central to eastern parts by confining layers of Uitenhage Group sediments, which form an aquiclude. To the south and west, the secondary TMS aquifer is separated horizontally by low-permeable sediments of the Bokkeveld Group (Figure 7). The Coega Fault marks the boundary in the UAB between artesian conditions in the SAU in the southern downthrown side, and the CRAU in the northern upthrown side.

No distinction is made in this study between the various formations of the TMG quartzites and sandstones, and the shales of the Bokkeveld Group. These formation divisions are only significant from a stratigraphic viewpoint rather than geohydrological.

The overriding geohydrological effect of the folding history of the area (Section 3.3) is the creation of cleavages and joints - aligned along the trend of the Cape folding, i.e. WNW-ESE. These structural failures result in secondary permeability being introduced, thereby permitting the passage of water in the massive quartz arenites of (mainly) the TMG Peninsula Formation. Without these structures, the TMG rocks in the study area would not be termed aquifers since these formations - in their undisturbed form - have an inherently very low primary porosity and permeability due to silica cementation during diagenesis.

The Elands River Syncline (Figure 4), striking east towards Port Elizabeth, exposes the Bokkeveld shales (classified as an aquitard for this study) below the Cretaceous rocks. The syncline is geohydrologically significant in the study area where the shales form an impermeable retaining wall, dividing the SAU into the southern Bethelsdorp and the northern Kruisrivier Compartments (Marais, 1965). The majority of abstraction in the SAU occurs in the Kruisrivier Compartment, where groundwater is pumped out of the aquifer for irrigation purposes.

Mudstones of the Kirkwood and Sundays River Formations are characterised by very low permeabilities and are considered to form an aquiclude for the purposes of the present study (although they do yield small amounts of poor quality groundwater). These mudstones confine the groundwater in the underlying secondary aquifer, resulting in artesian conditions. The impermeable mudstones also result in perched water tables occurring in the groundwater units above the Kirkwood Formation.

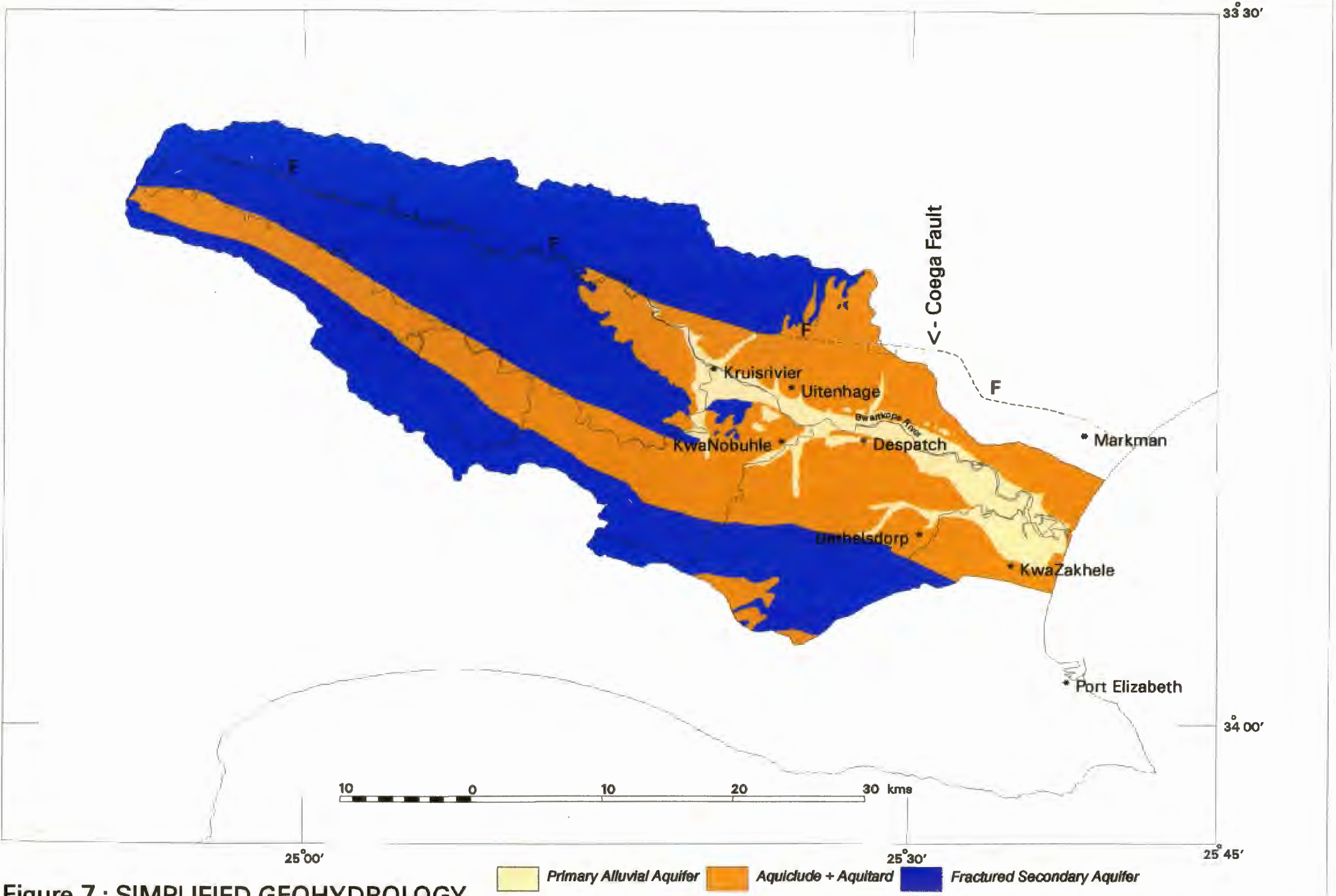


Figure 7 : SIMPLIFIED GEOHYDROLOGY

Late Tertiary to Recent alluvial deposits are restricted to the river valleys and floodplain areas and unconformably overlie parts of the Cretaceous strata. These deposits consist of sand, gravel, silt and clay beds generally less than 15m thick. Bush (1985) considered them to be of little geohydrological importance, with groundwater abstraction mainly taking place by means of shallow wells and seepage pits adjacent to the Swartkops River and upper tributaries.

The alluvium area comprising the primary aquifer - of significance to this study from the aspect of aquifer vulnerability - covers an area of 88.5km^2, of which 40km^2 occurs in the river reach from above the confluence of the Elands and Kwa-Zunga Rivers down-river to Perseverance. The aquifer is recharged by precipitation, direct infiltration from surface impoundments and induced river seepage during pumping (Section 13).

5.1. General Hydrochemistry

5.1.1. Hydrochemical Evolution

As groundwater moves along flow lines from recharge to discharge areas, its chemistry is altered by the effects of a variety of geochemical processes, dependent on the basin flow regime and/or aquifer hydraulic characteristics. Water chemistry changes thus occur with lateral and vertical movement of the groundwater along its flow path (Freeze and Cherry, 1979).

Major factors controlling the natural hydrochemical evolution of groundwater are geology, topography, climate and time. As groundwater moves along flow paths in the saturated zone the mineralisation increases, with an accompanying chemical evolution of groundwater towards the composition of sea-water (Chebotarev, 1955). This involves a change from a calcium bicarbonate/carbonate water to a sodium chloride water as it moves from a recharge to a discharge area.

The nature and degree of mineralisation of groundwater depend on:

- the composition of the recharge water,
- the composition of the rocks through which the water flows,
- the changes in the composition of the groundwater with travel through the soil or regolith, and
- climatic factors which affect weathering (and, therefore, the mineralogical composition of the regolith); and evapotranspiration rates (important with respect to salt concentration especially in shallow, unconfined aquifers).

Concentration of dissolved mineral matter is directly proportional to the length of the flow path and to the residence time of the groundwater. Very slow moving water, such as occurs in the relatively impermeable argillaceous siltstones and mudstones of the Kirkwood and Sundays River Formations, becomes highly mineralised with time (Ward, 1975). The "order of encounter" - the order in which minerals are encountered by water moving through the flow system - is one of the most important factors in the chemical evolution of groundwater (Freeze and Cherry, 1979).

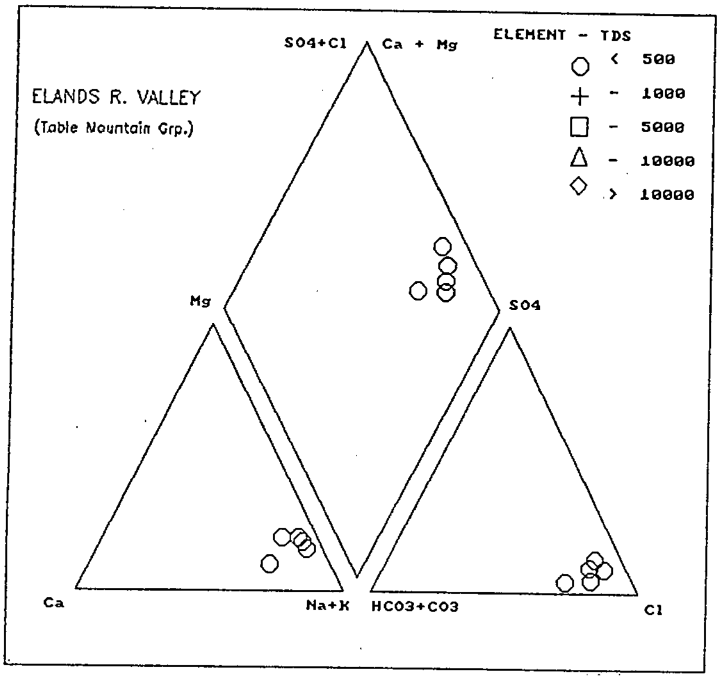
Groundwater mineralisation will generally increase from recharge to discharge areas and with movement from shallow to deeper lying lithologies. Recharge areas can be expected to have groundwater low in TDS, whereas deep circulating groundwater in discharge areas will have the highest TDS concentrations in any one system.

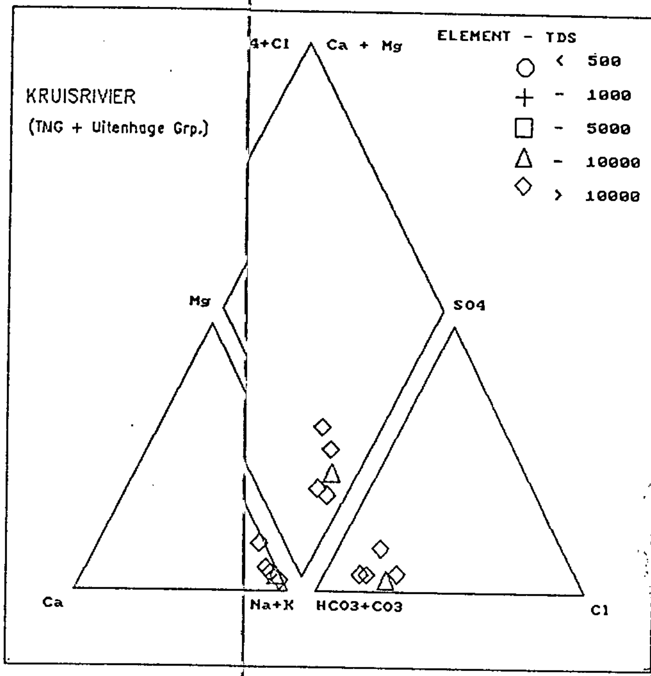
In the Swartkops River catchment movement of the more recently recharged groundwater from the upper catchment areas (TMS) to the lower lying discharge areas (alluvium, Tertiary and Cretaceous sediments) involves the removal or exchange of Ca and Mg bicarbonates and the introduction of Na and Cl dominated salts to the groundwater, as different formations are encountered along the flow path. This is clearly illustrated in Figure 8 for the various groundwater regions in the study area, by the progressive rapid increase in TDS with increasing distance from the recharge area.

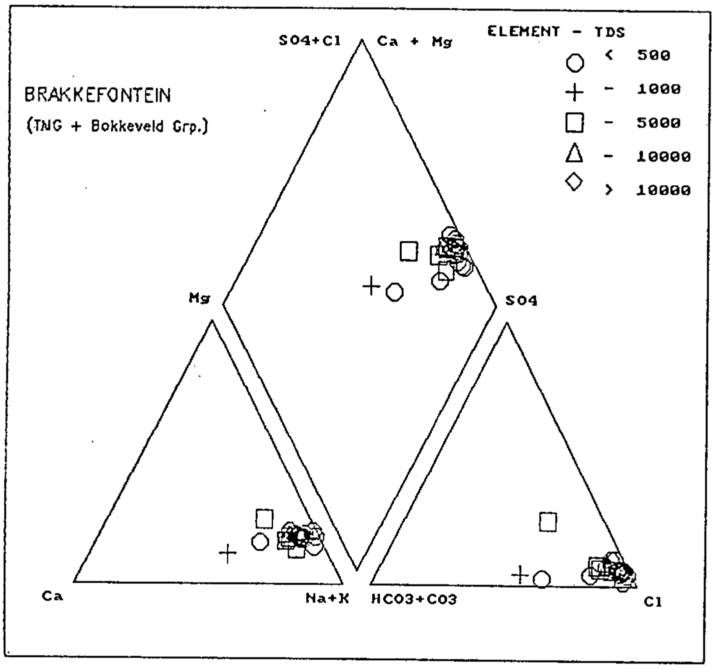
The striking characteristic of many groundwaters in stratified sedimentary sequences is the occurrence of sodium (and bicarbonate) as the dominant ions due in part to cation exchange (Freeze and Cherry, 1979). This feature is very apparent for groundwater sampled from the Uitenhage Group rocks in the discharge portion of the study area, e.g. the dug-well water analyses from the Despatch area presented in Appendix A and B.

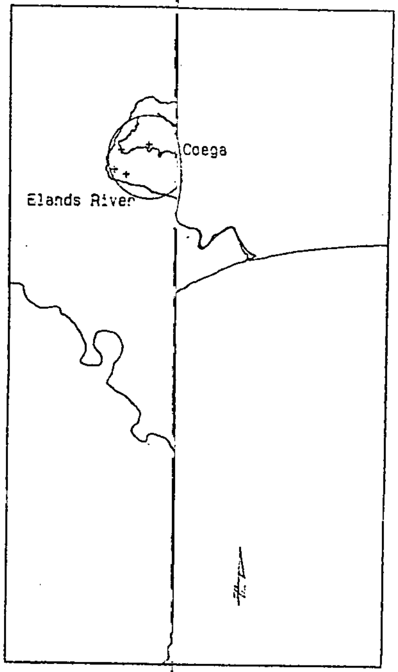
5.1.2. Hydrochemical Facies

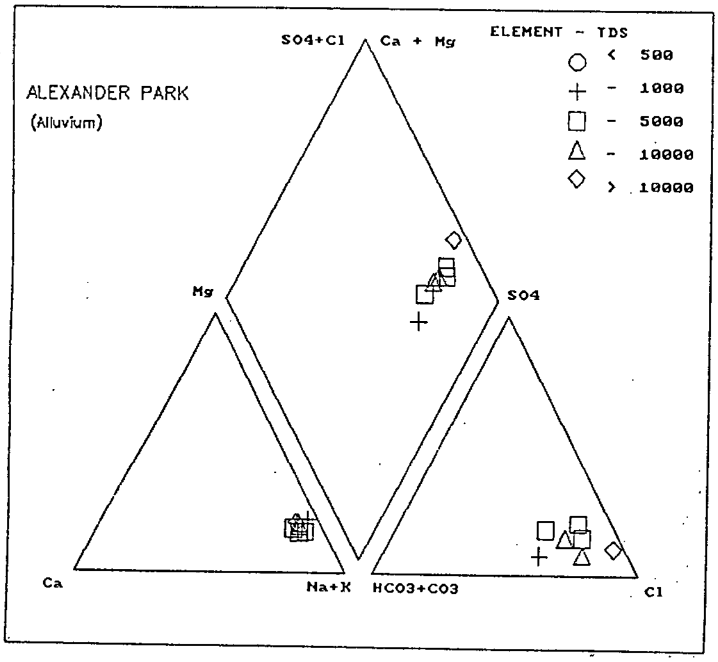
Evolutionary processes effective on a particular groundwater body, such as host rock mineralogy and groundwater flow pattern, will result in a distinctive chemical assemblage for that water. This is referred to as a hydrochemical facies. It is a useful tool for the classification of groundwaters from different sources, as well as observing the hydrochemical evolutionary stage of groundwater samples from the same source with movement from recharge to discharge zones. The hydrochemical facies concept assumes that the chemical composition of groundwater at any point along its flow path reflects a tendency towards equilibrium with the host rocks (Ward, 1975).

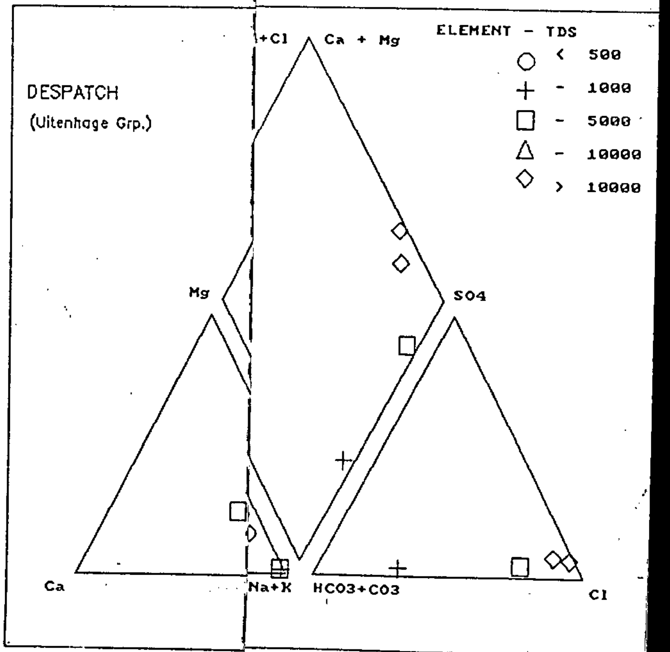

ELANDS R. VALLEY
(Table Nountain Grp.)
SO4+Cl
Ca + Mg
ELEMENT - TDS
○ < 500
+ - 1000
□ - 5000
△ - 10000
◇ > 10000
Mg
SO4
Ca
Na+K
HCO3+CO3
Cl


KRUISRIVIER
(TNG + Uitenhage Grp.)
4+Cl
Ca + Mg
ELEMENT - TDS
○ < 500
+ - 1000
□ - 5000
△ - 10000
◇ > 10000
Mg
SO4
Ca
Na+K
HCO3+CO3
Cl


BRAKKEFONTEIN
(TNG + Bokkeveld Grp.)
SO4+Cl
Ca + Mg
ELEMENT - TDS
○ < 500
+ - 1000
□ - 5000
△ - 10000
◇ > 10000
Mg
SO4
Ca
Na+K
HCO3+CO3
Cl


Coega
Elands River


ALEXANDER PARK
(Alluvium)
SO4+Cl
Ca + Mg
ELEMENT - TDS
○ < 500
+ - 1000
□ - 5000
△ - 10000
◇ > 10000
Mg
SO4
Ca
Na+K
HCO3+CO3
Cl


DESPATCH
(Uitenhage Grp.)
+Cl
Ca + Mg
ELEMENT - TDS
○ < 500
+ - 1000
□ - 5000
△ - 10000
◇ > 10000
Mg
SO4
Ca
Na+K
HCO3+CO3
Cl

5.1.3. Graphical Methods for Representation of Chemical Analyses

Numerous methods of graphing hydrochemical analyses have been developed (Hem, 1970), typically taking the form of ion concentration diagrams. These diagrams are useful for purposes of correlating and studying the analyses of a water sample or group of samples, and subsequent interpretation of hydrochemical facies. The three most commonly used and accepted methods are outlined below.

Piper Method : trilinear diagram developed by Piper (1944) providing a useful tool for the interpretation of hydrochemical analyses, as well as indicating the extent to which mixing of waters has occurred. In this method, groundwater is treated as containing 3 major cations (Na, Ca, Mg) and three major anions (HCO_3, SO_4, Cl), with the minor ions being summed together with the related major ions for plotting purposes. The relative concentrations (in meq/ℓ) of the anions and cations are plotted as a percentage on the diagram, with the central diamond field showing the overall chemical character of the groundwater (Figure 9). Different water types can be recognised and compared, as well as their position in the flow system, from their plotting position on the Piper Diagram. It is important to note that a Piper diagram displays ionic *ratios* only, and not total salt concentrations, thus water samples of widely different ionic concentrations should be compared with caution (Hem, 1970).

Stiff Method : developed by Stiff (1951) for graphically displaying the concentration of the four major cations and anions for the interpretation of water chemistry, and specifically for showing compositional differences or similarities. The Stiff method produces a distinctive polygonal shape, which can be used for visual comparison purposes, where the ionic concentrations (in meq/ℓ) are shown on the x-axis (see Figure 10). A shortfall of this method is that it is only able to indicate the hydrochemistry of a single sample.

Schoeller Method : nomograph form developed by Schoeller (1935), as a useful means of depicting a group of hydrochemical analyses. This method has the advantage (over, for example the Piper Method) of showing the relationship between the mg/ℓ and meq/ℓ (epm) for the different ions. A number of water samples can be simultaneously illustrated on the Schoeller Diagram for interpretation purposes. Waters of similar composition plot as near parallel lines on a Schoeller Diagram and the dominant ions can be easily seen (Figure 10).

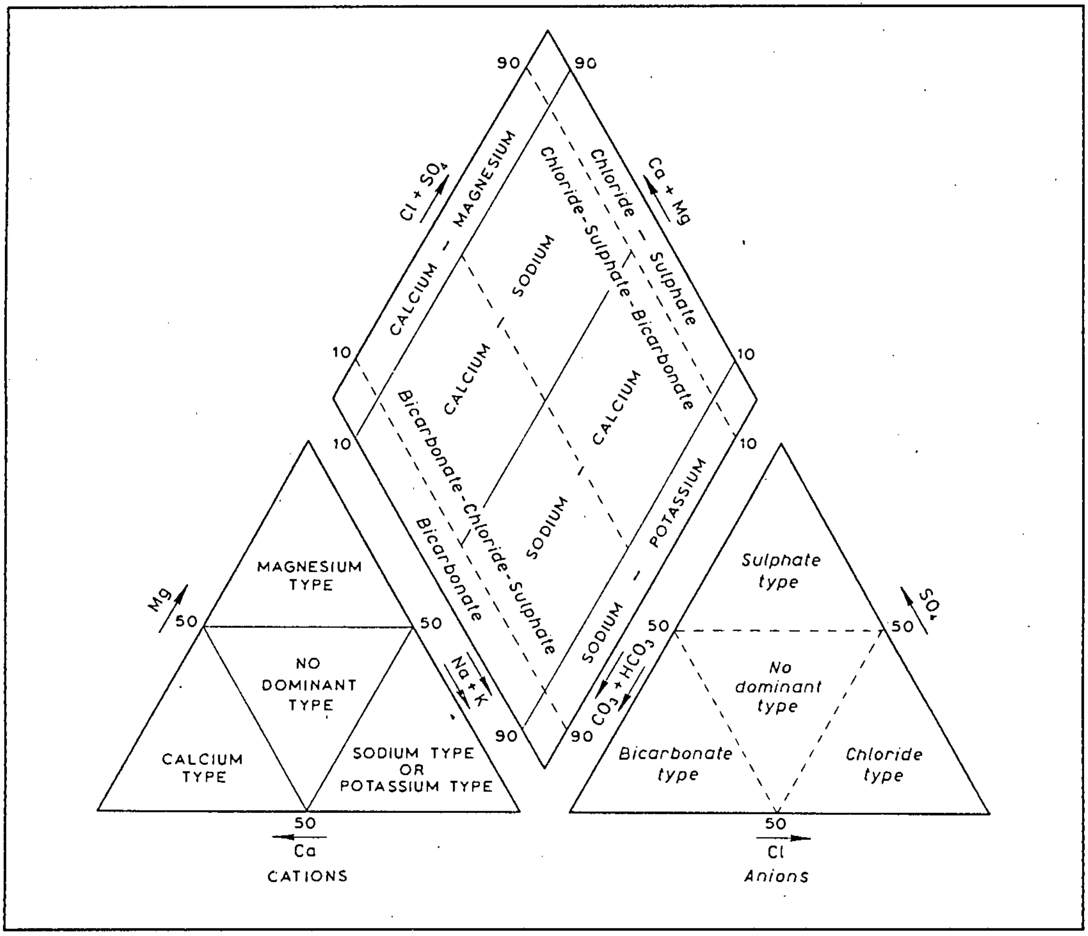


Figure 9: Piper trilinear diagram showing hydrochemical facies (from Ward, 1975).

5.1.4. Study Area Hydrochemistry

In his 1957 study, McNae reported the groundwater in the upper reaches of the Swartkops River catchment (sandstone and quartzite dominated) to be soft with low mineral content, but that by the time the groundwater reaches the estuary it is brack - having flowed through "marine" beds, i.e. the Uitenhage Group deposits. This general observation was confirmed in the catchment-scale hydrocensus by Maclear (1993) when, for example, the Elands River groundwater hydrochemistry (500mg/ℓ TDS) is compared with that from boreholes in the Perseverance area (>10 000mg/ℓ TDS). From Figure 8, where the plotting position of the groundwater sample point as well as its TDS range is shown on Piper diagrams for geographical clusters of groundwater samples, it can be seen that there is a general increase in salinity from the western recharge areas to the eastern discharge areas in the Swartkops River Basin.

The Cretaceous and Bokkeveld Formations have a high percentage of clay minerals that contribute to the argillaceous lithologies. Since clays are efficient ion exchangers (giving up sodium to base exchange) and the clay minerals have small pore spaces, resulting, e.g. in slow flow rates and therefore higher residence time in the aquiclude, a longer time is available for dissolution reaction of ions by percolating groundwaters. As a result, the groundwater in these formations has a high salinity.

The TMS, conversely, is composed almost exclusively of quartz grains in a silica cement matrix - resistant to erosion - thus producing a groundwater with a low total mineralisation. Widely varying water quality within a geologically complex basin - such as in this study - can thus be expected.

Sea-water was trapped in the shallow marine, lagoonal and estuarine sediments and associated evaporite deposits in the study area, as a result of periodic marine transgression and regression events during the Pliocene and Pleistocene epochs. This resulted in mineralised, brack connate groundwater in the Kirkwood and Sundays River Formations of the Uitenhage Group The sea water origin of the groundwater in these Formations is confirmed for the following reasons: the water has a typical NaCl character (Uitenhage Group in Figure 10) and concentrations of Sr and B similar to that of sea water (Appendix C). The Sr concentrations on their own are not indicative of a connate origin of the groundwater, since Sr is a common element in sedimentary deposits (Hem, 1970); however, together with the NaCl character, Ca/Mg ratios of 7 : 11, B concentrations and known depositional history (Section 3.2) of these formations, the sea water origin is confirmed.

The highest TDS values for sampled groundwater, from both boreholes and dug-wells, occur at Maclear's (1993) hydrocensus points DH3 and TM1 (Appendix A and Map 5). These points penetrate intermediate and low-level fluvial terrace gravels (Plate 4), lying as remnant deposits on the estuarine and marine Kirkwood and Sundays River Formations, and thus connate groundwater can be expected from these sediments.

Average pH and EC values of the groundwater for the regions indicated in Figure 8 are shown in Table 2. The regions are listed in this table in order of position within the proposed flow regime from west (recharge) to east (discharge) in the study area. It is clear that the mineralisation generally increases with increasing distance from the recharge area for the secondary, confined to semi-confined aquifers of Elands River, Brakkefontein, Kruisrivier, Perseverance and Coega, with the exception of the artesian Uitenhage Springs, where the deep circulating groundwater is of exceptional quality when it daylights. The unconfined to semi-confined primary aquifer groundwater at Alexander Park and Despatch is highly mineralised as a result of lithology and connate conditions, discussed further in Section 16.11.

Figure 10: Groundwater types - Swartkops River Basin.
Note scale changes on Stiff diagrams for different locations.

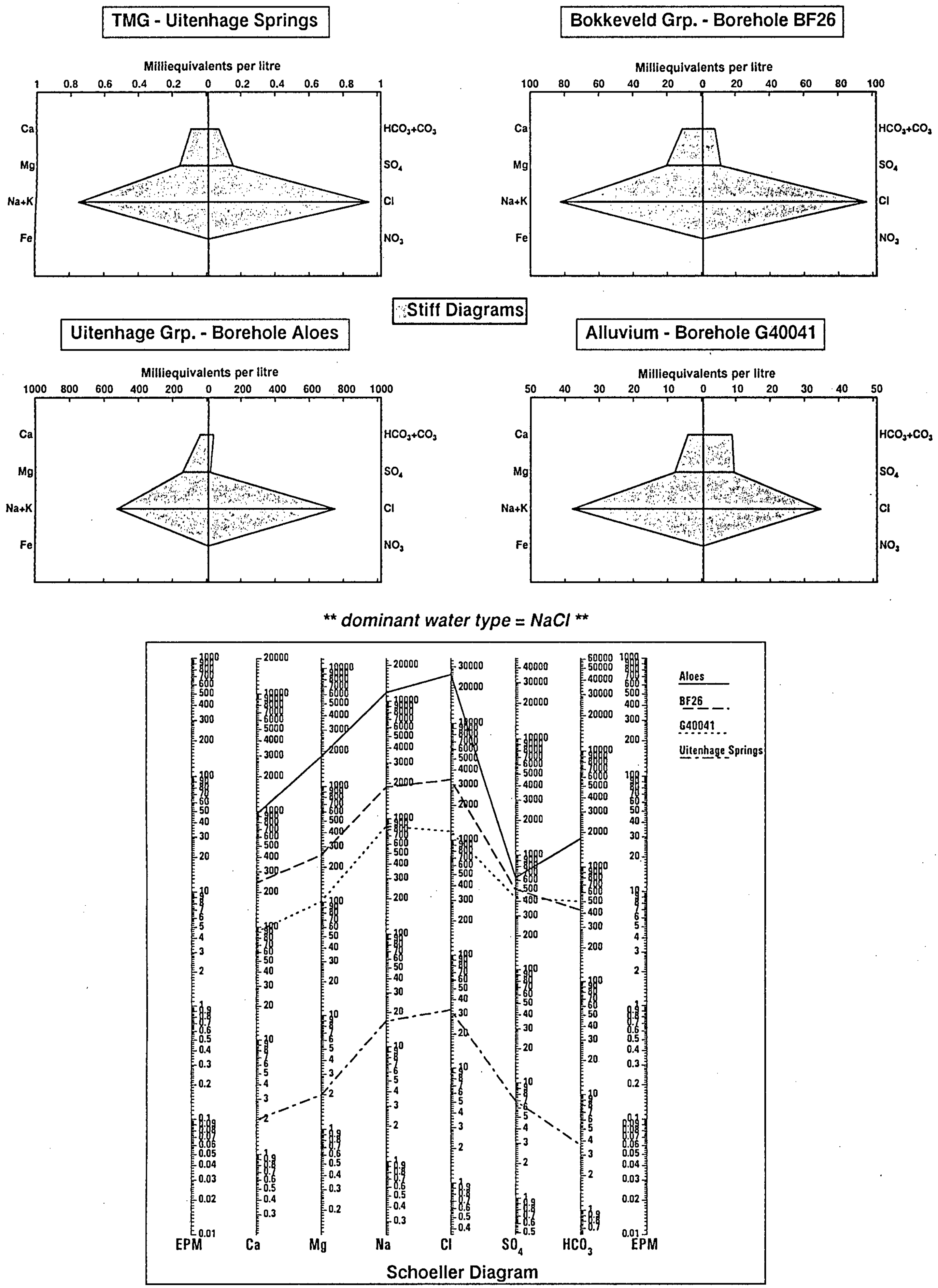


Table 2: Average groundwater quality for the study area, locations in sequence from west (recharge area) to east (discharge area).

Location	Number of samples	EC (mS/m)	pH
Elands River	5	24	7.2
Brakkefontein	25	182	7.4
Kruisrivier	18	122	6.7
Uitenhage Springs	1	15	6.0
Alexander Park	8	802	8.1
Despatch	10	980	7.8
Perseverance	3	661	8.4
Coega	23	715	8.4

The groundwater in the upper western parts of the study area is neutral to weakly acidic, the Uitenhage Springs water being the most acidic with a pH of 6. Rainwater and distilled water have a pH in the vicinity of 5.6 (Freeze and Cherry, 1979) and this, together with the very low mineralisation of the groundwater discharging from the Uitenhage Springs indicates this water to be fresh, relatively recently recharged and little changed from its original natural state (see also Section 12.2). This is a result of the reasonably high transmissivities, and therefore short residence times, for the TMS aquifer below Coega Ridge (Section 10). The fact that the groundwater in this aquifer is flowing through crystalline sandstone rocks, which are relatively devoid of calcareous deposits (e.g. limestone that would raise the pH, thereby increasing the alkalinity), also explains the slightly acidic nature of this groundwater.

Mildly alkaline groundwater (pH 7.5-8.5) exists in the central to eastern regions of the study area, to be expected as a result of the water residing in and passing through the calcareous silty and muddy sediments of the Algoa and Uitenhage Groups. This is explained with reference to the following chemical reactions:

H_2O (water)	+	CO_2 (carbon dioxide)	→ H_2CO_3 (carbonic acid)	*Reaction 1*
H_2CO_3 (carbonic acid)	+	$CaCO_3$ (calcium carbonate)	→ $Ca(HCO_3)_2$ (calcium bicarbonate)	*Reaction 2*

As rain falls, CO_2 in the atmosphere is absorbed to form diluted, weak carbonic acid (Reaction 1) that leaches through the soil and rock dissolving various minerals. On contact with clayey formations, feldspars are broken down and, in calcareous deposits, the acid dissolves the alkali limestone to form calcium bicarbonate (Reaction 2), thus raising the pH.

The hydrochemistry of the major geological units in the Swartkops River basin is shown for comparison purposes in Figure 10. The groundwater type of the various units is very similar, i.e. a predominantly NaCl character, indicated by the distinctive polygon shape on the Stiff Diagrams. The NaCl type of the study area water is explained by the proximity of the Swartkops River Basin to the sea - the source of recharge water to the aquifers via precipitation. This is confirmed by the chemical mixing exercise carried out for this study and detailed in Section 16.10.

The connate nature of the water trapped in the Uitenhage Group sediments further explains the NaCl signature of the study area groundwater contained in these sediments (Section 11.2.4). The secondary aquifer in the fractured TMG quartzites, however, also has a NaCl signature - therefore the effect of rain water on the observed hydrochemistry in the catchment is the over-riding influence.

From the Schoeller Diagram (Figure 10), it can further be seen that the concentration of the major ions in the groundwater, i.e. salinity, varies by four orders of magnitude in the study area. The groundwater from a borehole at the Aloes waste disposal site (Map 5) - situated on the Sundays River Formation of the Uitenhage Group, for example, has an extremely high salinity of 52 500mg/ℓ TDS, i.e. 1.5 times that of sea water; compared with the salinity of the groundwater issuing from the Uitenhage Springs of only 65mg/ℓ TDS - equivalent to that of rain water sampled in the study area (Appendix D).

The general characteristics of the groundwater contained in the various geological formations of the Swartkops River Basin are detailed further in Table 3 and Table 4.

Table 3: General hydrochemical characteristics of the UAB.

Geological Group	General characteristics	Water type
Table Mountain	• very low salinity, fresh groundwater, • slightly acidic due to the oxidation of FeS_2, therefore corrosive to steel borehole casing and concrete with time, • ferruginous material deposited on exposure to air, • relatively high SO_4 content - function of oxidation of pyrite.	NaCl / $Ca(HCO_3)$ + Ca / $MgSO_4$
Uitenhage	• highly variable quality, • generally very saline, especially the Sundays River and Kirkwood Formations, • mildly corrosive.	NaCl / MgCl + $Ca(HCO_3)$ / $CaSO_4$
Bokkeveld	• brack groundwater.	NaCl / $Ca(HCO_3)$
Mixed TMG + Bokkeveld	• moderately saline and corrosive.	NaCl
Alluvium	• water quality highly variable depending on overburden thickness, lithology and proximity to river (Section 13.1.3).	NaCl

Table 4: Fitness for use of groundwater in the UAB.

Formation / Aquifer	TDS (mg/ℓ)	pH	Hardness *	F (mg/ℓ)	Fitness for use
Uitenhage Springs	90	6	soft	0.1	• excellent • F below health requirements
Table Mountain Sandstone	190	6-6.5	soft	0.6	• good • excellent for irrigation • slight Fe taste, removed with standing time • F below health requirements • Marked presence of Mn + Fe due to presence of small manganiferous ore bodies.
Enon Formation sandstone	210	5.5-6	soft	0.3	• good • Na:Ca+Mg ratio (SAR) good for irrigation esp. vegetables • F below health requirements
Kirkwood Formation	450-9350 (highly variable)	6.5-7.5	moderately hard to very hard	1.1	• unfit for use • highly mineralised • stock watering only
Sundays River Formation	450-33500	7-8.5	very hard	1.5	• unfit for use • alkaline • stock watering only
Bokkeveld Group	3300	7.5	hard to very hard	0.3	• unfit for use • stock watering only
Alluvium	100-22000	7-8	moderately hard to very hard	0.6	• generally unfit for use • suitable for small-scale garden/orchard irrigation

- Averages of water quality variables are given unless a range is specified.
- Fitness for use related to domestic consumption.
- Data from Marais (1965), Bush (1985), Maclear (1993) and Maclear (1995).
* Hardness range ($CaCO_3$) based on USGS classification in Heath (1983).

5.1.5. Groundwater Irrigation Potential

Due to its low salinity in places, groundwater is extensively used for irrigation purposes in the Swartkops River Basin, especially in the Kruisrivier area and along the Coega Ridge. The suitability for irrigation of groundwater from various aquifers is shown on a Wilcox Diagram in Figure 11. This chemical analytical technique was developed specifically for the agricultural sector and indicates the salinity and SAR hazard of displayed waters.

The SAR (sodium adsorption ratio) predicts the degree to which irrigation water will enter into cation-exchange reactions with the soil (Hem, 1970), where Ca^{2+} and Mg^{2+} are displaced by Na^{+}. This displacement produces sodic (Na-rich) conditions in the soil, which is damaging to soil structure - specifically as a result of reduced soil permeability. As the SAR of irrigation water increases, the ability of a soil to absorb sufficient quantities of water for crop requirements is reduced.

Irrigation with saline water is also hazardous, since soil salinity is induced when salts are concentrated in the soil with time by evapotranspiration, and as the water is preferentially absorbed by the crop. Once the threshold soil salinity - specific for each crop - is exceeded, soil salinisation occurs and a reduction in crop yields results.

The guideline ranges suggested in DWA&F (1993b) for SAR and salinity of irrigation waters are as follows:-

- 0-1.5 SAR = *target* range to ensure adequate infiltration rates for sensitive soil; 10 SAR = *maximum* range above which soil infiltration rates cannot be maintained.
- <40mS/m EC (≡ 400µmhos/cm) = *target* range to ensure that salt-sensitive crops can be grown without suffering a yield decrease; 550mS/m EC = *maximum* limit above which a 25% crop failure of moderately salt tolerant crops will occur.

The groundwaters from the quartzitic aquifer beneath the Coega Ridge (Amanzi borehole), and the sandstone and shallow alluvial aquifers (boreholes KM1 and G40035, Appendix A and C) in the Kruisrivier area are highly suitable for irrigation - and are classified as S1C2 irrigation waters, i.e. having a low sodium hazard and medium salinity hazard (Figure 11). The Amanzi borehole is used for large-scale irrigation of citrus orchards along the Coega Ridge, and KM1 for irrigation of extensive vegetables lands (Appendix A).

In contrast, the aquifers in especially the Brakkefontein area (Bokkeveld Group, borehole BF8, Appendix A), as well as below Despatch (perched clayey gravel aquifer, dug-well DH147, Appendix A) are unsuitable for irrigation; with a very high salinity, and medium to very high sodium hazard. Borehole BF8 is used only for stock-watering purposes and the dug-well DH147 for small-scale fruit and garden irrigation.

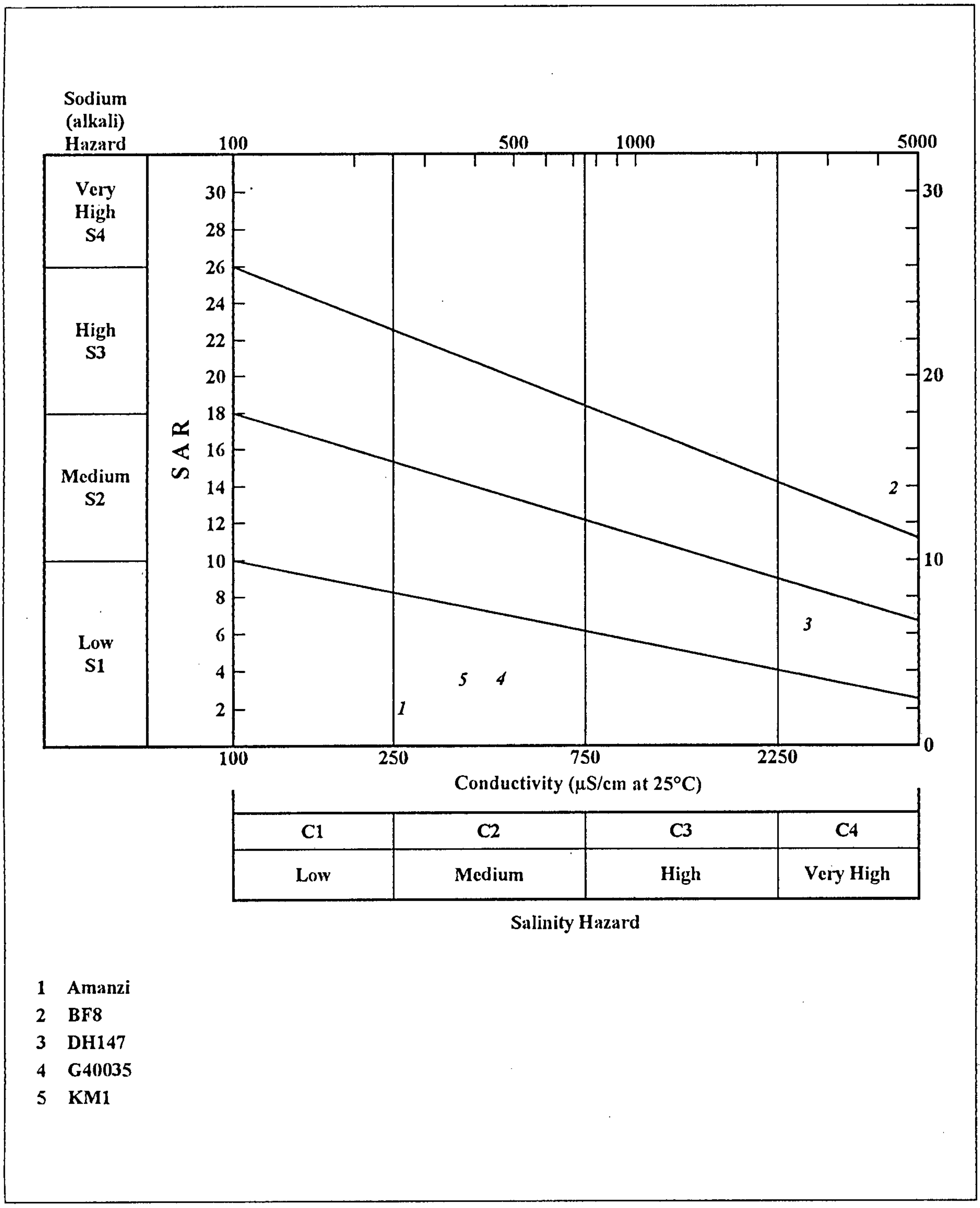


Figure 11: Wilcox Diagram showing groundwater suitability for irrigation in the Swartkops River Basin.

6. GEOHYDROLOGY OF THE TABLE MOUNTAIN GROUP

The orthoquartzites of the TMG have been highly fractured, jointed and brecciated by deformation resulting in structures of secondary permeability.

Petrographic analyses of the quartzitic TMG sandstone matrix shows that it is impermeable. The competent nature of the rock, however, resulted in the development of secondary zones of permeability during the Cape Orogeny. These jointed and brecciated zones are usually parallel to bedding and range from a few centimetres to about 100m in the Coega Fault Zone (Plate 6). The highly fractured nature of the TMG rocks in the west of the study area thus results in an excellent secondary aquifer, with strong borehole yields generally greater than 5*ℓ*/s.

Drilling in the mountainous area to the NW and W of Uitenhage is generally unsuccessful due to the rugged nature of the terrain resulting in rapid run-off (therefore reduced effective recharge) and groundwater drainage. This necessitates the drilling of deep boreholes to elevations below the valley floors, in order to intersect the water table. Marais (1965) reported that with increased drilling depth, the occurrence and density of structures decreased and structures became more closed.

6.1. Groundwater Quality

The groundwater in the TMG fractured aquifer is of an excellent quality and is generally fit for drinking in its raw state, although F addition or blending of groundwater with surface water is required, if it is to be a sole long-term supply (Table 3 and Table 4).

6.2. Groundwater Temperature

The available groundwater temperature data from boreholes drilled into the TMG in the study area, as presented in Marais (1965), shows no correlation between groundwater temperature and depth. The differing thicknesses of the overlying Cretaceous sediments makes interpretation difficult with respect to applying a simple geothermal gradient to the TMG, in order to determine the origin of the groundwater. The 160m deep borehole drilled into Eye 2 (Plate 8) at the Uitenhage Springs, for example, was drilled directly into the TMG, and has a groundwater temperature of 23°C; whereas the Amanzi borehole is only 55m deep, has a Cretaceous overburden of 38m and a temperature of 33°C. These anomalies in groundwater temperature and depth are a function of the depth of circulation of the groundwater system. From this, it should be noted that the depth of the water-strike in a borehole is not necessarily the actual depth of origin of the groundwater.

7. GEOHYDROLOGY OF THE BOKKEVELD GROUP

The Bokkeveld Group is not defined as a productive aquifer in the study area, but rather considered to be an aquitard (Section 5), since it has poorly developed structures which are often infilled due to the easily weathered nature of the shales.

Past drilling into the Bokkeveld Group in the Swartkops River Basin, has produced a poor success rate, with unreliable and low-yielding boreholes (0.5ℓ/s) being the typical result.

7.1. Hydrochemistry

The feldspathic sandstone and clayey shale composition of the Bokkeveld Group results in leaching of salts into the percolating groundwater, making the water brack (connate origin) and generally unusable (Table 3 and Table 4).

8. GEOHYDROLOGY OF THE UITENHAGE GROUP

The impermeable nature of the Uitenhage Group results in very low rates of groundwater transmissivities in these sediments, classifying it as an aquiclude for this study (Section 5). The major geohydrological significance of the Uitenhage Group in the study area is its role as a confining layer to the fractured secondary aquifer in the central and eastern portions of the study area, where this aquifer is overlain by the Uitenhage Group.

8.1. Enon Formation

The conglomerate layers of the Enon Formation have a very low porosity and permeability, whereas the interbedded semi-consolidated sandstone units are soft, semi-consolidated and granular in nature. This results in low to medium primary porosities in the sandstone units, producing localised high-yielding boreholes such as in the Kruisrivier and Chatty regions. Generally, however, boreholes drilled into the Enon Formation in the study area have proved unsuccessful. In addition, the Enon Formation is not a preferred target for groundwater development, due to the difficulty of drilling in this formation - a function of the instability of the semi-consolidated material.

The occurrence of ephemeral springs issuing from exposures of Enon Formation sandstone (in the Kruisrivier area) after good rains, however, indicates a moderate exploitation potential for these sandstone units. It is suggested that boreholes could be drilled in this formation, equipped with slotted screen, and developed as a primary aquifer.

8.2. Kirkwood Formation.

The clayey argillaceous mudstones and siltstones of the Kirkwood Formation are considered to be an aquiclude for the purposes of this study (Section 5), due to their inherently very low permeability and porosity. The low permeability was confirmed by Maclear (1995) during the drilling project to install a groundwater monitoring network in the SRAA (Section 13). The interbedded sandstone units form the only aquifer in the Kirkwood Formation, but the water is typically brack in nature, making the groundwater generally unusable, except for stock-watering purposes.

The boreholes are mostly low-yielding (0.2ℓ/s) with groundwater being encountered exclusively in the sandstone layers and yields being proportional to increasing thickness and depth of the intersected sandstone layers.

8.3. Sundays River Formation

Due to its similar lithology to that of the Kirkwood Formation, the Sundays River Formation is also defined as an aquiclude. This definition was validated in a study by Parsons (1994) where a horizontal conductivity (*Kh*) of $1x10^{-5}$m/day was determined for the Sundays River Formation underlying the Aloes waste disposal site near Motherwell.

In rare occasions low yields, generally <1ℓ/s, may be obtained in the Sundays River Formation, where groundwater is struck exclusively in the interbedded sandstone layers.

8.4. Groundwater Temperature

The geothermal gradient in the Cretaceous sediments of the Uitenhage Group is generally low. In rare instances where economically exploitable occurrences of groundwater are found - mostly at depths of 150-350m - moderate groundwater temperatures of 19.5-23.5°C have been recorded.

9. GEOHYDROLOGY OF THE ALGOA GROUP AND RECENT DEPOSITS

9.1. Algoa Group

The sediments of the Algoa Group are generally thin and located above the water table on raised, wave-cut platforms, forming plateau deposits. They are also generally well-indurated (Le Roux, 1989) and impermeable, and these characteristics therefore result in the Algoa Group not being considered as a viable aquifer.

9.2. Alluvium

The alluvium of the study area comprises predominantly fluvial sand and gravel overlain by an overburden of silt and clayey soil. It has an average thickness of 10m (Maclear, 1995) and reaches a maximum thickness of 25m in the eastern portions of the estuary.

The alluvium lies on an impermeable basement of Kirkwood and Sundays River Formations and is locally exploited for groundwater from excavated seepage dams or "kuile", mainly in the Kruisrivier area.

Water-table contours of the alluvial aquifer (Map 6, page 78) indicate that the dry-season flow of the Swartkops River is maintained by base-flow from the alluvial aquifer, making the Swartkops River a gaining system (Maclear, 1993).

9.3. Sinters

Numerous ferruginous and manganiferous sinter deposits have been formed over Recent (Holocene) time by concentration and deposition at the water table, and by flowing artesian groundwater. An example of this is the 6m thick ferricrete deposit forming Amanzi Kop at Amanzi Estates (Coega Ridge Aquifer) formed by thermal artesian groundwater. These sinters are typically dark-brown/black, weathering to an orange powdery deposit.

10. COEGA RIDGE AQUIFER UNIT

The eastern portion of the Coega Ridge Aquifer Unit (CRAU) falls outside the boundary of the Swartkops River Basin. The artesian system's catchment, however, is a function of hydraulic pressure and is not necessarily the same as that of the surface drainage catchment boundary which defines the study area. A general discussion of the geohydrology of the CRAU is thus considered relevant.

10.1. Aquifer Geometry

The CRAU (Figure 6) occurs in the north-central portion of the study area and is 470km^2 in areal extent. The aquifer is comprised of quartz arenites of the TMG, which are overlain by impermeable mudstones and siltstones of the Uitenhage Group which form an aquiclude. The aquifer stretches from immediately west of the Uitenhage Springs, eastward along Coega Ridge to the coast. The steep (50°) northerly-dipping TMG-Bokkeveld Group contact to the north forms the northern boundary to this aquifer unit.

Inliers of more resistant TMG rocks form a series of prominent outcrops "windowing" along the CRAU from Sandfontein in the west to Coega Kop in the east and extending to Jahleel Island in Algoa Bay. These inliers are remnant peaks of an original mountain range formed by the Swartkops Anticline and pre-date the Coega Fault. The morphology of the palaeo-topography is very uneven due to pre-Cretaceous erosion of the TMG after uplift. The defined morphology of this land surface is based on lithological contact data from borehole logs (Figure 3).

The CRAU is economically significant as the source of the artesian groundwater at points of large scale abstraction, *viz.* Uitenhage, Sandfontein, Amanzi, Wells Estate and Coega Kop, where groundwater is used for irrigation of citrus (for export) and lucerne on the fertile silt of the Coega River flood-plain, as well as for domestic use, e.g. the Sutton Vallance borehole which supplies the railway town at Coega station.

A strong degree of hydraulic connectivity exists between the boreholes along the Coega Ridge (Section 10.5). The nature of this relationship is, however, unpredictable and is a function of the degree of interconnection of the water-bearing structures, as well as the differing depths of groundwater circulation.

The TMG is well-fractured, faulted and jointed in the CRAU as an effect of the folding during the Cape Orogeny which created cleavages and joints in especially the quartz arenites of the Peninsula Formation. The strikes of these structures are aligned roughly along a straight line paralleling the trend of the Southern Cape Fold Belt, e.g. the Coega Fault Zone (E30°S). There is an attendant orientation of high-yielding, artesian and sub-artesian boreholes along these regional strikes, as occurs along the CRAU (see section WNW1-ESE1 on Figure 3). Maclear and

Woodford (1995) also postulated a relationship between the line of high-yielding boreholes and the strike of the Swartkops River Anticline (Section 3.3 and Figure 4).

It should be noted, however, that the majority of original open fractures and joints have been infilled with white vein quartz. This infilling is a result of precipitation of silica out of solution with a decrease in temperature of the circulating groundwater as it nears the surface. The effect of this infilling is a reduction in the density of open fractures - the obvious drilling targets in a secondary aquifer. During the first half of this century, when most of the exploitation of the CRAU occurred, the unsuccessful drilling attempts far outweighed the successful attempts as the sparsely distributed fracture systems were missed. Geophysical techniques utilised as aids in identifying drill sites were only able to determine the thickness of the Cretaceous overburden and not the occurrence of the fracture systems. An example of the dependence of a successful borehole on secondary permeability is where the artesian flow of a borehole at Amanzi Estates was increased by 53% in 1927 by utilising the explosive method of borehole stimulation.

Marais (1965) logged the existence in places in the CRAU, of a palaeo-weathered zone a few metres below the TMG-Uitenhage Group contact. This weathered zone formed a major groundwater aqueduct. Most of the artesian groundwater, and subsequently many of the high-yielding boreholes were sited in this confined zone, although water-bearing fractures are encountered deeper into the basement. Marais (1965) also noted that the lower sandstone layers of the Cretaceous aquiclude are pressure-fed to some extent by groundwater from this underlying zone, resulting in small-scale water-strikes during drilling through the Cretaceous sediments. These water-strikes sometimes acted as a precursor to the main artesian strike in the weathered TMG basement.

In the CRAU, borehole yields vary from an average of 3ℓ/s in the TMG to 0.5ℓ/s in the Uitenhage Group.

10.2. Abstraction and Recharge

Recharge to this aquifer unit is from precipitation on the mountainous, high-rainfall catchment to the west. Groundwater flow within the TMS aquifer is east-south-eastward from the recharge area to the discharge area, below the confining Cretaceous sediments and into Algoa Bay.

The total artesian flow from the CRAU was almost halved in the period from the early 1900's to the 1960's, as a result of over-abstraction (Maclear and Woodford, 1995). The effect of this reduction in flow at the Uitenhage Springs, e.g. from 82ℓ/s at the turn of the century, to 35ℓ/s in the late 1950's, resulted in the call by the local farmers and residents for the declaration of a control area, since the Springs provided Uitenhage's main water supply at the time (Section 4.2). It is of interest to note that the major increase in boreholes drilled in the CRAU during the period mentioned above did not increase the total yield of the Unit, which remained relatively constant at 80ℓ/s, but rather increased the depth to the piezometric level. If anything, the yield from the Unit decreased slightly towards the end of the 1960's, as a result of increased leakage (through rusted borehole casings) of groundwater - under artesian pressure - into the confining Cretaceous sediments.

All groundwater samples analysed from the confined CRAU, in Venables' 1985 study, had zero Tritium, indicating that no recent recharge (last 40 years) has taken place. There is a recognisable trend of increasing ages of groundwater (from ^{14}C dating in Talma et al., 1982), with increasing distance eastward along the strike of the Coega Ridge. The age of the groundwater ranges from recent to 1500 years at the Uitenhage Springs immediately east of the recharge area, to 28 000 years at the Coega Kop discharge area (Heaton et al., 1986). From these dates, the flow-rate along the flow-path in the Coega Ridge Aquifer is calculated at 0.8m/yr.

Talma et al. (1982) estimated that less than 3% of the total recharge to the Coega Ridge Aquifer flows into the confined section of the aquifer, the remainder daylighting from springs at the edge of the recharge area (Section 12.2).

The total abstraction from the CRAU was reported to be 4.7Mm^3/yr (Bekker, 1989). This abstraction figure will be updated during the planned re-survey of the Uitenhage SGWCA, as outlined in Section 1.2.

10.3. Aquifer Parameters

The TMG sandstones and quartzites of the CRAU have storativities in the order of $2x10^{-4}$ and generally high but variable transmissivities (T) ranging from 50m^2/day to 400m^2/day. These variations in T are a function of the nature and extent of the fracture system intersected by the borehole tapping the aquifer. The T of the overlying Cretaceous formations, conversely, is only in the order of 5m^2/day (Venables, 1985).

10.4. Groundwater Quality

Analyses of groundwater from boreholes drilled into the TMG of the CRAU show this groundwater to be mildly acidic (pH 6-6.5) due mainly to the oxidation of pyrite in the TMG (Table 3). The TMG of the CRAU has a low TDS (av. 170mg/ℓ) due to the predominantly quartzitic, and hence inert, lithology of the aquifer host-rock.

Groundwaters in the overlying Cretaceous deposits and north-bounding Bokkeveld Group shales have a much higher TDS (averages of 5 100mg/ℓ and 3 300mg/ℓ respectively) due to the high percentage of clay minerals (efficient ion-exchange sites) in the argillaceous lithology. The low T of these deposits also results in high salinities due to higher residence times of the groundwater in the host-rock, as well as the connate property of the groundwater resulting from the marine-estuarine environment of deposition (Sections 5 and 5.1).

There is a progressive increase in alkalinity, as well as pH (from 4.5-5 in the recharge area to 6.5 in the discharge portion of the aquifer), indicating the very slow rate of solution of rock carbonate during recharge in the unconfined section of the aquifer. Carbonate solution only starts to occur in the confined eastern section of the aquifer, where the groundwater is no longer in chemical contact with the soil and atmospheric CO_2. As a result of the above, the groundwater in the recharge area is more corrosive to steel casing than in the eastern section.

10.5. Variations in Groundwater Levels and Artesian Conditions

There are no distinct correlations between recharge and groundwater levels and/or artesian flow in this aquifer unit. The artesian system is shown instead by Marais (1965), and Maclear and Woodford (1995), to be susceptible to pressure changes as a result of the drilling of new boreholes and subsequent increased groundwater abstraction activities. A further factor affecting flow from boreholes in the CRAU is the leakage loss of groundwater and the collapse of boreholes over time. Borehole collapse is a result of rusted steel casings and has contributed to a decrease in the artesian yield of the system.

Periods of short-duration, high-intensity precipitation have no effect on groundwater levels or artesian flow, and the direct effect of precipitation variation on artesian flow was considered by Marais (1965) to be an open and unanswered question. The large size and elongated shape of the catchment area, and distance between recharge and abstraction areas, also plays a role in diminishing the observable effects of rainfall recharge on hydrographs. Maclear and Woodford (1995), however, demonstrated the effect of long-term rainfall cycles on the artesian system, using the Cumulative Rainfall Departure (CRD) technique, detailed further in Section 12.2. A positive correlation between rainfall and artesian flow from the Uitenhage Springs (used as a barometer for the artesian conditions in the CRAU) was shown to occur only during periods of little or no abstraction from the artesian system. During periods of intensive abstraction, the effects of rainfall recharge were masked by man's exploitation of the aquifer.

It is of interest to note that natural rhythmic water level variations - in phase with the tides - were recorded by Marais (1965) for the confined aquifer system, as a result of the daily variation in gravitational attraction of the moon on the aquifer. These variations in gravitational forces result in micro changes in structure width and therefore variations in secondary permeability over a regional scale, which in turn affect piezometric conditions.

In the UAB, the total flow from the CRAU has remained constant at about 89ℓ/s and there has generally been no increase in the total artesian flow with an increase in number of boreholes drilled. Yield gained from new boreholes drilled has been at the expense of old boreholes, and the aquifer exploitation has resulted in an overall change in pressure gradient of the aquifer piezometric surface, from 0.002 in 1910 to 0.001 in 1980 (Figure 3). The borehole drilled at Amanzi Kop was a good indicator of changing artesian pressure in the CRAU where changes in the piezometric surface resulted in the need to lower the borehole collar over time (e.g. 4m in 1927), in order to maintain the free-flowing artesian conditions at the Amanzi borehole.

A further example of the regional effect of drilling on artesian conditions in the CRAU, from Marais (1965), is the following: In September 1950 a borehole was drilled at Motherwell 235m through the Cretaceous layers and into the TMG aquifer, where a free-flowing artesian yield of 23ℓ/s was obtained. The casing was poorly secured and the flow was unable to be contained or controlled. Within 2 weeks of drilling, the flow at Amanzi's borehole 10km to the west had decreased by 20%, and ceased to flow within 15 months; and within 1 month of drilling the Motherwell borehole, the flow at Uitenhage Springs had decreased by 4% and was reduced by a total of 28% from 1950 to 1954 (Figure 12).

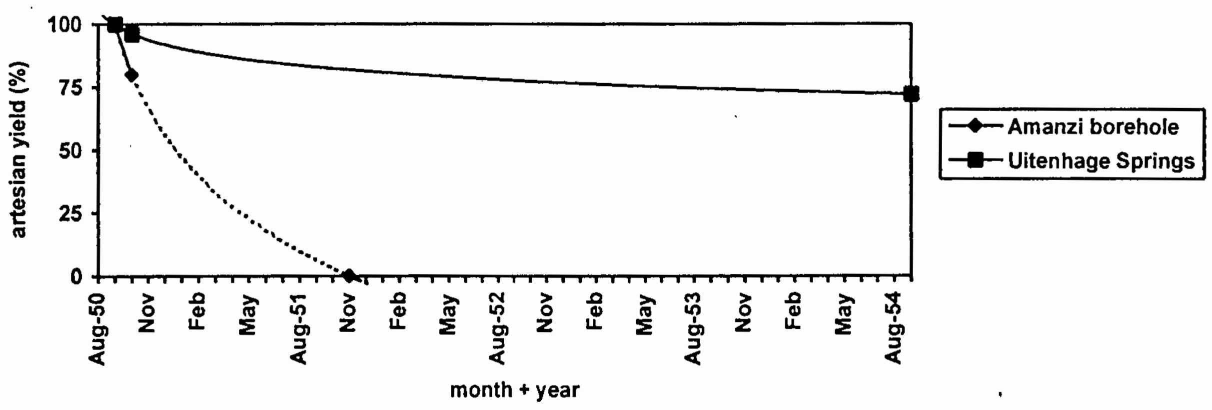


Figure 12: Reductions in free-flowing artesian yields caused by the drilling of Motherwell borehole (prior to lowering of the Amanzi borehole collar elevation).

11. SWARTKOPS AQUIFER UNIT

The Swartkops Aquifer Unit (SAU) has similar geohydrological conditions to the Coega Ridge Aquifer Unit, with the only major difference being the greater depth to the TMG aquifer - a function of a thicker overburden of Cretaceous sediments. As a result of the increased depth, the piezometric level and thus hydrostatic pressure is 100-120m lower than that of the CRAU.

11.1. Aquifer Geometry

The aquifer unit comprises the area south of the Coega Fault and stretches from Groendal Dam in the west to below Port Elizabeth in the east (Figure 6). The palaeo-topography of this region was much more subdued than that of the CRAU and formed a broad flat valley with its deepest part against the fault plane. From lithological information for the Zwartkops Spa borehole (detailed in Section 11.4) it is determined that the base of the SAU plunges from 140m AMSL at Groendal Dam, to 1 050m BMSL below the town of Swartkops.

11.2. Kruisrivier Compartment

The Kruisrivier Compartment forms part of the SAU (Figure 5 and Figure 6), lies immediately south of the Coega Fault and is located roughly central to the study area. It covers an area of about 110km², and the major aquifers of this Compartment are comprised of the basal arenaceous sandstone of the Kirkwood Formation, and the rudaceous Enon Formation conglomerate. The low permeability, Upper Kirkwood Formation mudstones and Sundays River Formation siltstones form the overlying aquiclude, and result in the artesian conditions experienced in this compartment. The aquifers in the Enon and Kirkwood Formation form one system but have different geohydrological properties (Table 5). Measured borehole yields range from 0.4-10ℓ/s in the Enon Formation conglomerate and basal sandstones, with maximum yields of 16ℓ/s having been measured (Maclear, 1993). The groundwater in the Kruisrivier Compartment is intensively utilised for the irrigation of vegetables (Orthophoto 2).

Table 5: Transmissivities of the formations in the Kruisrivier Compartment (Bush, 1985)

Geological formation	Lithology	Transmissivity (m^2/day)
Kirkwood Formation	sandstone	25-75
Kirkwood and Enon Formations	sandstone + conglomerate	40-50
Enon Formation	conglomerate	2-90

The pre-Cretaceous basement of the Kruisrivier Compartment is formed by competent and fractured TMG quartzites in the north and centre of the Compartment, and Bokkeveld Group shales in the south. The overlying Cretaceous strata of the Sundays River, Kirkwood and Enon Formations represent a lateral facies of sedimentological progression (east to west) from marine to estuarine to fluvial, with an interfingering contact (Section 3.6).

From Kruisrivier eastward the Enon Formation is overlain by sediments of the Kirkwood and Sundays River Formations, where the impermeable nature of these formations results in localised perched water tables. The Kirkwood Formation is geohydrologically significant as an aquifer in the palaeo-proximal area of the Kruisrivier Compartment only, since grain-size in this formation decreases dramatically with increasing progression eastward from proximal to distal facies. This results in decreasing permeabilities of the Kirkwood Formation, from west to east along the strike of the UAB.

Drilling is successful in the Kruisrivier compartment due to the relatively thin deposits of overlying Cretaceous sediments to be penetrated, before the TMG quartzites or the basal sandstone layers of the Enon Formation are intersected. Drilling success, however, decreases dramatically eastward as the thickness of the Cretaceous sediment package increases, requiring deeper, more expensive drilling.

11.2.1. Abstraction and Recharge

The mountain ranges of the Groot Winterhoekberge, Elandsrivierberge, and Groendal Forest Reserve to the west of the Kruisrivier Compartment comprise the recharge area to this compartment. The recharge areas are bounded by the relatively impermeable overlapping Enon Formation foothills to the north and northeast, and the impermeable Bokkeveld shale to the south. A TMG inlier immediately east of Kruisrivier (Searle Hill) forms a local recharge point to the southern and eastern portions of the Kruisrivier Compartment.

The total recharge to the Kruisrivier Compartment was calculated by Bush (1985) at 1.5Mm^3/yr from a recharge area of 68km^2 and assuming 5% of rainfall as recharge. As a result of observations by Marais (1965) that artesian pressure increases with increasing depth in the sandstone, it was deduced that there is no direct surface recharge to the artesian sandstone aquifer. Groundwater in the TMG aquifer (recharged by rainfall on the upper catchment) instead recharges the basal sandstone unit of the aquifers in the Kirkwood and Enon Formations by lateral flow and inflow to the sandstone unit from below. This observation was supported by findings in Bush (1985), where groundwater quality analyses, carried out during pumping tests on exploration boreholes in the Kruisrivier Compartment, showed that there was a decrease in salinity and an increase in acidity of the groundwater with increasing duration of the test. This was considered to be a function of progressively increasing contribution of groundwater from the TMG quartzites and decrease in groundwater derived from the overlying mudstone.

Enslin (1970) calculated the total abstraction from the Kruisrivier Compartment to be 0.9Mm^3/yr in 1963, i.e. over half the annual recharge to the aquifer. By 1965, Marais (1965) estimated that the abstraction from the Kruisrivier Compartment exceeded natural recharge, providing additional motivation for declaring the UAB a control area. In Bush (1985), a groundwater balance indicated that there was an annual deficit of recharge over abstraction of 1.8Mm^3.

As a result of stricter control, abstraction was reduced from 3.3Mm³/yr in 1985 to 2.1Mm³/yr in 1989 (Bekker, 1989) and by Maclear's (1993) hydrocensus, had decreased further to an annual abstraction of 1.3Mm³. A re-survey of the Kruisrivier Compartment (for this study) showed that abstraction had increased marginally from the 1993 rate to 1.7Mm³ in 1995 (Figure 13).

It should be noted that this latest rate of abstraction still exceeds the calculated recharge rate and represents a net loss of 0.2Mm³/yr of groundwater from the Kruisrivier Compartment. The author is of the opinion that the progressive reduction in abstraction in the Kruisrivier Compartment has not only been a function of better abstraction-control, but also an effect of the diminishing exploitation potential of the groundwater resource, as the storage component of the aquifer has been progressively mined-out.

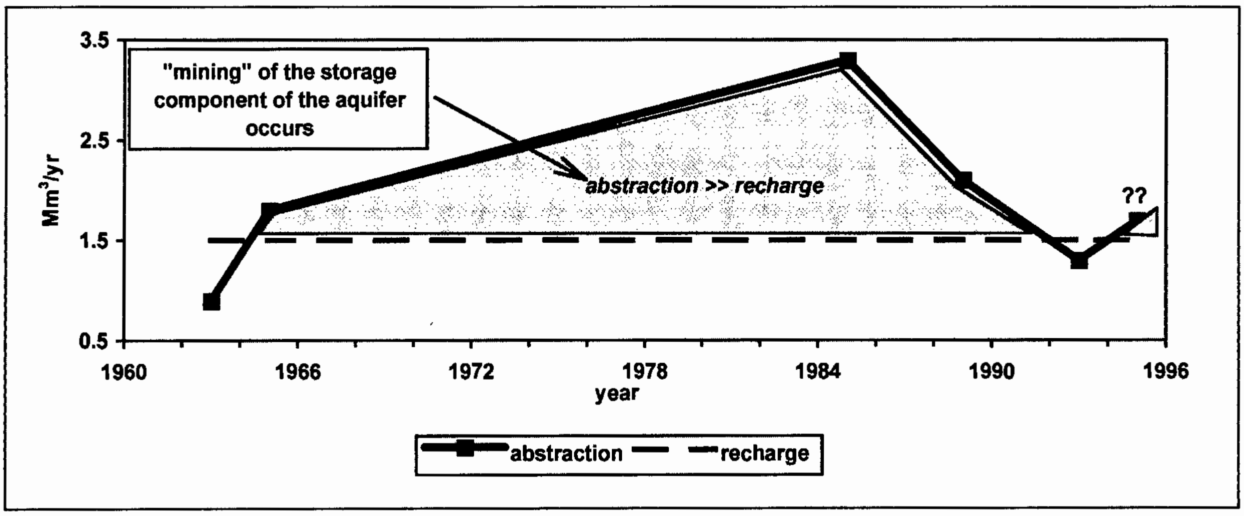


Figure 13: Abstraction versus average recharge - Kruisrivier Compartment.

11.2.2. Groundwater Temperature

From Kruisrivier, the groundwater flows eastward and northeast under the Cretaceous cover in the permeable basal sandstone layer, along regional joints and fracture and along the pre-Cretaceous palaeo-weathered zone. In an easterly direction the groundwater temperature increases from an average of 18°C in the vicinity of Kruisrivier to reach a recorded temperature of 54.5° at the now disused Zwartkops Spa borehole (Section 11.4). This increase in temperature is a function of increasing depth of groundwater circulation beneath the thickening Cretaceous formations with flow from the recharge to the discharge area.

11.2.3. Aquifer Parameters

The arenaceous Kirkwood Formation sandstones and rudaceous Enon Formation conglomerates have the highest transmissivity (T) in the Kruisrivier Compartment (Table 5). Transmissivity generally increases with depth as a function of facies changes in the stratigraphic column and, specifically, increasing thicknesses of sandstone encountered. In areas of the aquifer with a Bokkeveld Group sediment provenance instead of TMG (i.e. the southern portion of the Kruisrivier Compartment), the T is lower due to the higher clay content of the matrix and thus slower groundwater travel time. The groundwater storage component of the Kruisrivier Compartment is calculated at 540Mm^3, assuming a specific yield (Sy) of 5-8% for the aquifer.

11.2.4. Groundwater Quality

The Kruisrivier agricultural region is the most significant in the study area with respect to groundwater utilisation and abstraction (Map 6 page 78), and the general hydrochemistry of this area is thus outlined for reference purposes.

Large variations in the TDS values in the Kruisrivier area (100-11 000mg/ℓ TDS) were found by Bush (1985) to be a function of the varying ability of the water-bearing formations to transmit groundwater, thus resulting in variations in groundwater travel and residence times and dilution effects. The groundwater is generally good ("fresh" with TDS as low as 190mg/ℓ) in the rudaceous Enon and arenaceous Kirkwood Formations, and poor (saline) in the argillaceous members of these Formations (Table 6). Groundwater in this aquifer unit, in particularly the argillaceous Kirkwood and Sundays River Formation mudstones, was found by researchers such as Marais (1965), Bush (1985) and Maclear (1993) to be highly mineralised (with salinity increasing with depth), probably as a result of evaporite deposits formed in the shallow marine to estuarine environments of deposition of these Formations.

Table 6: The effect of source-rock on groundwater quality of the Kruisrivier Compartment (after Bush, 1985).

Geological Formation	Lithology	Palaeo-source	TDS (mg/l)
Kirkwood	mudstone	TMG	8800
	sandstone	TMG	370
	sandstone	TMG + Bokkeveld	4600
Enon	conglomerate	TMG + Bokkeveld	700
	conglomerate	TMG	200

Bush (1985) concluded that the Kruisrivier groundwater was of a diluted sea-water origin - the dominant cation and anion being Na and Cl, respectively. The high salinities, NaCl nature and depositional environment (Section 4) classifies this groundwater as connate, where recent rainwater is unable to penetrate to any significant depths through the confining sediments in order to dilute and "flush" the saline water.

High TDS concentrations in the Kruisrivier groundwater also result in regions where mixing of water derived from localised TMS outcrops and local Cretaceous formations occurs. From Table 6 it can also be seen that boreholes which abstract groundwater from an aquifer of mixed provenance have a higher salinity than those from a quartzitic provenance. The areas of Kruisrivier with low TDS concentrations, and therefore the areas of large-scale groundwater abstraction, correspond to areas obtaining their recharge from the Groot Winterhoekberge and Elands River Forest Reserve, rather than from seepage from the overlying clayey mudstones of the Uitenhage Group.

Johnstone (1982) found the Kruisrivier borehole water to be weakly acidic (av. pH of 6.1) and thus corrosive. The nitrate concentrations from groundwater samples of boreholes which penetrated the underlying secondary aquifer were expected to be high as a result of the agricultural activities in this area. They were found instead to be low and this is explained as a function of the origin and depth of the groundwater abstracted in this area, where the percolation of contaminated surface water into the confined aquifer is minimal due to the presence of the overlying impeding Uitenhage Group deposits. These findings are confirmed by the low NO_3 concentrations for most of the Kruisrivier samples analysed for the present study (Appendix C). Johnstone (1982) also found the silica concentrations to be low, even though the sandstones of the TMG - comprising the aquifer host rock - consist essentially of Si. This is a result of the relatively low pH of the Kruisrivier water, since Si concentrations in groundwater only increase above a pH of 9 to 11 (Hem, 1970).

Most of the Kruisrivier boreholes are cased for the first 30-50m to prevent hole collapse in the upper clay and mudstone deposits, as well as to case off the inferior quality water from these deposits. Most of these boreholes, however, are 30 to 60 years old and the casing is corroded and rusted as a result of the reducing conditions of the acidic TMS groundwater. This casing corrosion has resulted in mixing of groundwater from the Cretaceous and Tertiary lithologies with the deeper TMS aquifer under sub-artesian conditions; as well as the loss of good quality TMS groundwater to the overlying sediments under artesian conditions. In the former case there will be a deterioration in the quality of the TMS groundwater.

During the hydrocensus reported on by Maclear (1993), it was noted that groundwater samples taken from old boreholes drilled into the sandstone aquifer of the Kruisrivier Compartment generally had a high TDS. This was considered to be a function of mixing of saline groundwater from the overlying Kirkwood Formation mudstone with the deeper, fresher groundwater as a result of the rusted condition of the old borehole casings. The salinity of the groundwater was found by Bush (1985) to also be affected by the size of the recharge area, where TDS content is inversely related to recharge area. The borehole ME1 situated on the farm Mimosadale (Appendix A and B) is an example of this, where the saline groundwater is a function of low recharge from a small area, i.e. the TMS inlier east of Kruisrivier, *viz.* Searle Hill.

This effect of lithology on water quality is also apparent from a comparison of the salinities of the main tributaries of the Swartkops River, *viz.* the Elands (>200mg/ℓ TDS) and Kwa-Zunga Rivers (<200mg/ℓ TDS). Maclear (1993) showed that water salinity was relatively high in the Elands River - which drains a predominantly shale catchment, compared with lower salinities for the Kwa-Zunga River which flows through a quartzitic catchment. Downstream of the confluence of these tributaries, the salinity of the Swartkops River water, however, becomes influenced by pollution rather than natural salinity (Section 16).

11.2.5. Variations in Groundwater Levels and Artesian Conditions

As a result of the building of numerous small farm storage dams in the upriver portions of the Elands River, mainly in the first half of the century, the flow of the river declined. This factor, together with the introduction of turbine pumps to the area, was the main catalyst which resulted in an increase in the number of boreholes drilled and concomitant increased pumping rate from the Kruisrivier Compartment in the period 1910-1960. This ultimately resulted in a change from artesian to sub-artesian conditions in the area, similar to the effects noted in the CRAU (Section 10.5). This change was manifested by an average drop in the piezometric level over the Kruisrivier area of 30m, i.e. a 0.5m/yr rate of lowering of the level for that period (Reynders, 1987). It is difficult to accurately measure present piezometric surfaces in the aquifer, due to pressure loss through leaking borehole casings, although a pressure gradient of 0.0004 was reported in Marais (1965). This very flat gradient indicates the possibility of sea-water intrusion, due to abstraction likely exceeding recharge, especially if the gradient is locally reversed in the Kruisrivier Compartment in the future.

With continuing abstraction of groundwater in excess of recharge from this compartment (11.2.1 and Figure 13), there will be a further progressive decline in piezometric levels. If this decline is allowed to continue unchecked, the water-levels will eventually drop below the confining layer. The aquifer will then become phreatic (or unconfined), and artesian conditions will cease to exist. In the interest of all the users of the aquifer, this must not be allowed to occur, and it is hoped that the re-survey of the UAB will provide a tool for better future management of the presently over-exploited Kruisrivier groundwater resource. Additional aquifer management recommendations are discussed further in Section 19.

The lowering of the piezometric level in the Kruisrivier Compartment, although dominant in the long-term, is not a continual process, since local small-scale rises in water-levels are recorded after significant recharge events. The water-level recoveries are a function of temporary reductions in the requirements for irrigation water in the area after heavy rains, when the aquifer is allowed time to recover to equilibrium levels during periods of lowered or no pumping. This again indicates that abstraction has an overriding effect on water levels and artesian flow, as discussed in Section 10.5. The overall lack of recent water-table, artesian flow and groundwater abstraction records, however, makes any correlation between recharge and water levels difficult.

11.3. Bethelsdorp Compartment

The Bethelsdorp Compartment is located in the SAU on the southern margin of the UAB; and is bounded by the Cape Supergroup outcrop to the south, the Elands River Forest Reserve and Groot Winterhoekberge to the west, the shale-filled syncline to the north and Algoa Bay to the east. The major aquifer in the Bethelsdorp Compartment (Figure 6) is situated beneath the low-lying foot of the Bethelsdorp escarpment in the fractured TMG quartzites, which are overlain by low-permeability, confining layers of the Bokkeveld Group sediments (Figure 4). Where the TMG aquifer is absent, the arenaceous Kirkwood Formation sandstone and the rudaceous Enon Formation conglomerate are considered as the aquifer, with the argillaceous Kirkwood Formation mudstone acting as the aquiclude.

The Bethelsdorp Compartment is under utilised compared with the Kruisrivier Compartment, is artesian to sub-artesian in places, and has not been a focus of intensive study in the past. Boreholes of variable, moderate yields can be drilled with some degree of success. The boreholes drilled into this compartment are relatively shallow (25-200m) with the highest yields being obtained from boreholes which first penetrate the confining Bokkeveld Group before intersecting TMG quartzites, thereby resulting in artesian conditions, with a general increase in yield with an increase in depth of TMG penetrated (Marais, 1965).

11.3.1. Abstraction and Recharge

Groundwater recharge to the Bethelsdorp Compartment is from precipitation on the TMG sandstones and quartzites outcropping along the St. Albans Terrace west of Port Elizabeth. The yield of the compartment is reduced in those regions of the aquifer with limited exposed areas of recharge.

The Bethelsdorp Compartment was initially exploited, mainly in the 1940's, as a water supply for the increasing population settling in the area. Moderate yields of 1-4ℓ/s were obtained by drilling through about 150m of Cretaceous sediments into the TMG. The increased urbanisation into previously agricultural areas enveloped the boreholes and resulted in a reduction in groundwater abstraction from this compartment.

The TMG sediments in the Bethelsdorp Compartment dip northwards and are isolated from the Kruisrivier Compartment by the confining unit of the Bokkeveld Group infill to the Elands River Syncline (Figure 4). Any possible increase in groundwater abstraction from the Bethelsdorp Compartment in the future (for domestic supply-augmentation purposes) will, therefore, have no effect on the storage of the economically more significant Kruisrivier Compartment.

11.3.2. Groundwater Quality

The groundwater quality in the Bethelsdorp Compartment is good, having an average TDS of 500mg/ℓ in the TMG. The Bokkeveld Group shales, which bound the Bethelsdorp Compartment to the north and northwest, have poor quality, brack water. The Kirkwood Formation mudstones forming the aquiclude to the north-eastern portion of the Bethelsdorp Compartment, contain highly saline groundwater with an average TDS of 30 000mg/ℓ (Section 8.2).

11.3.3. Variations in Groundwater levels and Artesian Conditions

Abstraction in the Bethelsdorp Compartment decreased from 0.8Mm³/yr in 1961 to 11 500m³/yr in 1985 (Bush, 1985). Maclear (1993) reported an abstraction rate of about 10 500m³/yr, with the "abstraction" being from 4 very weak artesian boreholes flowing to waste. The decrease in exploitation of the Bethelsdorp Compartment, as described above, was accompanied by a gradual 5m recovery in piezometric levels in the period 1967-1982 (Bush, 1985). This again illustrates the inter-relationship between abstraction and recharge in the confined secondary aquifers of the study area (Sections 10.2 and 11.2.1).

11.4. Zwartkops Spa Borehole

A discussion of the Zwartkops Spa borehole is considered relevant, since this famous borehole (location shown on Figure 6) provides the only geohydrological information available for the deep discharge portion of the SAU in the east of the study area; and also provides structural and lithological data for this part of the UAB.

After the formation in 1906 of a small oil exploration company, the purchase of a drill rig and the employment of professional drillers from the oil-fields of Poland, drilling began in 1908 on a borehole for oil. The borehole was located in the Swartkops River valley on the northern outskirts of Port Elizabeth. The borehole was drilled to a final depth of 1 082mbs, or 1 075m BMSL; where drilling ceased when scalding thermal (54.5°C) artesian groundwater, flowing at a rate of 13ℓ/s was struck. The upward pressure of the artesian groundwater balanced the total weight of the drill string, and drilling had to cease in 1909 in a hard sandstone. The artesian flow of the Zwartkops Spa borehole is associated with a regional fault of similar character to that of the Coega Fault (Section 3.3.1). As the achievements obtained during the drilling of this borehole were exceptional for that time, a summary of borehole and drilling details as well as the pictorial borehole log are given in Appendix E, for interest and reference purposes.

The sandstone encountered at final depth was of uncertain geological origin since, although chip samples were obtained on surface for logging, the sample was mixed and ground. Argument occurred between the geologists who logged the hole as to whether the sandstone was of a TMG or Bokkeveld Group origin (see geological profiles through the Zwartkops Spa borehole in Figure 3 and Figure 4).

Kent (1949) proposed that the thermal water was struck in weathered Bokkeveld Group sediments - which act as the aqueduct - whereas the groundwater was derived from the underlying TMG sediments. Kent (1949) further maintained that since the Zwartkops Spa borehole water is more mineralised than the Cape System thermal spring average, this indicates the groundwater to be of a mixed origin, i.e. TMG, Bokkeveld Group and Cretaceous. The author concurs with this opinion of a mixed source of the groundwater, since the hydrochemical nature of the groundwater indicates it to be a mixed sample of at least two major rock types: high Fe typical of TMG, but relatively high TDS (560mg/ℓ) indicative of Bokkeveld Group (Section 7.1).

Due to the reported medicinal properties of the artesian groundwater, a hotel and health spa was built up around the borehole, *viz.* the Zwartkops Spa. The claimed medicinal properties were a function of the high Fe content and hypotonic nature of the groundwater, which was used consumptively, mainly in the treatment of anemia. The Zwartkops Spa subsequently became one of the leading resorts of its type in the country. In 1965 the borehole became disused as the steel casing rusted through and groundwater subsequently leaked - under artesian pressure - into the Cretaceous sediments and overlying surficial alluvial deposits. The surface expression of this leakage loss from the UAB was the formation of a vlei, 0.5m deep around the hotel.

The Zwartkops Spa borehole was subsequently sealed by grouting (in 1969) as a result of this loss of groundwater from the SAU (estimated in Brown, 1972 at 410 000m^3/yr). Since the borehole was located within the Uitenhage SGWCA and it was (and still is) the DWA&F's responsibility to eliminate unnecessary losses of artesian groundwater from the UAB, the sealing of this borehole was carried out by the Drilling Division of the Department.

There has since been recent renewed interest in reopening the Spa - but this has obvious financial implications since the borehole would have to be re-drilled and reamed down to the original depth in order to obtain the same thermal artesian conditions. The cost of drilling and equipping such a borehole today, would amount to at least R0.25M - making it an improbable project at the outset.

11.4.1. Hydrochemistry

The Zwartkops Spa borehole water was classified as *chalybeatic* (<Gk *chalyps* = steel / *khalkos* = metallic), i.e. metalliferous, due to its high Fe, Mn and P content (hydrochemical breakdown presented in Appendix E). The oxidation of the dissolved Fe and Mn bicarbonate to hydrated oxides of Fe and Mn produced a flocculant in the water which formed a brown-yellow ochre deposit in overflow channels leading from the Spa. The moderate acidity of the thermal water - the cause of the corrosion of the steel casing - was a result of dissolved CO_2.

11.4.2. Origin of Thermal Groundwater

Due to the absence of Recent or Tertiary igneous activity in SA, the origin of all thermal springs and artesian boreholes is explained by continuously circulating localised convection cells where meteoric recharge water descends, via structures, to depth. This groundwater then aquires terrestrial (geothermal) heat and the heated water returns to surface, discharging at a rate which is fast enough to prevent significant loss of the naturally acquired heat.

The thermal properties of the TMG aquifer host-rock - tapped over a 50 year period by the Zwartkops Spa Borehole - are a result of an increase in groundwater temperature with depth. This temperature increase is a function of the geothermal gradient of the host-rock, as well as residual heat from the structural deformation (specifically Mesozoic folding) which the Cape Supergroup underwent.

11.4.3. Groundwater Temperature of the Zwartkops Spa Borehole

A literature survey by the author has indicated that to date, there has been no systematic country-wide survey of geothermal gradients for different rock types - with studies having been related mostly to the mining industry, and subsequently concentrated around the Witwatersrand Basin. Specifically, there have been no studies on the geothermal gradient in the Cretaceous sediments. The effect of the Uitenhage Group on the underlying TMG aquifer in the SAU is uncertain with respect to the groundwater temperature in the aquifer. It is proposed that in the absence of more specific data, the geothermal gradient of the Karoo sediments, i.e. 25-30°/km, or 0.027°C/m (Jones, 1992), be taken as representative for the Cretaceous sediments, which display similar sedimentological and lithological characteristics.

The movement of groundwater through fractured rock is recognised by Jones (1992) to be the most important environmental factor which reduces the actual geothermal gradient. It can, therefore, be expected that the actual geothermal gradient in the UAB - a geological unit in which significant flow of groundwater takes place - is steeper than that inferred from the temperature of thermal groundwater, since this flowing groundwater has cooled the aquifer host-rock. It is also significant to note that the thermal property of the Zwartkops Spa Borehole water represented an integrated temperature over the full depth of the circulation profile, where waters of different temperature originating from various depths were mixed, with flow of the groundwater to surface.

Moderately thermal groundwater was first struck from 300-800m in the Zwartkops Spa Borehole, with no indication that there would be a dramatic increase in groundwater temperature with depth. At about 1 050mbs, however, artesian groundwater flowing at 2ℓ/s and at a temperature of 40.5° was encountered, increasing to a temperature of 54.5°C at the final drilled depth of 1 082mbs.

This indicates that groundwater temperature does increase as a function of depth in the Cretaceous, but that the temperature is rather influenced by the characteristics of the water-bearing formation and structure intersected, and specifically the circulation depth of the groundwater in the aquifer.

The depth of groundwater circulation for this part of the SAU can be calculated from the following equation (after Bredenkamp et al., 1995):

Equation 1 : Depth of groundwater circulation from geothermal gradient.

$$\boxed{D_{av} = \frac{T_{bh} - T_{ambient}}{Gt_{gradient}}}$$

where: D_{av} = average depth from which groundwater originates (m)
T_{bh} = temperature of borehole water (°C)
$T_{ambient}$ = temperature of shallow groundwater or surface average (°C)
$Gt_{gradient}$ = geothermal gradient (°C/m).

From Equation 1, the depth of circulation (D_{av}) of the Zwartkops Spa borehole is calculated at 1 330m ; using $T_{bh} = 54.5°C$, $T_{ambient} = 18°C$ from isothermal map of Port Elizabeth area, and a $Gt_{gradient} = 0.027°C/m$.

According to this calculated depth of circulation, the groundwater that fed the Spa borehole originated from at least 250m deeper than the depth of the thermal water-strike. This illustrates the structural complexity of the Swartkops River Basin and the effect this has on the groundwater circulating conditions within the fractured secondary aquifer, as outlined in Section 10.2.

12. SPRINGS

Numerous ephemeral springs occur in the study area, in the Brakkefontein region as well as the deep kloofs of the upper Kwa-Zunga and Elands River valleys (Map 5 and Appendix A). These springs only flow after heavy rains, with the yield and consistency of flow increasing eastward as the catchment area to the springs increases. The springs daylight almost exclusively from the TMG outcrops, although groundwater has forced its way - under artesian pressure - through thin Cretaceous layers, e.g. at Amanzi Estates, to flow on the surface as natural springs.

Most of the springs - from which farms in the study area originally derived their names, e.g. Brakkefontein, Boschfontein, Springfield - have since dried up as a result of drilling activities which have lowered the piezometric surfaces (Figure 3 and Figure 14). This reaction of the springs to man's drilling activities indicates the high degree of hydraulic connectivity between the water-bearing structures within the artesian aquifer units. These springs are structurally controlled, long narrow fractures and fissures acting as aqueducts for the groundwater, with the springs emerging mainly at topographic lows.

Perennial springs occur at places in the study area along the CRAU from the renowned Uitenhage Springs (Section 12.2) westward to Sandfontein, as well as in the Kruisrivier Compartment of the SAU. These springs have been used as a water supply for settlers in the region since the early 1800's, and fossils and artefacts found during cleaning of numerous springs in the study area indicate that the springs have been a source of water for early inhabitants since at least the Tertiary times.

12.1. Groundwater Quality

Springs rising from the quartzitic sandstone of the TMG are all excellent quality (TDS <200mg/ℓ), acidic, and generally contain dissolved Fe and Mn which precipitate on oxidation when the groundwater daylights at the eye of the spring. The mineral content of the TMG springs increases from west to east (i.e. from recharge to discharge). Strontium (a common element in sedimentary rocks) is the most abundant minor cation and the presence of boron indicates juvenile water (Hem, 1970).

The gas emitted from the springs in the study area consists chiefly of nitrogen, i.e. air from which most of the oxygen has been removed by reactions with the minerals in the host-rock through which the groundwater passes along its travel-path from the recharge area to the eye of the spring.

12.2. Uitenhage Springs

The Uitenhage Springs (Plate 8) lie between ridges of TMG sandstone at the foot-hills of the Groot Winterhoekberge within the Swartkops River catchment, and are located on the cadastral farm Sandfontein 291, approximately 8km north-northeast of Uitenhage (Map 5 and Figure 3)

Stone-age artefacts and a pre-historic mammal tooth found at the present-day Uitenhage Springs, as reported in Hickson (1989), indicate that the eyes have been a constant supply of water to early inhabitants for at least 200 000 years. In the middle 1960's the Springs supplied 25% of Uitenhage's water and presently supply about 15% of Uitenhage's bulk water requirements (Maclear and Woodford, 1995).

The raw water quality is excellent with an EC of 14.5mS/m and a sodium-chloride character (Figure 10). The average age of the spring water is 1580 years based on ^{14}C dating presented in Talma et al. (1982).

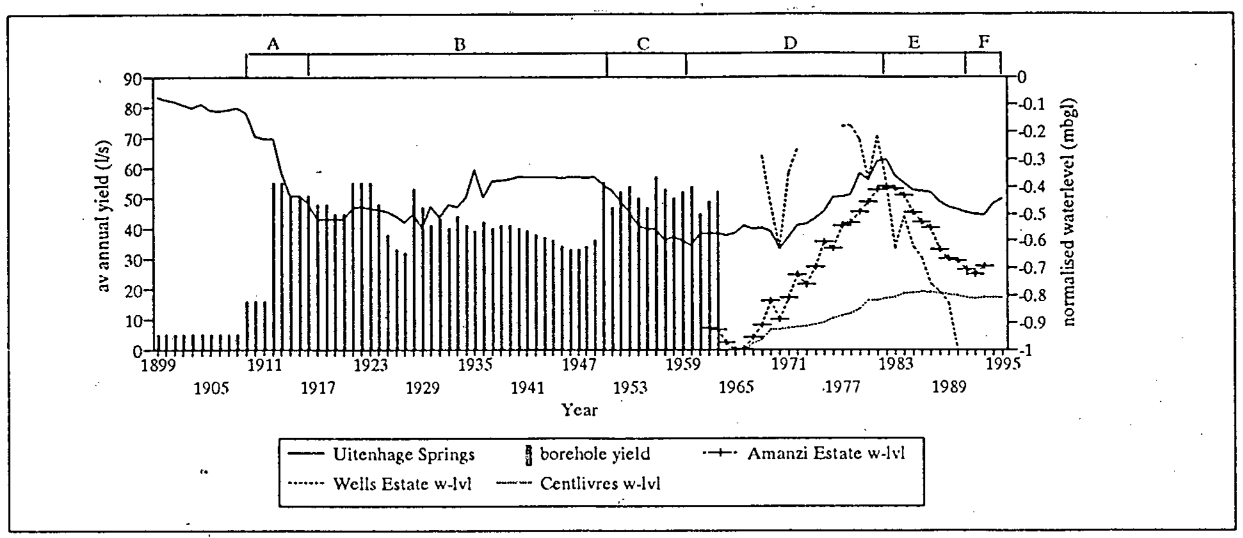
The Uitenhage Springs occur on the W margin of the UAB within the CRAU, where they mark the boundary between confined groundwater conditions to the east and unconfined conditions to the west. At the Springs, the groundwater daylights from 9 eyes at the Table Mountain- Uitenhage Group contact, where the Kirkwood Formation of the Uitenhage Group overlaps the Peninsula Formation of the TMG. These eyes lie along a 120m N-S seepage front, conforming to the strike of this contact.

The Uitenhage Springs mark the western extent of large-scale groundwater abstraction within the CRAU. The reason for the geohydrological characteristics of the Springs is not fully understood (Mountain, 1955) although Maclear and Woodford (1995) propose a structural control, *viz.* a zone of tensile fracturing associated with the stress regime in the axial plane of the Swartkops River Anticline (Section 3.3). This zone forms a natural conduit, in which groundwater is under artesian pressure as a result of the confining overlapping deposits of the Uitenhage Group to the east of the Springs (Figure 3).

12.2.1. Variations in Spring-flow

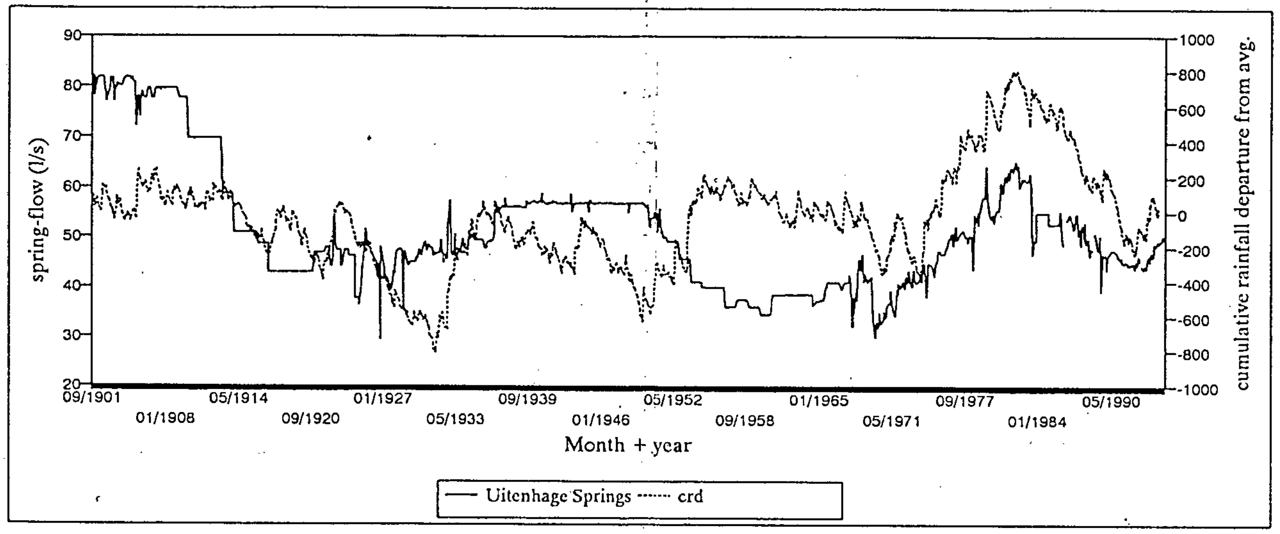
Hickson (1989) records that in 1773 the total yield from 20 different eyes was estimated at 105ℓ/s, whereas in 1829 this flow had decreased to 80ℓ/s. The first official and reliable gauging was in 1867 when a flow of 89ℓ/s was recorded. Since 1899, artesian flow at the Uitenhage Springs has decreased by 40% to its present day flow rate of 45ℓ/s (Figure 14a and Figure 14b); with variations of 10-20% about the mean annual flow rate of 52ℓ/s (Maclear and Woodford, 1995).

Figure 14: Factors affecting flow variation at Uitenhage Springs, 1899-1994 (from Maclear and Woodford 1995).

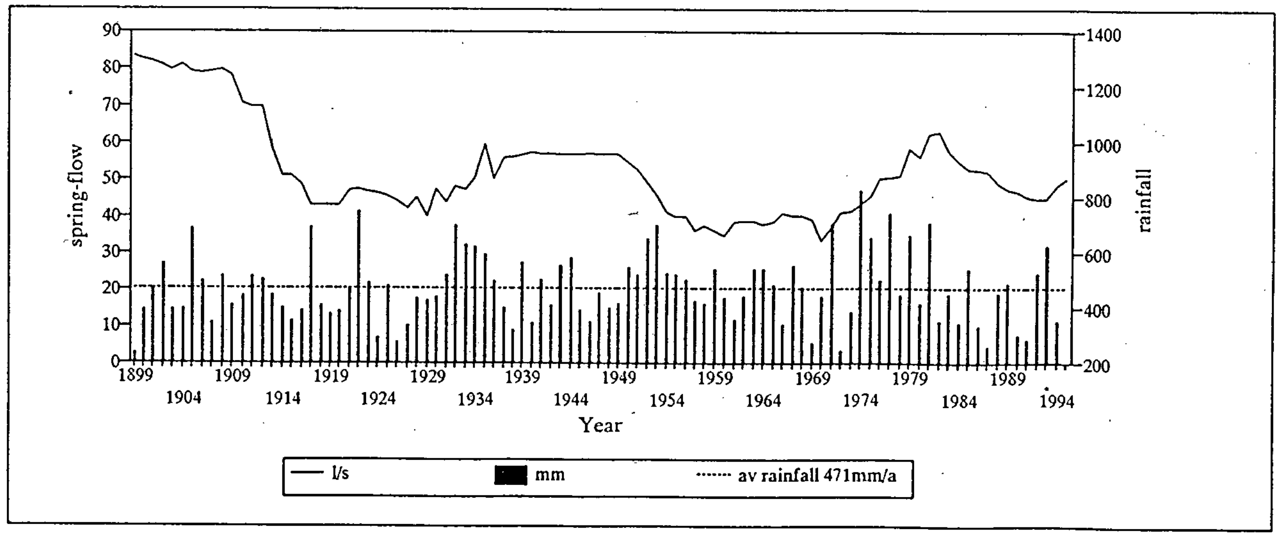


A	1909-1916	Uncontrolled drilling increases abstraction from 16ℓ/s to 55ℓ/s at Amanzi. Number of boreholes increases from 4 in 1909 to ±25 in 1912.
B	1916-1950	New boreholes continually drilled at Amanzi and Sandfontein to replace old boreholes which dried up as a result of over-abstraction.
C	1951-±1960	Large-scale abstraction from artesian boreholes drilled at Motherwell, Coega Kop + Wells Estate.
D	1960-1982	Reduced abstraction as a result of declaration of Uitenhage SGWCA in 1957.
E	1983-1992	Increased abstraction as a result of drought.
F	1993-present	Spring-flow recovery considered to be result of DWA&F program of sealing of old artesian boreholes (pers. comm., Venter 1995).

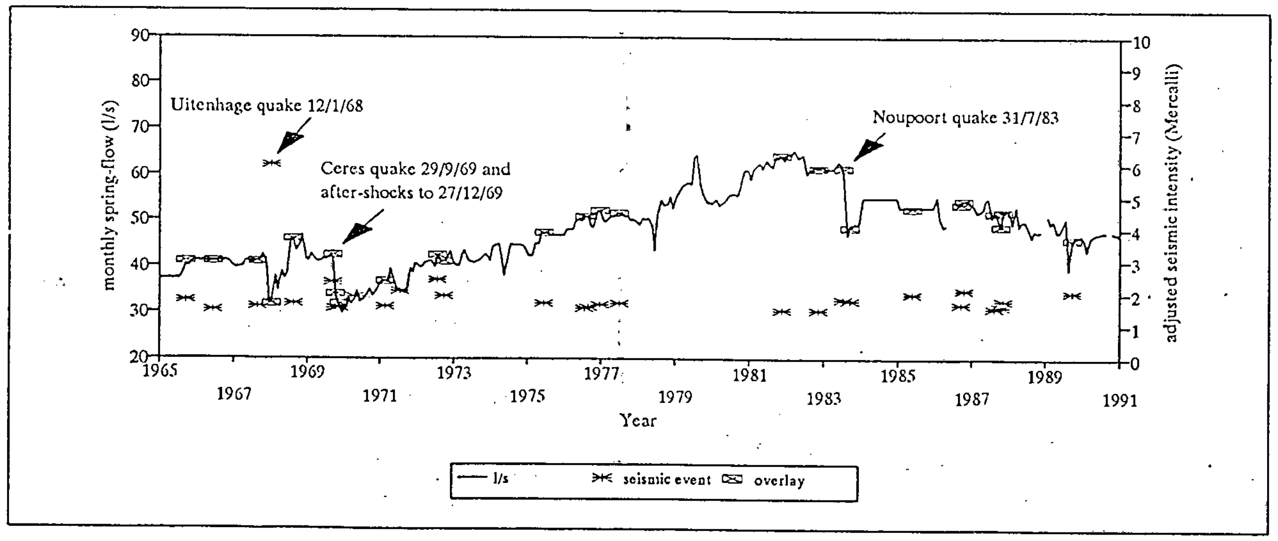
14a: The effect of drilling and groundwater abstraction on spring-flow variations.



14c: Spring-flow variations compared with the cumulative rainfall departure (crd) curve.



14b: Variations in spring-flow and rainfall with time.



14d: The effect of seismic events on spring-flow for the period 1965-1991 (overlay position of seismic event shown on spring-flow graph).

Maclear and Woodford (1995), conducted a study on variations in flow at the Uitenhage Springs over a period spanning almost a century (1899-1994), in order to gain a better understanding of factors which affect and control variations in geohydrological conditions in the CRAU. Flow variations were compared with abstraction and drilling history in the UAB (specifically the CRAU), rainfall and seismic events, in order to assess the order and degree of these effects on flow variations.

From Figure 14a the effect of abstraction on spring-flow is clearly illustrated, where periods of increased drilling activity and subsequent higher abstraction from the CRAU, resulted in an equivalent decrease in spring-flow for the same period. Generally, no strong correlations were found between spring-flow and rainfall. These findings were supported by Marais (1965), although he stated that such a relationship would be expected, given the geohydrological and topographic conditions existing in the area. Talma et al. (1982) stated that the relatively young age of the spring-water indicates that discharge may be subject to short- to medium-term fluctuations in rainfall. It was considered by Maclear and Woodford (1995) that any correlation which may exist between spring-flow and rainfall is masked by the effect of large-scale abstraction from the CRAU.

During periods of reduced abstraction from the aquifer, it could be expected that spring-flow may reflect rainfall variation. By plotting the cumulative rainfall departure (CRD) curve of the average monthly rainfall against spring-flow (Figure 14c), no strong correlation between rainfall and spring-flow was found for the whole study period; however, from the middle-1960's onwards, a good correlation was found to exist. This was considered by Maclear and Woodford (1995) to reflect the natural relationship between recharge and spring-flow. For example, in period D (Figure 14a), reduced groundwater abstraction from the CRAU - after declaration of the control area - resulted in a recovery of flow rates at the Uitenhage Springs. This again illustrates the remarkable degree of hydraulic inter-connectivity within the separate aquifer units in the study area. Maclear and Woodford (1995) further determined that the long-term yield of the CRAU remains constant at about 90ℓ/s, irrespective of the number and yield of groundwater abstraction points. These findings are supported by Marais (1965), Talma et al. (1982) and Venables (1985).

Seismic activity was also determined by Maclear and Woodford (1995) to have an effect on flow rates at the Springs. A total of 53 seismic events with a calculated hypocentre intensity at Uitenhage of greater than 1.5M (modified Mercalli scale) occurred during the study period. Of these, only three events (>2M hypocentre intensity) appeared to have had an obvious effect on spring-flow. All the events of note, with the exception of that of 12/1/1968 (Figure 14d), resulted in a rapid decrease in spring-flow immediately after the event. The Ceres earthquake of 1969, for example, caused an immediate reduction in spring-flow of 10ℓ/s in the month of the disturbance, with a gradual increase to the pre-earthquake flow by 1973, i.e. a four year recovery period. These effects on spring-flow were considered by Maclear and Woodford (1995) to be a result of a rapid pressure release within the UAB during seismic activity, caused by elastic deformation of the host-rock which results in the development and/or dilation of structural features.

Once the shock waves have passed, the openings reduce in size to their pre-shock state, and the artesian pressure returns gradually to a state of equilibrium. In this way, spring-flow records could be used to some extent as a type of seismic barometer in the absence of conventional seismic records.

In conclusion it was determined that the Uitenhage Springs act as very useful and reliable constant-level monitor of changes in the hydrostatic pressure in the confined section of the CRAU. The study by Maclear and Woodford (1995), emphasised the vulnerability of an artesian aquifer to over-exploitation, where the only effective method of ensuring the long-term sustainability of the resource is to implement a management system based on joint utilisation and control by the local users. The following factors were ranked in order of degree of decreasing effect on the Springs:

- Increased abstraction from the CRAU for irrigation purposes had the main reducing effect on spring-flow.
- The effect of rainfall on spring-flow was long-term but generally masked by man's activities.
- A small number of seismic events resulted in a marked temporary reduction in spring-flow.

12.2.2. Groundwater Quality

The quality of the Uitenhage Springs groundwater is excellent and is suitable for drinking in its raw form (Table 4 and SP1 in Appendix B). The spring water is very soft and its low Fe content also makes it non-corrosive to metal pipelines. The low F and Ca content of the groundwater, however, would require blending with surface water, or F and Ca addition (in order to avoid tooth decay and the development of a weak bone structure, which would occur with time) if this groundwater was to be used as a sole supply.

The hydrochemistry of the Uitenhage Springs has remained constant over at least a half century of detailed analyses. The bubbles rising continually to surface at the numerous eyes are due to the release of N gas, dissolved in the water, with a pressure change as the groundwater is discharged on surface.

12.2.3. Groundwater Temperature

The temperature of spring water can be used in conjunction with the local geothermal gradient to indicate the depth of circulation of the groundwater in an aquifer (Equation 1, Section 11.4.3).

The temperature of the Uitenhage Springs groundwater is on average 23°C, which classifies it as hypothermal (20-25°C from Kent, 1969). The groundwater temperature also remains constant over time, which indicates a constant depth of circulation. Assuming a geothermal gradient of 0.027°C/m for the quartzitic TMG host-rock to the spring-water (from Jones, 1992) and an ambient temperature of 18°C (from Section 11.4.3), the average depth of circulation of the Uitenhage Springs groundwater is determined at 250m. By way of example of the varying depths of circulation of the groundwater cells in the CRAU, thermal artesian groundwater from the Amanzi borehole, 8km to the east of the Springs (Figure 3), has a calculated depth of circulation of 800mbs. The very different chemical character of this water, compared with the Uitenhage Springs, also indicates a different geological origin with probable mixing with Bokkeveld Group deposits (due to the high Fe and Mn content and higher salinity than the Springs water).

13. SWARTKOPS RIVER ALLUVIAL AQUIFER

The Swartkops River Alluvial Aquifer (SRAA) occurs in the central and eastern regions of the study area where alluvial deposits of gravel, sand, silt and clay unconformably overlie the Cretaceous formations. This aquifer forms the least significant of the two major aquifer types (referred to in Section 4) from the aspect of groundwater volume, but is nevertheless considered as highly relevant to the study, since it is the most vulnerable of the two aquifers to pollution.

Only a few very localised studies on the SRAA have been conducted to date and as a result the knowledge base on the geohydrology of the primary alluvial aquifer in the Swartkops River Basin has been very limited, until the recent DWA&F drilling project to construct a monitoring network and carry out tests on this aquifer. The results of this project, including experiences gained on network design and drilling difficulties in the alluvial material, are presented in Maclear (1995), and the data obtained in this report, relevant to the present study, is summarised below to describe the geohydrological characteristics of the SRAA.

13.1. Aquifer Geometry and Conceptualisation

There is a marked and expected lateral alluvial facies change with distance down-drainage in the portion of the Swartkops River Basin underlain by alluvium. The proximal portion of the trough was filled with a predominantly coarse-grained, unconsolidated assemblage of boulder and gravel beds. With increasing distance eastward down the depositional slope, away from the sediment source, there is a progressive reduction in grain size of the fluvial deposits, from a coarse gravel bed in the Kruisrivier area (Plate 9), to a fine-grained shelly sand at Redhouse (borehole G40040 in Appendix F).

During the drilling project to install a groundwater monitoring network, Maclear (1995) found that the drilling depth was generally shallower (av. 10m), and the coarse alluvial package was thinner (av. 3.5m) than was originally expected from field observation and initial hydrocensus data presented in Maclear (1993). The boreholes were drilled using the ODEX simultaneous-casing emplacement method and the pictorial borehole logs are presented in Appendix F. The location of the monitoring network on the SRAA is shown on Figure 15 and a lithological longitudinal-section through the alluvial aquifer, from Kruisrivier in the west to Redhouse in the east is shown in Figure 16.

13.1.1. Alluvium

The alluvial package intersected during the drilling project occurs as a poorly-sorted, oligomictic, pebble to boulder deposit in a sand (and occasionally clayey) matrix, lying unconformably as a basal lag on a mudstone and siltstone bedrock. Field observation of these deposits in raised fluvial terraces show them to be clast-supported and loosely-packed (Plate 4).

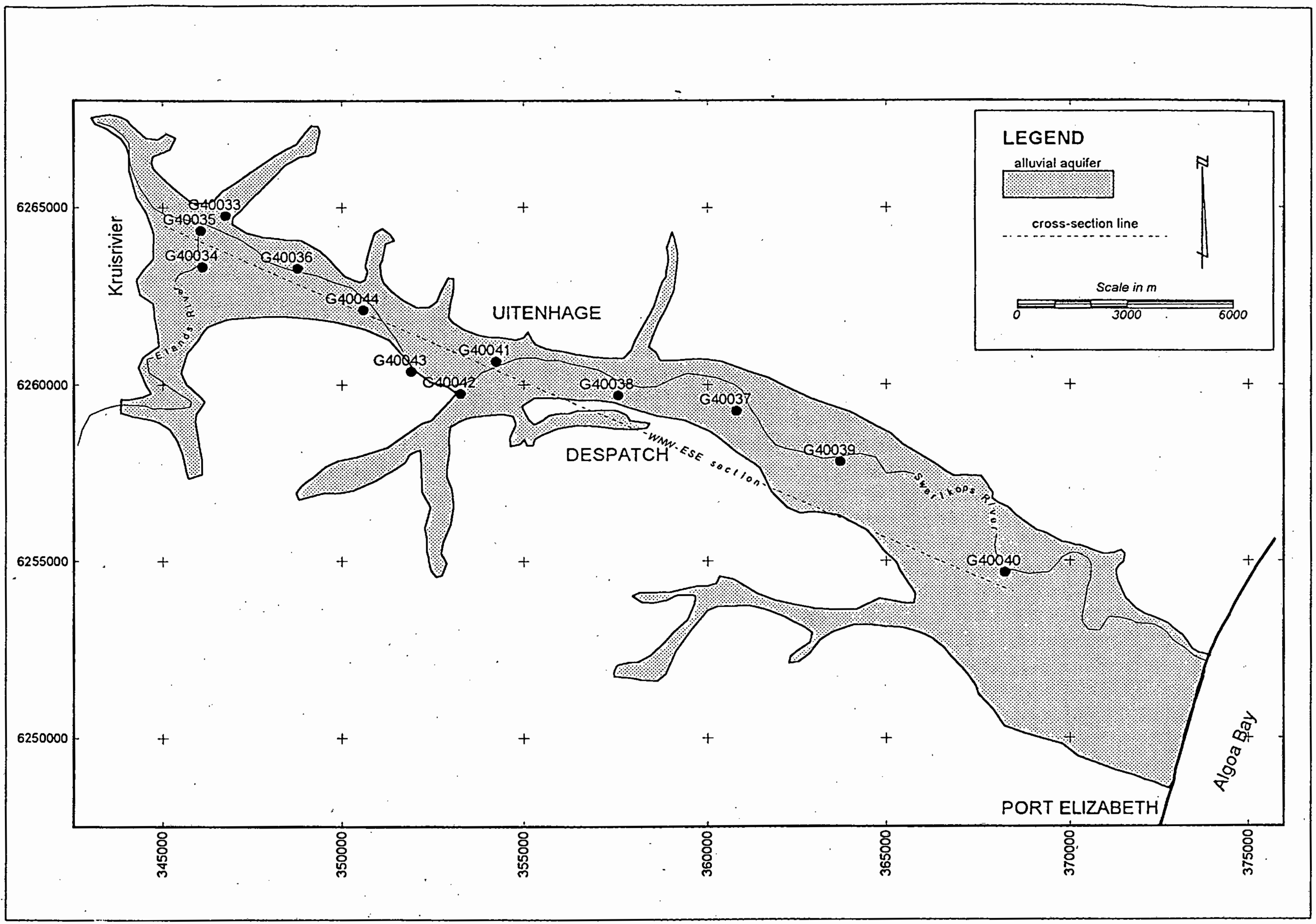


Figure 15: Location of monitoring boreholes - Swartkops River Alluvial Aquifer (from Maclear, 1995).

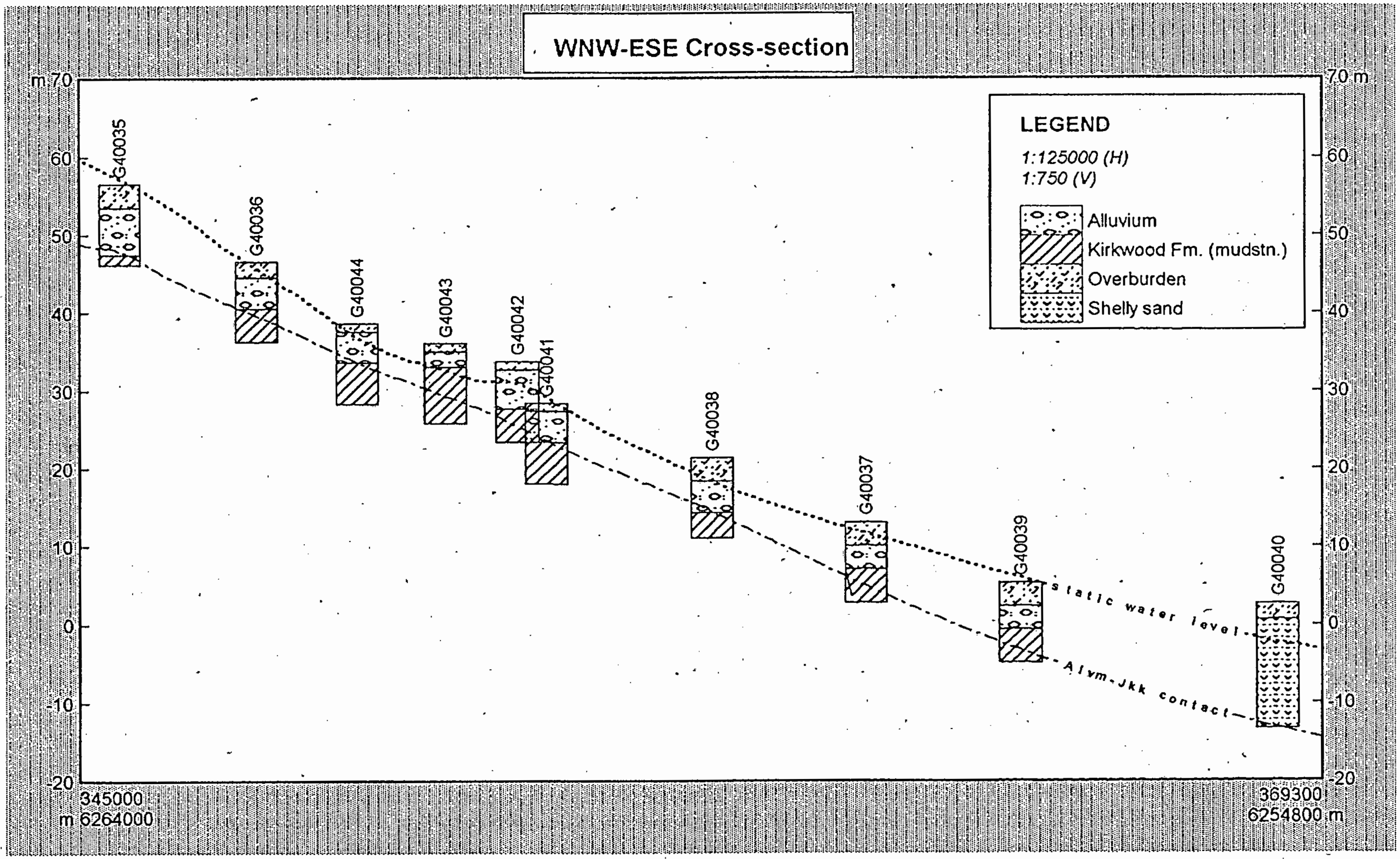


Figure 16: Lithological cross-section through the Swartkops River Alluvial Aquifer (from Maclear, 1995). Refer to Figure 15 for section line location.

In all but 2 of the boreholes drilled, the coarse alluvium was overlain by an overburden package (av. thickness 3m) of fine-medium grained, sandy soil and silt containing scattered pebbles and grits. This confining overburden is interpreted as a composite package of:

- levee (overbank) deposits formed over time as the Swartkops River and its braided channels have meandered across the floodplain - as is well documented to have occurred, even in recent time, in McCallum (1974), and
- residual valley-slope scree material, i.e. weathered Uitenhage Group.

13.1.2. Bedrock

The bedrock intersected during the drilling was mudstone and siltstone of the Kirkwood Formation in all but borehole G40040 - the furthest east in the monitoring network - in which case the borehole was stopped at a depth of 15.3m in Recent estuarine deposits of shelly silt and sand. It is of interest to note that during the drilling of the monitoring network, the Kirkwood Formation intersected in all the boreholes was slightly damp and clayey for only a short penetration distance (0.5-1m), after which the drilling samples were dry. This was the case even for borehole G40044 - which was erroneously located in the channel of the Swartkops River below the Nivens Drift bridge - in direct hydraulic contact with the river. This observation confirms the expected highly impermeable nature of the Kirkwood Formation.

13.1.3. Interpreted Geohydrology

The basal alluvial package described above (Section 13.1.1) is considered as the primary SRAA for this study.

13.1.3.1.Overburden

Initial interpretation indicates that the thick sandy soil and silt overlying the basal alluvial package, comprising the aquifer, is geohydrologically significant for the following reasons:

- The thickness of the overburden affects the vertical permeability rate (Kv) through the soil, and ultimately the recharge rate to the alluvial aquifer (Figure 17).
- As the overburden thickness increases, the residence times of recharging water in the overburden package will increase, thus increasing the time available for geochemical reactions to take place. Leaching of salts from the formation eventually results, and the salinity of the recharging groundwater increases.

The relationship outlined above was confirmed by the fact that groundwater salinity was highest for those boreholes with a thick overburden, e.g. G40034 (Appendix F), which has a 5m thick package (comprising sandy soil, silt and clay) and a naturally high EC of 3 650mS/m. An exception was borehole G40035 which has a 4m thick overburden but an EC of only 90mS/m. The aquifer test carried out on this hole (Section 13.2), however, showed the groundwater to be in direct hydraulic connection with the Elands

River. The low salinity, therefore, is a result of the dilution effect of the river water on the groundwater, as infiltration of water from the river to the aquifer is induced with pumping. The high salinity of other boreholes with only a thin overburden, e.g. G40036, is a function of pollution rather than natural salinity (discussed further in Section 16.11).

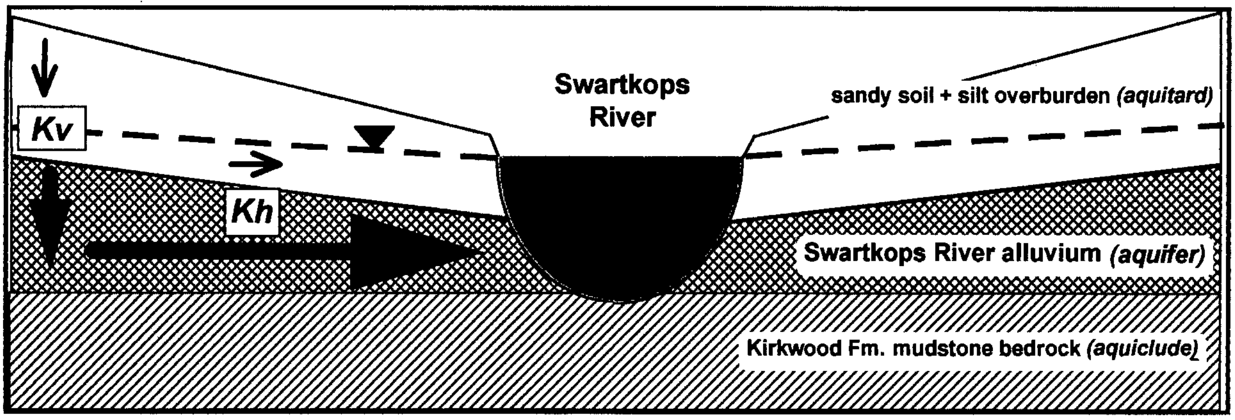


Figure 17: Conceptual geohydrological cross-section through the Swartkops River Alluvial Aquifer, from Maclear (1995). Note that *K* in the aquifer (45-55m/day) is much higher than in the aquitard (<5m/day).

13.1.3.2. Coarse Alluvium

The thickness of the coarse alluvial package comprising the aquifer is significant for the following reasons:

- the transmissivity of an homogeneous alluvial package is directly proportional to thickness and conductivity of the package, thus flow rates through an alluvial package will increase with increasing thickness and/or increasing sorting and coarseness (grading) of the package,
- as horizontal conductivities (*Kh*) increase, the residence times of groundwater in the alluvial aquifer decrease, and therefore natural groundwater salinity is less for the parts of the aquifer which are unaffected by pollution, and which have thick and/or coarse-grained alluvial packages, e.g. G40037 (Appendix F),
- high aquifer transmissivities cause a short-circuiting of the attenuation process (Xu and Braune, 1995) which results in limited treatment of groundwater contaminants in the aquifer.

13.2 Aquifer Parameters

Aquifer tests are one of the most effective ways to obtain values for hydraulic characteristics of geological formations through which groundwater flows (Kruseman and De Ridder, 1991). The aquifer system is first identified and then, to derive the aquifer hydraulics, an applicable theoretical model is applied for interpretation of the aquifer drawdown characteristics obtained in the field.

Aquifer parameters for the SRAA were determined by aquifer testing after completion of the drilling project. The drawdown curves, summary of results and discussion on individual site-tests and test limitations, are presented in Appendix G.

For the purposes of aquifer test data interpretation, a simplified conceptual model for the SRAA (shown schematically in Figure 17) was proposed as follows:

- Semi-confined/leaky, primary alluvial aquifer consisting of homogeneous, isotropic aquifer material. The overlying, confining sandy soil and clayey silt - comprising the aquitard - results in the total saturated alluvial package (aquifer and aquitard) being vertically inhomogeneous and stratified.
- The boreholes are fully-penetrating and it is assumed that well-storage is negligible (due to small borehole diameter and saturated thickness). It is further assumed that flow in the aquifer is predominantly horizontal (*Kh*) and flow in the aquitard is vertical (*Kv*), and that the horizontal flow is dominant (*Kh* >> *Kv*).
- The flow of groundwater to the pumping borehole in all the aquifer tests carried out (after the installation of the monitoring network) was unsteady-state, i.e. the water-level changed continuously for the duration of the test. It was thus assumed that the water discharged from the borehole was from a combination of leakage through the aquitard as well as a reduction in storage from both the aquitard and pumped aquifer.

The drawdown curves from the aquifer tests (Appendix G) and the aquifer parameters derived from these tests (using the Theis method of analysis) are summarised below:

- The SRAA consists of a basal lag of coarse, permeable river alluvium confined by a leaky overburden layer of clayey soil and silt and underlain by mudstone of the Kirkwood Formation (Uitenhage Group).
- Transmissivities for the alluvial aquifer ranging from 6-450m²/day were derived from the aquifer tests, and hydraulic conductivities estimated at 6-130m/day.

As a result of the variable nature of the geohydrology of the alluvial aquifer over the study area, it is not possible to extrapolate these figures over a regional scale. They do, however, provide a useful first estimate, and are the only practically derived estimates of aquifer hydraulics available for the study area to date. It should be noted that the original intention of the network of boreholes was to monitor groundwater quality and water levels, and not to provide groundwater on a safe-yield basis for water-supply purposes. The measurement of aquifer parameters (T + *K*), therefore, was a secondary aim of the drilling project. The hydraulic parameters obtained are nevertheless considered useful in terms of providing an initial first estimate for future studies and management purposes. For a detailed discussion on the results of the aquifer tests carried out on the SRAA, and interpretation of the drawdown curves presented in Appendix G, the reader is referred to Maclear (1995).

13.3. Abstraction and Recharge

The groundwater contained in the alluvial deposits is locally exploited on a small-scale only, by means of shallow dug-wells and seepage pits. The groundwater abstraction from the SRAA is concentrated mainly in the Despatch area, where it is utilised for garden irrigation, and topping up of swimming pools, as well as some local fruit and vegetable irrigation. Perched water tables were noted in Maclear (1993) to occur in these raised alluvial terrace deposits in the Despatch area. Due to the difficulty in judging pump yields from the very low-transmissive aquifer in Despatch, Maclear (1993) gave a conservative annual abstraction figure of 5 000m^3 from the SRAA.

The primary source of recharge to the alluvial aquifer is directly from precipitation incident on the aquifer surface. The generally lower salinity of the shallow groundwater in the middle to upper reaches of the catchment than in the lower reaches, is a function of orographic influences, with a greater recharge by precipitation occurring over the relatively high-lying areas to the west. The annual recharge to the SRAA is calculated at 5.2Mm^3, from Section 15.

13.4. Groundwater Quality

The groundwater type of the SRAA is predominantly NaCl (Figure 10) of moderate to high salinity. The quality of the alluvial aquifer groundwater is, however, highly variable (Appendix C) and is a function of aquifer lithology, especially overburden thickness and degree of clay content (Section 13.1.3); and possibly a component of inflow from the bedrock which would cause variable mixing. Proximity to unlined sources of pollution, from which contaminated effluent is able to leach into the alluvium, is also a factor which significantly affects the quality of the alluvial aquifer groundwater. The issues of pollution to the SRAA are discussed further in Section 16.

The groundwater quality in the seepage pits on the river-banks in the Kruisrivier area, is generally good and of similar characteristics to the river water. This is to be expected, since the pits are dug to below river water level and are tapping the base-flow component of the river.

13.5. Water level fluctuations

Water levels in shallow boreholes drilled in the Swartkops River estuary (McCallum, 1974), showed a maximum fluctuation of 0.5m only, during a 5 month monitoring period. Monitoring of groundwater levels at the five piezometers installed at the Gubb & Inggs wool-washing factory (Orthophoto 3) over a 2 year period for this study, showed similar fluctuations (Figure 18). The peaks in the graph on this Figure are related to high rainfall events, e.g. September 1993, as well as a function of hydraulic head in the evaporation dams, which causes a mound of artificially recharged water beneath the dams. The levels of the waste water in the evaporation dams, as well as rates of seepage inflow, have a localised and temporary effect on the water-table, as measured in nearby piezometers.

The levels of effluent in the evaporation dams vary in response to market demand for wool and it is, therefore, difficult to relate waterlevel fluctuations purely to climatic recharge influences in areas of the alluvial aquifer in proximity to surface water impoundments.

The lack of large-scale abstraction from the SRAA results in seasonal rainfall recharge being the dominant factor affecting water-levels in this aquifer. This is contrary to what is experienced in the CRAU and Kruisrivier Compartment of the SAU, where large-scale abstraction has caused significant declines in water-levels (Sections 11.2.1 and 12.2.1).

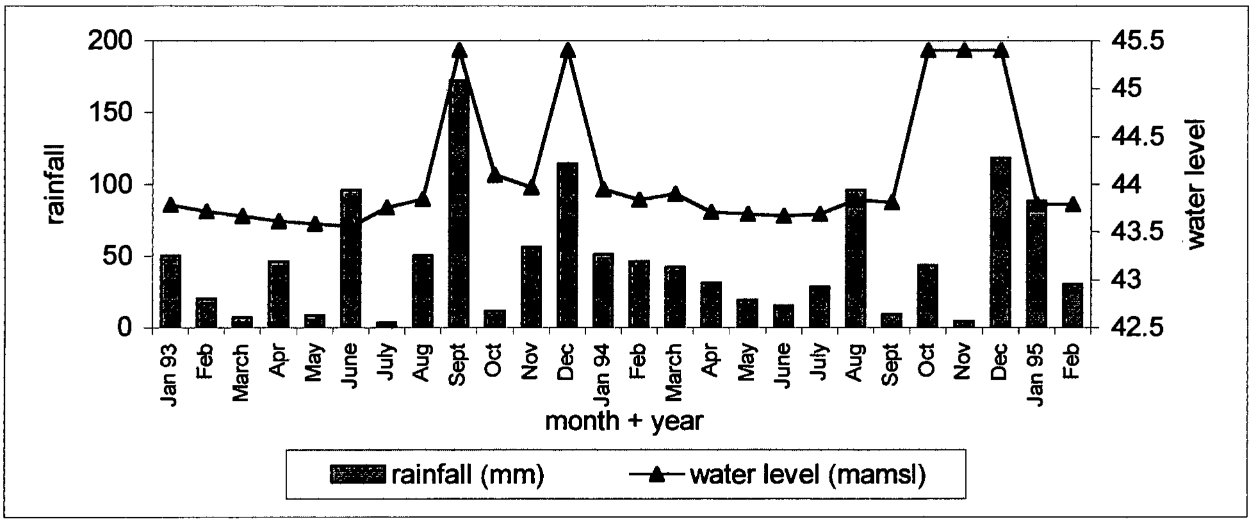


Figure 18: Water-level fluctuations in the alluvial aquifer below Gubb & Inggs in response to rainfall. The water-level is a composite from 5 piezometers.

14. SURFACE WATER - GROUND WATER INTERFLOW RELATIONSHIPS

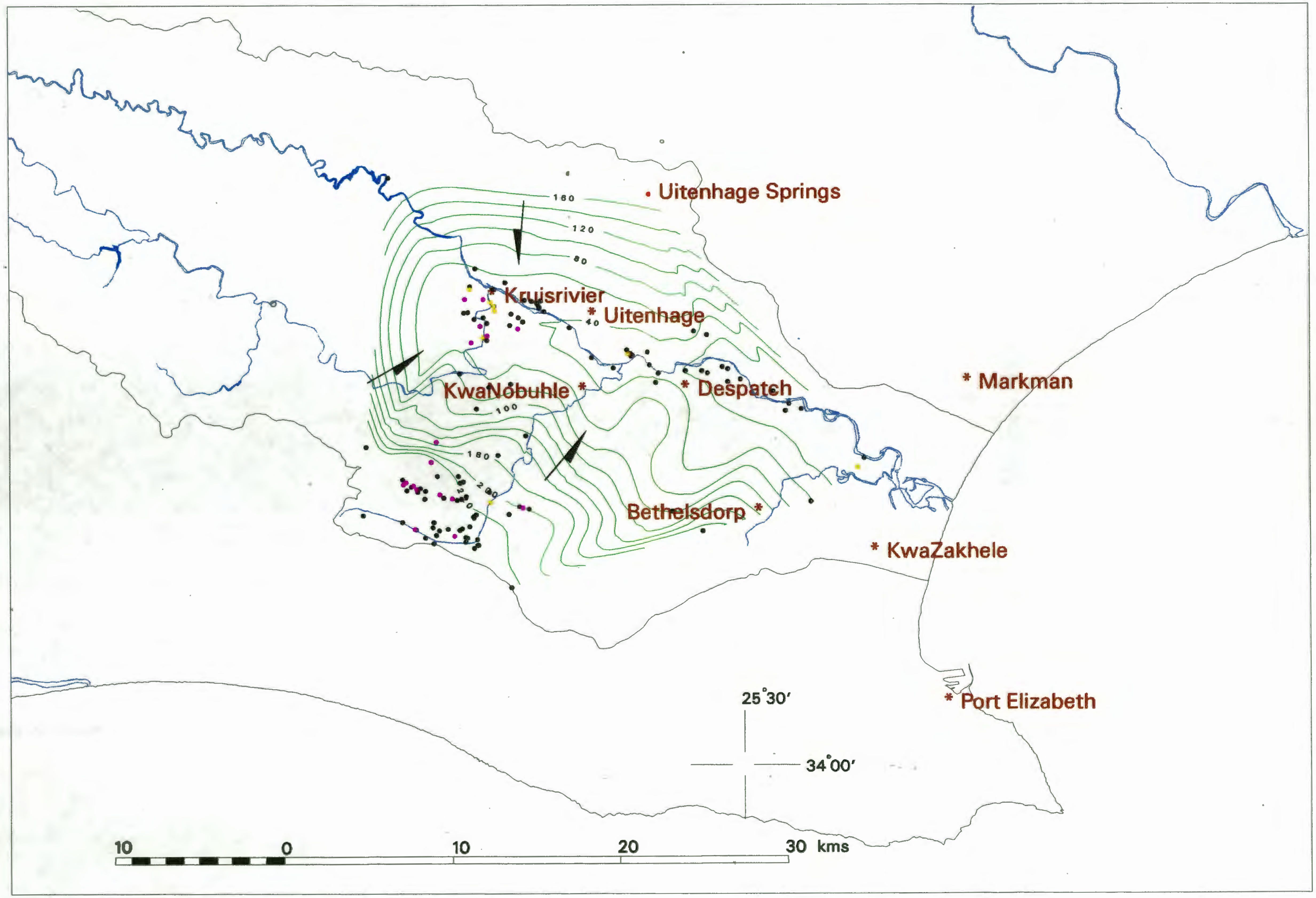
The major rivers in the investigation area are influent (gaining) hydrological systems, i.e. water flows from the primary alluvial aquifer to the rivers under the given piezometric and water-table conditions (Map 6). In this context, the aquifer becomes an effluent (losing) system. Only very small volumes of alluvial aquifer groundwater are lost to the secondary aquifer by downward leakage, a function of the presence and characteristics of the aquitards (as defined in Section 5). The main input to the shallow groundwater regime is from direct infiltration of precipitation, as well as from upper catchment tributaries which act as losing systems. Outputs from the groundwater system in turn are by discharge to gaining rivers, spring-flow, evapotranspiration, groundwater abstraction and underflow to the sea.

14.1. Primary Aquifer

Results obtained during the study by Maclear (1993) indicate a general inter-relationship between the surface and shallow groundwater regimes (alluvial aquifer), especially during low flow periods. The seasonal river runoff is reflected on a smaller scale by seasonal groundwater level fluctuations such as those described in McCallum (1974) and those recorded in the G&I boreholes for this study, discussed in Section 13.5. This confirms the assumptions and postulations made in previous studies, e.g. SRK (1991), regarding the surface water - groundwater interflow relationship.

The reasons for this close interflow relationship are the shallow water table in the primary aquifer, coupled with the relatively high porosity and permeability of the rudaceous to arenaceous alluvial material. These factors will result in relatively rapid base-flow of groundwater from the alluvial aquifer to the river, especially after a prolonged rainfall event, as well as interflow of water between the river and the SRAA, evidenced by the water quality of pumped boreholes immediately adjacent to the river.

Further evidence of the hydraulic connectivity between the surface- and groundwater bodies was provided in Maclear (1993) where groundwater quality of the shallow alluvial aquifer was shown to directly influence surface water quality, e.g. in the upper reaches of the Swartkops River immediately down-gradient of the G&I ponds (Section 16.1). During the aquifer testing of borehole G40035 (Inggsville farm, Kruisrivier, Orthophoto 2) it was observed that the Swartkops River, 60m away, was in direct hydraulic contact with the pumped aquifer and was acting as a recharge boundary to the borehole. Induced infiltration of the river water to the borehole was occurring via the alluvial aquifer with pumping. It is proposed that similar induced flow (from the river to the primary aquifer) will occur during flood events, when the high river stage will provide a raising of the hydraulic head, and subsequent reversals in the normal groundwater flow directions, temporarily making the river a losing system.



MAP 6 : WATER LEVEL CONTOURS (20m interval) and GROUNDWATER ABSTRACTION

Groundwater flow direction

● 0 - 10 000cu.m/a
● 10 000 - 100 000cu.m/a
● 100 000 - 1 000 000cu.m/a
● > 1 000 000cu.m/a

With reference to Figure 19, the similarity between the quality of the river water (Bullmers Drift) and that for the alluvial aquifer groundwater - measured in boreholes immediately adjacent to the river (G40035 - Inggsville, and G40044 at Nivens Drift bridge, Orthophoto 4), is clearly apparent. Borehole G40044 has a relatively higher salinity than G40035 due to its location about 5km downstream, where the river water quality deteriorates severely as a result of industrial activity (Section 16.1). The hydrochemistry of rain recharge and Kirkwood Formation lateral seepage input to the hydrological system of the SRAA is given for purposes of comparison.

14.2. Secondary Aquifer

Tritium age dating, on a Kruisrivier borehole reported in Bush (1985), determined an age of greater than 60 years for the main TMS artesian aquifer water, making it unlikely that the borehole derives any water as a result of river recharge. It was also found that the water level data for the area showed no seasonal recharge influence related to the Elands River flow. An aquifer test carried out on borehole KR16 (LE1 in Appendix A) situated on the banks of the Elands River exhibited no boundary recharge effects that would have been expected for river recharge.

Considering the evidence from the study of Bush (1985) and the very fine-grained and impermeable nature of the Kirkwood Formation mudstones which act as an aquiclude, it is highly unlikely that the river water has any direct hydraulic influence on the secondary aquifer groundwater in the study area, except in the upper courses of the Elands and Kwa-Zunga Rivers where no "buffering" Cretaceous cover is present.

Local leakage may exist as a result of indirect anthropogenic influences, e.g. rusted borehole casings. By way of illustration, Bush's (1985) study reports on the grouting and sealing of a borehole (in the Kruisrivier area) whose casing had rusted opposite the Kirkwood Formation. The sealing resulted in the immediate improvement of groundwater quality in an adjacent production borehole which was tapping the underlying sandstone aquifer, since the adjacent borehole had been influenced by saline water intrusion into the aquifer from leakage of mineralised groundwater, through the rusted casing, from the overlying Kirkwood Formation siltstones and mudstones.

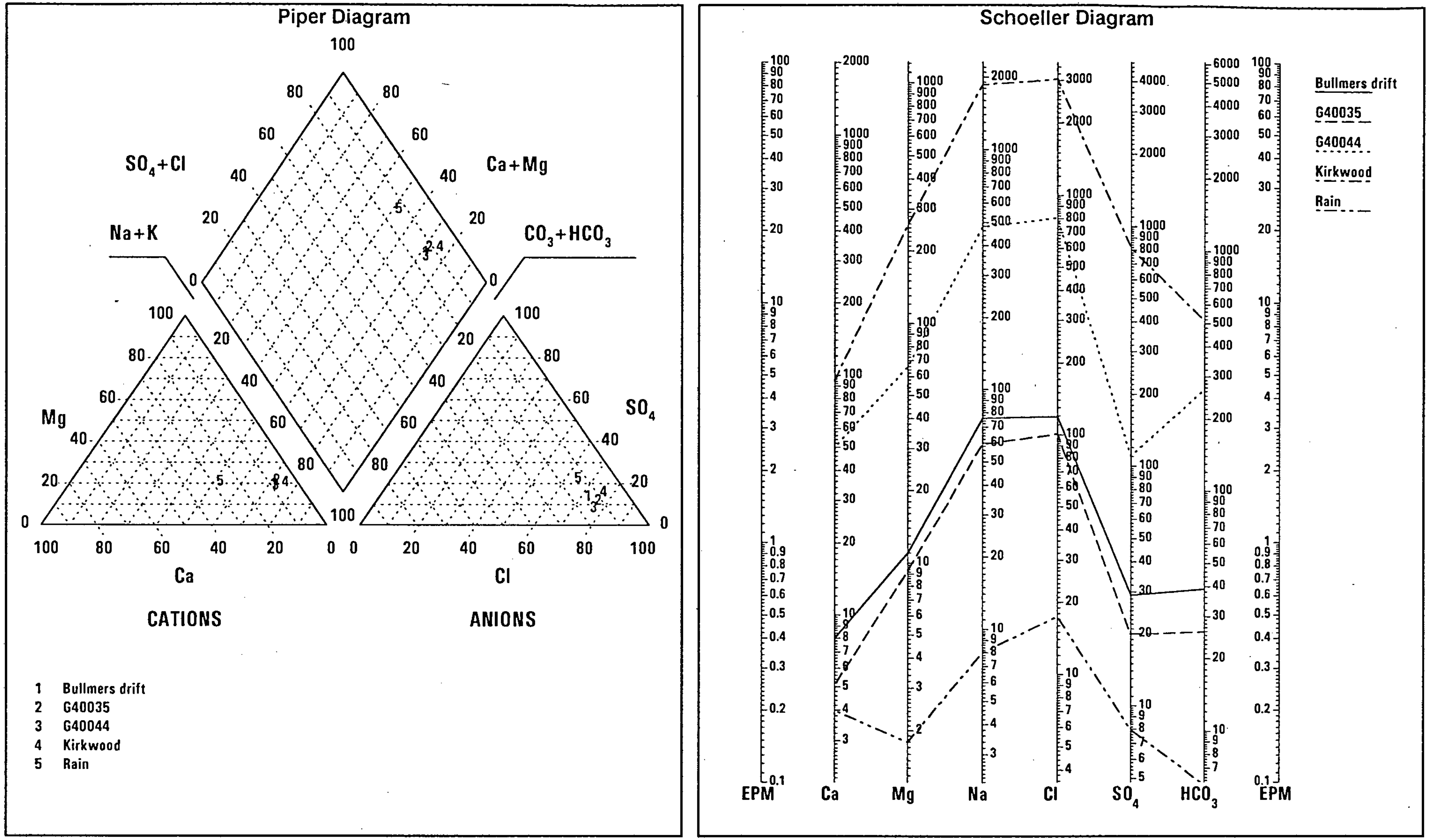


Figure 19: Similarities in river and alluvial aquifer hydrochemistry.

15. STORAGE AND RECHARGE ESTIMATIONS

Groundwater storage and the rate of aquifer recharge are some of the most difficult and uncertain factors to measure in the evaluation of groundwater resources (Sophocleous, 1991), since recharge, and thus changes in storage, exhibit high spatial and temporal variability. Groundwater storage and recharge volumes can be determined by means of simple calculations. However, unless the aquifer geometry is well defined, a representative water level monitoring network is in place, and an adequate database of aquifer behaviour (water level fluctuations) over time exists, any computed volumes should be viewed as estimations only. Following on from this, abstraction volume calculations based on approximations may be misleading and can result in incorrect decisions being made, e.g. with respect to the exploitation potential of an aquifer or the sustainable yield of a groundwater system.

Crucial factors affecting aquifer recharge and storage are the thickness and nature of the vadose zone, the pre-existing soil-water conditions and the timing, amount and duration of precipitation. For groundwater recharge to be effective, the recharging water must by definition enter the aquifer, hence the term *effective recharge*. The permeable vadose or unsaturated soil layer zone, where water moves freely above the water table under the influence of gravity and capillary action, is not the same as the saturated phreatic zone where groundwater moves under the influence of gravity and head pressure differences below the water table.

The above-ground source of recharge to an aquifer is either precipitation falling directly on the recharge area of the aquifer, or a permanent body of surface water such as a lake or stream which overlies the aquifer. This source of recharge governs the magnitude of the perennial groundwater supply obtainable from any aquifer (Kazmann, 1948).

15.1. Primary Aquifer

In the coastal areas of South Africa, numerous researchers have calculated recharge values for sand aquifers - mainly along the Cape West Coast - but little work has been carried out for recharge to coastal gravel aquifers, such as that of the study area (Bredenkamp, pers. comm., 1993). Sophocleous (1992), in a study of an area of similar aquifer characteristics, rainfall and topography to that of the Swartkops River, obtained a recharge value of 10% of rainfall for the shallow, alluvial Great Bend aquifer (Kansas).

Using the line showing the rainfall / recharge relationship for coastal alluvial aquifers, based on chloride profiles in Bredenkamp et al. (1995), a percentage recharge of MAP to the alluvial aquifer in the Swartkops River is calculated at 14% (using a MAP figure of 470 mm from Section 2.2). Although this recharge figure is theoretical with regard to application in the Swartkops River basin, no specific work on the rainfall / recharge relationship to the primary aquifer in the study area has yet been carried out. The derived relationship of Bredenkamp et al. (1995), based on scientific case studies, is accordingly considered to be the best information available to date.

Recharge to the alluvial aquifer in the study area is thus estimated at between 10% and 15% of MAP based on the preceding arguments. If this is accepted, the annual recharge (RE) to the alluvium is approximately 5.2Mm^3 and the total volume of groundwater in storage (S) in the alluvium is calculated at 66.4Mm^3, from Table 7. It should be noted that these calculations are based on estimations and averages, assumptions of homogeneous aquifer conditions occurring over the whole alluvial area in the catchment and the best information available at present.

Table 7: Swartkops River Alluvial Aquifer - storage and recharge estimates.

Swartkops River Alluvial Aquifer

Storage (S) = $A \times T \times Sy$ = 53.1Mm^3
Recharge (RE) = $A \times Rf \times r$ = 4.2-6.2Mm^3/yr = av. 5.2Mm^3/yr

A (Mm^2)	T (m)	Sy	Rf (m/yr)	r
88.5	4	0.15	0.47	0.1-0.15

A - digitised alluvial aquifer area, Maclear (1993).
T - average saturated aquifer thickness, Maclear (1995) and this study Section 13.1.3.
Sy - specific yield for medium gravel to boulder deposit, Ward (1975).
Rf - average annual rainfall, Maclear (1993).
r - recharge index range, this study Section 13.3.

15.2. Secondary Aquifer

The recharge to the Uitenhage Springs will be discussed here in some detail. This discussion is considered relevant since it provides an indication of estimates of recharge to the fractured secondary aquifer in the study area, specifically the Coega Ridge Aquifer. The difficulties in obtaining representative estimates for recharge to secondary aquifers are also highlighted.

In a groundwater system, the overflow from groundwater compartments - as springs - is approximately equivalent to the average annual recharge, if losses of infiltrated rainwater (to leakage and evapotranspiration) are negligible (Kok, 1992). Since the recharge areas of springs are usually not the same as the surface catchment area - due to the structural complexity of the spring system - it is extremely difficult to estimate the area parameter to be used in conventional recharge calculations. This is the case with the Uitenhage Springs, where it was shown in Maclear and Woodford (1995) that the geohydrology of the Springs is complex and structurally controlled.

From Equation 2, and using the following inputs: Q = 2.4Mm^3/yr (flow from Uitenhage Springs), Rf = 0.46m (rainfall) and A = 6.3km^2, Kok (1992) obtained a recharge (*RE%*) estimate for the Uitenhage Springs of 83% of rainfall.

Equation 2: Recharge estimate from spring flow.

$$\boxed{RE\% = \frac{Q}{Rf \; x \; A} x\, 100}$$

This is considered, by the author, to be an impossibly high over-estimate of recharge - since generally accepted average rainfall recharge to secondary aquifers in the RSA range from 3.5%-8% (Enslin, 1970). Kok's (1992) estimate implies that 83% of rainfall incident on the small catchment area infiltrates into the aquifer as recharge.

It is suggested that the error in Kok's (1992) recharge calculation is due to an under-estimation of the recharge area to the Springs. Figure 20 shows the aerial photograph covering the Uitenhage Springs on which an interpreted fault - considered to be the aqueduct to the Uitenhage Springs and associated with the Coega Fault (Section 3.3.1) - is indicated. The approximate surface catchment area to the Uitenhage Springs, i.e. Kok's (1992) recharge area to the Springs is also outlined.

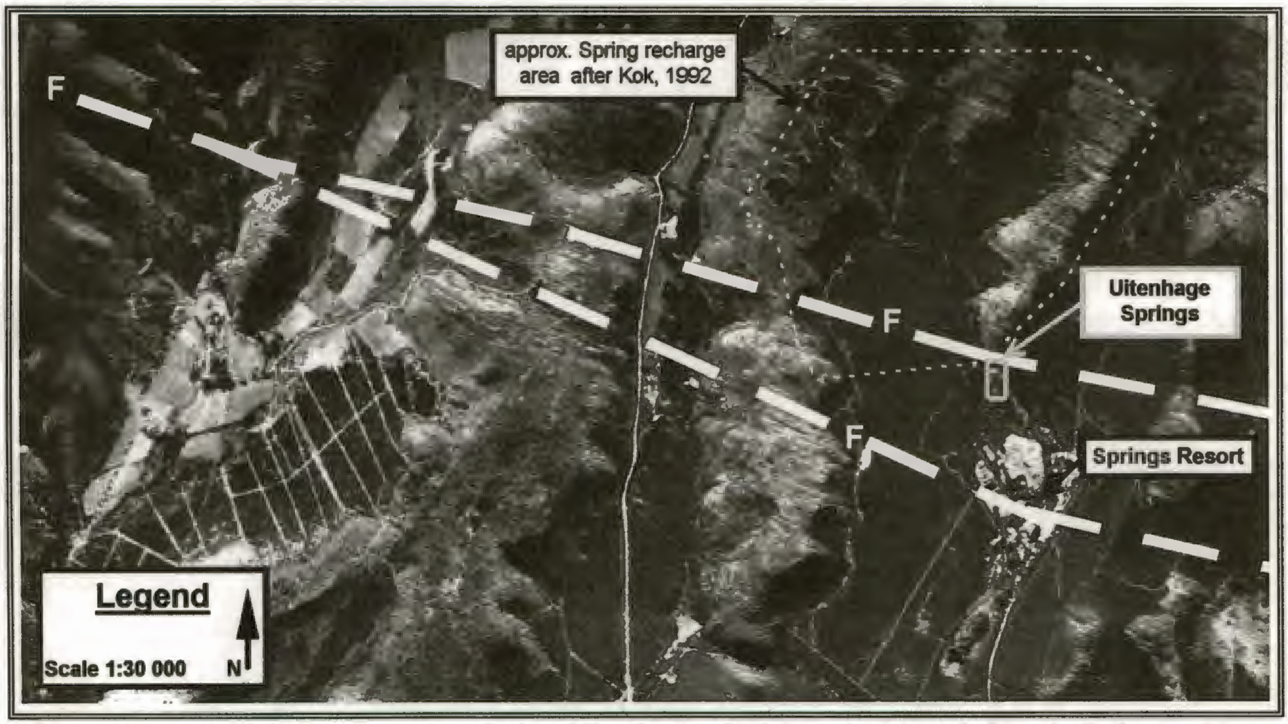


Figure 20: Aerial photograph of the Uitenhage Springs showing inferred fault positions determined from aerial photo interpretation. (Aerial photo 3332 of 13/6/90).

Based on the discussions presented above, it is proposed that the chloride-mass balance method (Equation 3) provides a more accurate determination of estimating recharge in the fractured secondary aquifers of the study area, than reliance on an inaccurate areal parameter (Equation 2). The chloride-mass balance method provides a useful and inexpensive technique for the evaluation of recharge to aquifers, that is independent of physical parameters (Wood and Sanford, 1995).

The method assumes that:

- the majority source of Cl in groundwater is from precipitation,
- the recharge mechanism is from direct precipitation on the surface and subsequent infiltration of this water through the unsaturated zone to the aquifer,
- Cl is concentrated in the recharge water by evapotranspiration, and
- Cl is a conservative tracer and does not react with the aquifer host-rock.

This method is mostly used as an initial indirect estimate of recharge, but is considered relevant to calculations of recharge for the secondary aquifer of the study area since:

- The fractured secondary aquifers of the study area have experienced "flushing" by low TDS (Table 3) groundwater for millennia (Hickson, 1989).
- The flushing has removed any leachable soluble Cl from the fractures through which the groundwater flows.
- Cl contamination from the Uitenhage Group deposits is not possible, as these deposits are confined to the more distal (central) regions of the study area.

The assumption that the only Cl present in the groundwater is that derived from rainfall, is, therefore, considered to be reasonable.

Equation 3: Chloride-mass balance method for recharge estimation.

$$\boxed{\begin{aligned} RE(mm) &= \frac{Cl_{input}}{Cl_{groundwater}} x\, Rf \\ RE(\%) &= \frac{RE(mm)}{Rf(mm)} x\, 100 \end{aligned}}$$

From Equation 3 and utilising the range in rainfall Cl concentrations (Cl_{input}) obtained for this study of 8-18mg/ℓ (Appendix D), the Cl concentration of the Spring water ($Cl_{groundwater}$) of 33mg/ℓ (Maclear, 1993) and the average annual rainfall (*Rf*) at the Uitenhage Springs of 471mm (Maclear and Woodford, 1995), the annual recharge (*RE*) to the Uitenhage Springs is calculated at between 24% and 55% of rainfall.

While these recharge estimates for the fractured secondary aquifer of the Swartkops River Basin are still high - and will no doubt be the subject of some future controversy - it is suggested that the Cl-mass balance method for calculating recharge is the most suitable for application in this study region, where catchment areas are difficult, if not impossible, to estimate due to structural complexity (Section 3.3 and 3.3.1). A more representative and accurate estimate of recharge could be made if a larger sample population of Cl_{input} were available (Section 17). To this end, it is suggested that additional rain samples - under different climatic conditions - be obtained for the study area.

16. GROUNDWATER POLLUTION

A summary of investigations into the surface and groundwater pollution* at specific sites in the Swartkops River basin is given below for purposes of reference and comparison, and to highlight the historical problem of water contamination in the upper river reaches adjacent to Uitenhage.

A shortcoming of a recently completed Water Research Commission (WRC) report on the water quality of the Swartkops Estuary (Mackay, 1993) is the lack of assessment of contribution of the groundwater component to the total pollution load of the hydrological system. The groundwater pollution study presented here is therefore considered to be highly relevant and will assist in providing an appraisal of the extent of groundwater pollution in the study area, especially in the shallow alluvial aquifer (SRAA). In addition, it is hoped that the data provided hereunder will fill the knowledge gap which presently exists on the extent to which the hydrological system is contaminated on a basin scale.

16.1. Reasons for Concern

It could be argued that, since the alluvial aquifer is not extensively "used" as a water supply in the conventional sense (e.g. abstraction from boreholes and well fields), there is no need to protect this groundwater resource and maintain its sustainability with respect to groundwater quality, i.e. pollution of the aquifer is not significant. Such a viewpoint is, however, dangerous and should be discouraged for the following reason: the Swartkops River is a gaining system (refer to Section 14 and Map 6), which implies that *pollution of the alluvial aquifer is pollution of the Swartkops River.* In this context, the river - and ultimately the environment - is the end-user of the groundwater from the alluvial aquifer; and thus if the river's water quality is to be maintained, then the groundwater quality must first be safeguarded.

Further, pollution of the Swartkops River and its tributaries is important due to the impact of pollution on the following systems and activities which the river supports:

- aquatic life, e.g. fresh-water aquaculture and fish breeding,
- ecology and ecosystem diversity,
- estuarine mariculture, and
- contact recreation (swimming, sailing, fishing).

Data on river water quality variations in the Swartkops River presented by Maclear (1993) showed that the quality of the river water deteriorated dramatically with distance downstream (Figure 21). The river water is unpolluted upstream of the Kwa-Zunga - Elands River confluence (EC <50mS/m), with salinity increasing (EC >200mS/m) from immediately downstream of the

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* For the purposes of this study, pollution of a water body is defined as the artificially induced degradation of the natural water quality of that body; a state of pollution being recognised when the concentration of contaminants - introduced into the hydrologic environment by human activities - attains a level considered to be objectionable (Goudie, 1981).

Gubb & Inggs (G&I) evaporation dams to the Perseverance causeway, where the quality becomes influenced by tidal reach. This salinity increase coincides with the flow of the river through the industrialised portion of the Swartkops River, mainly in the Uitenhage and Despatch districts, and indicates the degree to which the river is impacted by anthropogenic influences. Potassium was found to be a very good indicator of pollution originating from the wool-washing industry (discussed further in Section 16.6) illustrated by the K peak in Figure 21.

It could be argued that the river water changes in chemical character downriver with increasing distance from the river source, in response to the progressive changes in channel bedrock geology over its flow length, and that this would explain the increase in mineralization of the river water.

This is unlikely, however, for the following reasons :

- there is no major difference in bedrock geology or groundwater residence times upriver of Kruisrivier to that downriver, which could explain the observed salinity increase - the bedrock to the Elands River (of a lower salinity than the Swartkops River) is in fact shale of the Bokkeveld Group,
- the relatively short flow length of the river results in a short residence time in the basin and subsequently short contact time of the river water with the bedrock,
- the alluvial channel-fill material over which the river flows acts as a buffer between the eroding water and the bedrock,
- although the Tertiary shelly limestone of the Alexandria and Nanaga Formations is calcareous (high in carbonates of Ca and Mg), these salts are relatively immobile in their sedimentary form, mobilities of 3%-2% respectively (Chebotarev, 1955), and would thus be resistant to erosion.

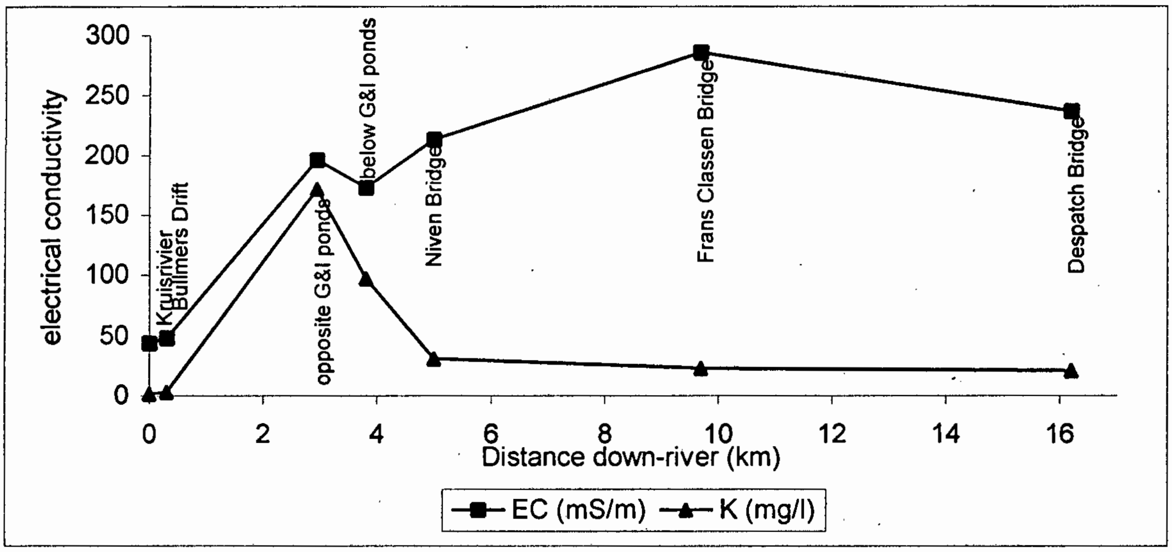


Figure 21: Down-river water quality variations in selected parameters - Swartkops River.

From the preceding paragraph it can be seen that water quality is not significantly affected by geology, and thus the impact of anthropogenic influences (e.g. industrial activity) on water quality becomes the over-riding factor. For further detailed discussion on the forms and quality of surface water pollution points in the study area, the reader is referred to Maclear (1993) and Environmental Services (1993).

Since none of the major diffuse pollution sources identified in this or previous studies (Appendix H and Orthophotos 1-11) have major canals which drain the liquid effluent sourced on the pollution site to the river, and since almost all of the diffuse pollution sources are unlined, it is assumed that the effluent mostly enters the river via the groundwater system, where it negatively affects the quality of the river water. A discussion on the causes and effects of groundwater pollution with reference to the study area is now appropriate.

16.2. General Groundwater Pollution

Groundwater quality is often negatively affected by the application of fertilisers and pesticides, urban development, mining activities, and the disposal of refuse and industrial effluents to land. The contamination of aquifers by leachates from these processes constitutes a massive problem (e.g. the *Superfund* sites in the USA), and the problem worsens if not managed properly.

For this study, contamination of a water resource is considered to occur when the concentration of introduced solutes, substances and chemicals is significant but within the currently accepted limits, and therefore does not necessarily imply a degradation in water quality. Pollution occurs when the contaminant concentration attains levels considered to be objectionable, i.e. exceeding the accepted limits set for a particular use of the water body. This pollution is usually artificially induced and results in a degradation of the natural water quality, thereby impairing the use of the water and often creating public health hazards.

Prior to extensive research into the subject of groundwater pollution, groundwater was traditionally considered always to have an excellent quality, since the soil barrier was thought to be effective in providing an isolating barrier (buffer) between the pollution source and the groundwater. It has since been determined that this barrier has a limited attenuation capacity and is often "short-circuited" in the process, and that pollution of groundwater by surface sources of contamination is a very real threat.

Groundwater has long residence times in an aquifer, ranging from decades to millennia. Pollution of an aquifer, therefore, takes place over a long period before being detected, by which time it is often too late or uneconomical to effect rehabilitation. It is often the case that pollution is only detected when the groundwater resource is needed, by which time it is unfit for use.

Once an aquifer has become contaminated it generally remains so because of insufficient dilution, slow movement of water through the aquifer, limited natural "self-cleaning" of the aquifer and the technical and economic difficulty of restoring the polluted aquifer to its original state. The lack of systematic monitoring of the water quality in South African aquifers is a cause for concern and probably underestimates the extent to which groundwater contamination has occurred in the country.

Within groundwater, chemicals are transformed by microbiological and ion-exchange processes and changes in pH and redox potential (Eh); which leads to precipitation, dissolution, oxidation and reduction of the chemicals. The degree of decomposition, adsorption and elimination of substances in groundwater differs fundamentally from that in surface water since: a) the processes are retarded - by a factor of 1000 to 100 000 compared with surface water - because of the slow movement of pollutants through the groundwater system (DWA&F, 1991), and b) pollution remains in the system long after the contaminants have entered the groundwater, whereas a flowing river has a flushing (attenuating) capability by rapidly removing and diluting the pollution from its point of origin.

Contaminant transportation in groundwater:

- Contaminants must first travel through the vadose zone before reaching the groundwater. Within the vadose zone retardation processes of adsorption, precipitation and complexation occur.
- Once a contaminant reaches the groundwater the rate of transport increases significantly, with the movement being in the direction of the regional groundwater flow direction.
- Within the phreatic zone there are 2 main processes of contaminant transport, *viz.* :
  advection - solute movement due to transport by flowing groundwater, and
  dispersion - lateral flow direction deviation as a result of mixing and diffusion.

Contaminant attenuation in groundwater:

- Attentuation of contaminants in the subsurface depends on microbiological and physico-chemical filtering processes, where for example fine-grained sediments can act as semi-permeable membranes.
- Contaminant mobility through the soil profile is inversely proportional to its molecular size, e.g. soil was found by Fourie and van Reyneveld (1993) to have a removal efficiency of 90% for P and only 50% for N.
- As the soil and/or aquifer material immediately in contact with the pollution source becomes clogged due to the filtration of the solid particles, the sorting of the soil or aquifer medium is altered and the filtering capacity is, therefore, decreased (Section 13.2).
- The extent of pollution from the source is determined by the permeability of the soil buffer between the pollution source and the water table, this permeability being highly variable, in both the horizontal and vertical extent (heterogeneity).

Diffuse pollution (significant in the Swartkops River study area and discussed hereunder) is more problematic than point pollution, since it can affect an entire aquifer and go unnoticed for decades. Once the effects appear it may be necessary to abandon the aquifer. Point pollution, conversely, is generally quick to reveal itself and can often be corrected.

To assess the impact of waste disposal sites on groundwater quality Engelbrecht (1993) states that the following factors need to be addressed:

- what are the potentially harmful constituents in the leachate,
- what are the local hydrogeological conditions, and
- what is the significance of the attenuating factors such as adsorption, ion exchange and precipitation?

Leachate contaminants of concern in a water body used for domestic or for "hands-on" recreational purposes - such as the Swartkops River - are:

- the major salts (Na, Cl, K, Ca, Mg) - harmless at normal concentrations but ecologically harmful and can cause health problems at high concentrations making the water undrinkable,
- nitrogen compounds - poisonous effect of increased levels of NO_3 (e.g. methaemoglobinaemia),
- heavy metals - toxic effects, and
- dissolved organic compounds - affect taste and odours.

(Refer to minimum standards for these constituents in Appendix B).

16.3. Swartkops River Basin - Aquifer Vulnerability

As already mentioned (Section 16.1), an important consequence when considering groundwater pollution in the study area is that pollution of the SRAA results in pollution of the Swartkops River, i.e. effluent deposited on the surface of the aquifer ultimately becomes influent to the river. The pathways for contaminants to reach the groundwater in the SRAA are via seepage into the unconsolidated alluvial material from unlined liquid effluent disposal ponds (Orthophotos 1-11, Appendix H).

Alluvial aquifers are the second most vulnerable aquifer system of the five basic groundwater systems existing in the RSA (Xu and Braune, 1995). As outlined in Section 14, the only aquifer in the study area which is considered by the author to be significantly polluted is the SRAA. This aquifer has a high pollution vulnerability for the following reasons:

- Lewis et al. (1980) in Fourie and van Reyneveld (1993) classified porous, unconsolidated coarse alluvium and gravels to have the highest relative pollution risk potential of all soil types. The high pollution risk is due to the poor attenuation of contaminated groundwater as a result of high permeabilities of the material and therefore short-circuiting of the contaminant treatment and filtering processes within the aquifer.

- The coarse nature of the alluvium results in a lower adsorption capacity due to the reduced surface area.
- The overburden to the SRAA consists of the high-risk aquifer material - described in the preceding paragraph - in the vadose (buffer) zone, as well as immediately below the water table (Section 13.1.3), and therefore the contamination risk and aquifer vulnerability is high.

To illustrate the relative vulnerability of the SRAA to pollution, a *DRASTIC* Index point score (as proposed by Aller et al., 1985) of 84/100 and a *DAS* Index of 27/30 was determined for this aquifer, i.e. indicating a very high potential for groundwater pollution.

In contrast, the *WASP* technique (devised by Parsons and Jolly, 1994 for determining the suitability of an area for waste disposal with respect to potential for groundwater contamination) was used by Parsons (1994) for the Aloes Waste Disposal Site (Section 14). The result of this investigation showed that the Uitenhage Group - bedrock to the SRAA - was an excellent natural buffer horizon to leachate migration, and had a very low contamination potential. From this it is apparent that the vulnerability of the secondary aquifer to pollution is almost nil, provided it is overlain by a substantial buffering layer of Uitenhage Group sediments.

16.4. Groundwater Monitoring Network

A network of boreholes was drilled in the SRAA at the end of 1994 as a result of recommendations made by Maclear (1993). The design and construction of this network is reported by Maclear (1995) and the aquifer geometry and parameters are summarised in Section 13.1. The objectives of the monitoring network were as follows:

- to ascertain the *status quo* of the groundwater quality with respect to the presence and degree of contamination;
- to identify point and non-point pollution sources impacting on the quality of the groundwater in the alluvial aquifer;
- to determine the groundwater - surface water interflow relationships;
- to achieve the long-term aquifer monitoring (groundwater quality) and measurement of seasonal water level fluctuations;
- to obtain parameters for inputs to a geohydrological model of the alluvial aquifer, and
- to derive initial aquifer hydraulic parameters from aquifer tests, since no data existed on the geohydrological parameters of the alluvial aquifer system prior to this study.

After identification of the known and suspected sources of pollution to the alluvial aquifer, the boreholes were sited down gradient of the pollution sources, e.g. unlined evaporation dams, maturation ponds and storm-water outflow points. The conceptual model for the network design is illustrated in Figure 22. The drilling and borehole details are presented in Appendix I, and the relative location of the monitoring boreholes and the identified sources of pollution are shown in Orthophotos 1 to 11. The regional location of the monitoring boreholes within the SRAA is shown in Figure 15.

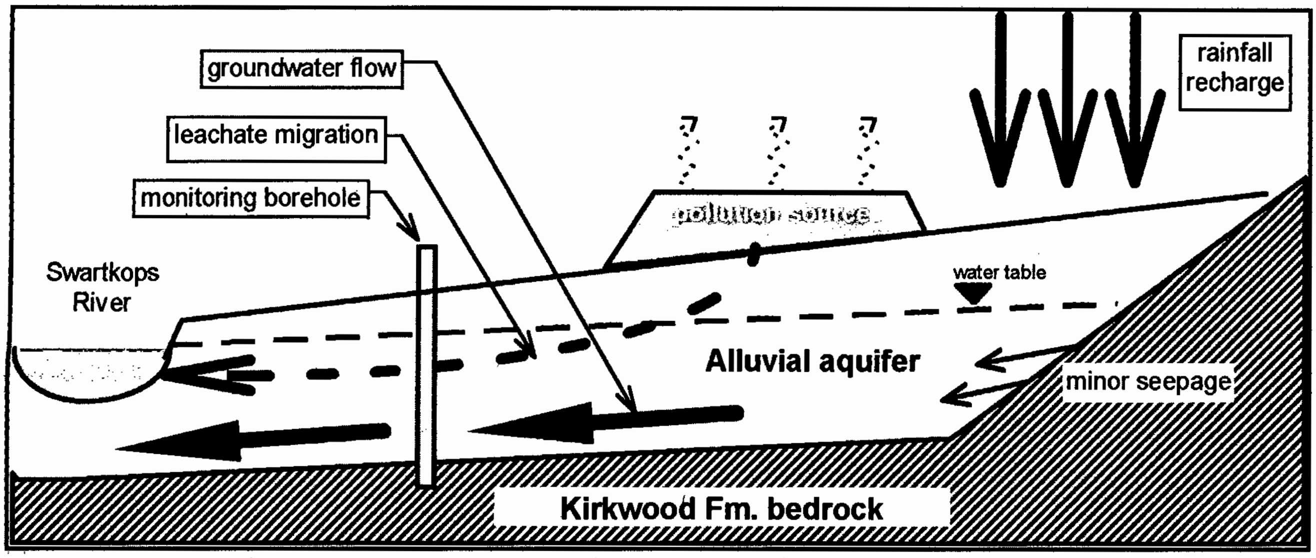


Figure 22: Schematic groundwater monitoring network design.

Appendix C lists the results of the first 3 water quality sampling runs carried out on the monitoring boreholes and known pollution sources in the SRAA.

Each industry which has a known or suspected significant impact on the quality of the surface and groundwater bodies within the study area will now be discussed separately. The order of discussion is not ranked according to any degree of significance.

16.5. Leather Tanning Industries

This industry tans and softens animal hides, and is represented within the study area by the East Cape Tanning (ECT) Co., one of the largest tanneries in the RSA. The evaporation dams for this plant cover an area of 9.5ha and are located on a thin unsaturated alluvial package (borehole G40043, Appendix F) in a relatively narrow valley (Orthophoto 5, and Plate 10).

The tanning industry is a non-consumptive user of water - water being used mostly for cleaning and wash-down of working spaces. Almost all the water used in the tanning process becomes waste-water, producing a liquid effluent of an intractable nature. Technology for the economic purification of this effluent to river water standards exists. It is, however, very expensive, consisting of ultrafiltration and reverse osmosis processes. As a result, the most common form of "treatment" of this effluent in the RSA is by disposal to evaporation ponds.

The tanning process is summarised as follows (from Natsurv 10, 1989):

- the hides are cured with salt to prevent their degradation before tanning begins,
- during the pre-tanning soaking of the hides, to remove blood, dirt and to rehydrate the hides, a major proportion of this curing salt is removed and enters the effluent stream,
- the hides are un-haired and de-fleshed with a lime sulphide solution resulting in an effluent consisting of degraded protein, hair, surplus lime, sulphides and high pH,

- the hides are then smoothed and softened using a weak acid and ammonium salts, before being pickled in a solution of sulphuric acid,
- the hides are tanned by adding Cr tanning salts, which produces an effluent stream containing Cr and salt in solution,
- finally, the hides are dyed resulting in an effluent containing spent dye.

The specific pollution load (SPL) in the final waste water, therefore, typically has high pH, TDS and Cr with average analyses of the raw waste-water quality from the tanning industry of 8.4, 19 700mg/ℓ and 120mg/ℓ, respectively (Natsurv 10, 1989).

16.5.1. Discussion of results

The ECT evaporation ponds are situated in a narrow valley formed by stream erosion of Kirkwood Formation mudstones and siltstones. Borehole G40043 was drilled through a relatively thin (3m) residuum of sand and clayey soil before intersecting bedrock and subsequent measurements of the water level in this borehole showed the alluvium to be unsaturated over the measuring period. The water level in G40043 (Appendix F and I) reflects the piezometric level of the groundwater in the Kirkwood Formation and results from a slow migration of seepage water out of the Kirkwood Formation, underlying the alluvium, into the screened monitoring borehole with time. The rapid lowering of the water table in this borehole, which occurs during purging operations prior to taking a sample, supports this.

The borehole chemistry thus reflects that of the connate groundwater in the Uitenhage Group, with high natural salinity (Figure 23). With reference to Appendix C, it is relevant to note that no Cr concentrations of significance are detected in the sampled borehole water. As outlined in the preceding section, chrome is an indicator parameter used for the tanning process; and, based only on the Cr concentration in the groundwater (G40043, Appendix C) it could be assumed that minimal leachate from the evaporation dams is entering the groundwater system below the ECT site. This is, however, incorrect, since Cr salts will precipitate rapidly out of solution under the reducing conditions in the evaporation ponds, and will therefore become immobilised in the sludge in these ponds or attenuated within the vadose soil-zone beneath the ponds. Chromium, therefore, cannot be used as an indicator of groundwater contamination from leachate generated from the tanning industry.

The unnaturally elevated SO_4, TAL and K values of the borehole water, instead indicate that some degree of groundwater pollution, via leachate from underneath the dams, is occurring from ECT. It is assumed that leachate generated below these ponds would seep laterally into local ephemeral drainage features (Plate 11); and/or gravitate down to the Kirkwood Formation bedrock where it would flow down-valley to discharge into the Swartkops River. The high concentrations of SO_4, TAL and K are thus suggested to be a function of pollution which is either seeping slowly into the Kirkwood Formation, or flowing preferentially by means of localised "unnatural" entry next to the borehole casing.

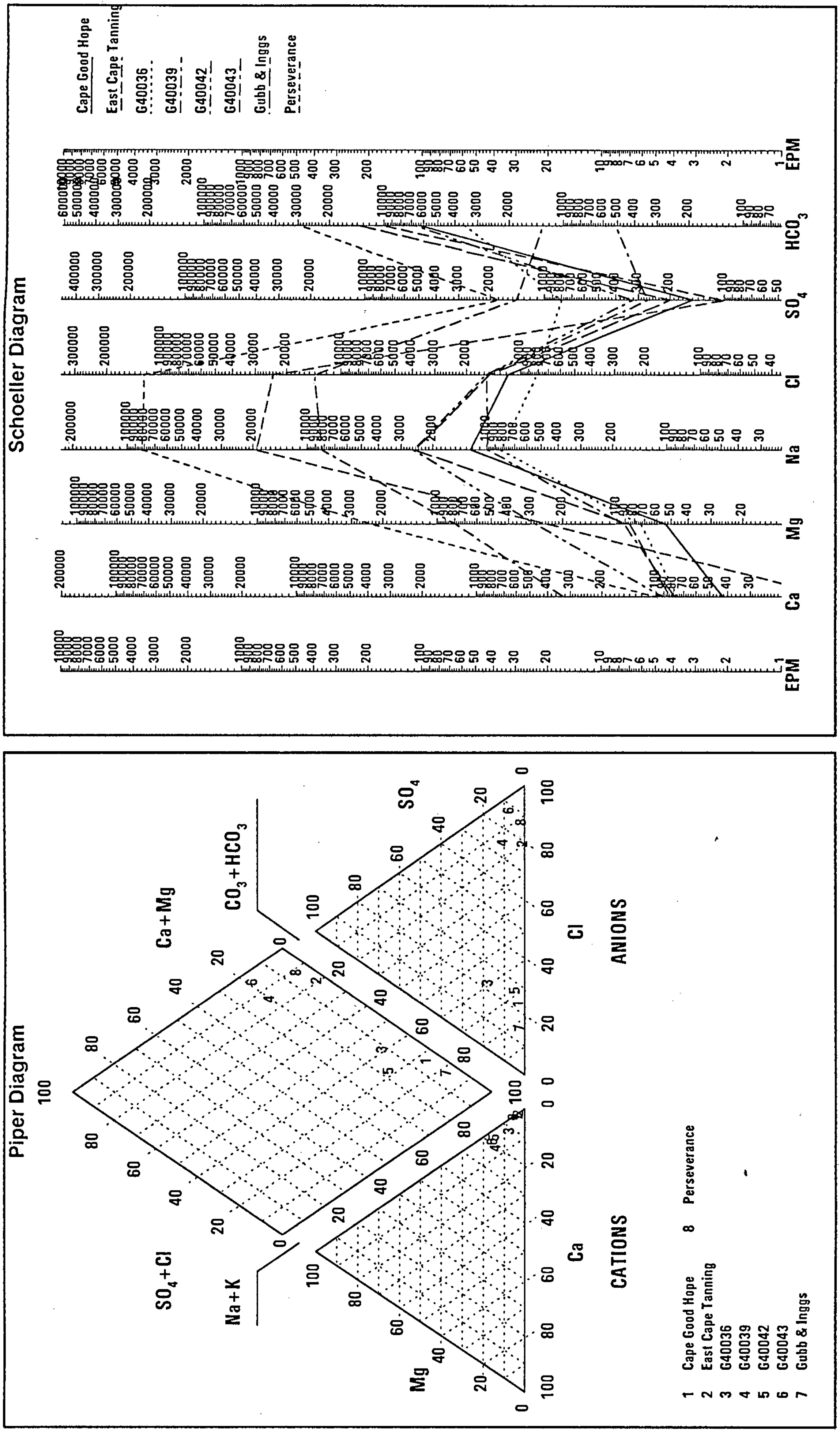


Figure 23: Wool-processing and tanning industry hydrochemistry.

16.6. Wool Processing Industries

The wool processing industries relevant to the study area are the wool-washing and wool-combing plants of Gubb & Inggs (G&I) and Cape of Good Hope (CGH) Pty. (Ltd.), respectively, and the wool-pulling plant of Perseverance Wool-Pullery (PWP). The final product from G&I and CGH is combed "wool top".

Wool-combing is the physical combing of the wool to remove solid matter such as vegetation, soil and faecal matter adhering to the wool as well as the alignment of the fibres. The wool-washing process produces semi-processed wool-top from raw wool fibre, as well as the recovery of grease in the form of lanolin.

These wool processing industries use water extensively and mostly non-consumptively in their processing operations, with 70-80% of the water used being returned to the environment as industrial effluent (Natsurv 13, 1993). The textile industry in general has difficulty in meeting waste-water discharge limits and most of the liquid effluent stream is therefore disposed of in evaporation dams.

In the study area the wool processing industries' evaporation dams cover considerable areal extents, *viz.* 17.9ha (G&I), 8.4ha (CGH) and 4.1ha (PWP). The function of the evaporation dams is two-fold: a) settling of sediment, and b) evaporation of water. This process thus leaves a residual sludge (Plate 12) which dries out by evaporation and downward leaching, whereafter it is removed to a solid waste disposal facility.

Wool-washing involves the following processes (from Natsurv 13, 1993):

- scouring - aqueous treatment of the wool with hot concentrated sodium carbonate and detergents, to remove grease and *suint* (saline excretions from the skin of the sheep which accumulates in the raw wool),
- carbonising - sulphuric acid washing of the wool to remove residual vegetable matter, and
- fulling - treatment of the wool with alkaline detergent to increase the body, density and stretch characteristics of the wool.

Effluent from a wool scouring mill is alkaline, has widely varying pH, and typically has a very high organic and inorganic pollutant load (about 10 000mg/l TDS), since raw wool contains a high proportion of impurities by mass (about 60%) - including dirt, suint, grease and vegetable and faecal matter adhering to the wool.

Wool-pulling is the process whereby the wool remaining in the sheep-skins after the sheep are slaughtered is pulled from the skins, and the pulled-wool is then baled and sent to a wool finishing mill. The sheep-skins from which the wool is pulled are cured in salt for storage prior to pulling. During the pre-pulling soaking of the hides, a major proportion of the curing salt is removed and enters the effluent stream, resulting in extremely high TDS values of the waste water (e.g. about 256 000mg/ℓ TDS for the PWP evaporation dams, which is approximately 7.5 times the salinity of sea-water!).

16.6.1. Discussion of Results

Wool-washing process.

The boreholes developed for the SRK (1990) groundwater survey at G&I, as well as the boreholes drilled for the installation of the SRAA groundwater monitoring network (Maclear, 1995) intersected alluvium discoloured by seepage down-gradient of evaporation ponds associated with the wool-processing industries (Plates 13 and 14). Analyses of the groundwater below these sites (G40036, G40042 and G40039, Appendix C) shows extensive pollution to have occurred, characterised by high EC, Na, Cl and specifically K.

Sulphate values increase down-gradient of the evaporation dams as a result of the sulphuric acid used in the wool cracking process. Potassium and to a lesser extent sodium, are good pollution tracer indicators for the wool-processing industries, with K values ranging from 1 200 to 1 900 mg/ℓ for the CGH and G&I boreholes, respectively (G40036 and G40042).

In Maclear's (1993) study the K / Na ratio was found to range from 1.8 : 1 to mostly 2 : 1 for the G&I borehole samples analysed. Natural background K / Na ratios of the water in the vadose zone of Eastern Cape soils are typically in the range of 1 : 2 (Vosloo, pers. comm., 1993), thus indicating a complete concentration ratio reversal in the G&I area immediately below the water table. There are very few fresh waters in which the K concentration nearly equals or even exceeds the Na concentration, such as occurs in the G&I area, and K values of more than a few tens of mg/ℓ are decidedly unusual (Hem, 1970). All these factors point to the high concentrations of K originating on the wool-washing sites to be a result of unnatural influences, and directly attributable to the effluent stream from the wool-washing process.

The H_2S smell in the area around these industries is also due to the wool washing process (Mostert, pers. comm., 1993). The breakdown product of the scouring process carried out in the wool-washing is an organic oil-in-water emulsion of mainly esters with minor percentages of acids, alcohols and hydrocarbons, in which the oily phase consists of fine droplets of wool grease (Mozes, 1979). The dissolved salts present in these wastes come from the wool wax or *suint* fraction present on the raw wool, as well as chemical additives added during scouring.

Suint is anhydrous lanolin, the water-soluble constituent of fleece, consisting largely of potassium salts of fatty acids. It is of significance that potassium comprises 60% of the calcined *suint* residue forming its main inorganic fraction, with the remainder being made up as follows: carbonate 26%, chloride 4%, sulphate 3%, sodium 2% and calcium, phosphate, magnesium and silicate comprising 1% each (Mozes, 1979). This explains the anomalously high K concentrations in the G&I and CGH groundwater samples (G40036 and G40042 in Appendix C, and Figure 24) and confirms the usefulness of potassium as an indicator of pollution resulting from the wool-washing process. The high K values in the groundwater below the wool-washing sites cannot be ascribed to natural salinity, since groundwater seepages from the Kirkwood Formation (sample ST1, Appendix B) had a low K content (about 25mg/ℓ). The high K is, therefore, directly attributable to leachate generated from the evaporation dams.

The total alkalinity (TAL) of the G&I and CGH samples is excessive, ranging from five to ten times the SABS maximum allowable limit for water used for domestic purposes, with an average $CaCO_3$ concentration of 4 200mg/ℓ. The alkalinity of natural groundwater seldom exceeds 500 mg/ℓ and it is most uncommon to obtain values greater than 1000 mg/ℓ (Hem, 1970). Alkalinity (or hardness) is a measure of the concentration of calcium and magnesium cations in bicarbonate and carbonate form. The high alkalinity of the G&I and CGH groundwater is a function of the wool-washing process, where one quarter of the suint residue consists of carbonate, indicating the usefulness of TAL as an indicator of pollution resulting from the wool-washing process.

The relatively high As content of the G&I and CGH groundwater (0.2-0.6mg/ℓ) compared with that of the evaporation dam water (generally <0.05mg/ℓ, Appendix C) is possibly a result of the residual effect of a sodium arsenite signature in the groundwater, from the historical use of this chemical as a pesticide in sheep-dip to combat ticks (Galvin, 1996). If this is the case, and considering that wool-washing has been ongoing in this area since the 1840's, the As would have been introduced to the evaporation dams via the sheep wool prior to the 1950's, whereafter the use of this type of pesticide was discontinued (Whitehead, 1973). The present effluent would not be affected, however, it is suggested that As could still be present in the vadose and shallow phreatic zones from the old farming practice described. The strong smell of sheep-dip at the exposed remnant silt layer at the base of an old evaporation dam at Gubb & Inggs (Plate 15) seems to verify this observation. Further analytical studies should be carried out to confirm this.

Figure 23 provides probably the most conclusive evidence of the contaminating effect of the wool-washing process on the groundwater down-drainage of its evaporation dams, where the borehole waters plot together with the pollution source groundwaters in the Na+K/HCO_3 field on the Piper Diagram. The Piper plotting position is anomalous with respect to the general hydrochemical trend of the study area (Figure 8 and Figure 10), and the grouping in the anion and cation fields indicate the groundwater and pollution water to be of a similar type.

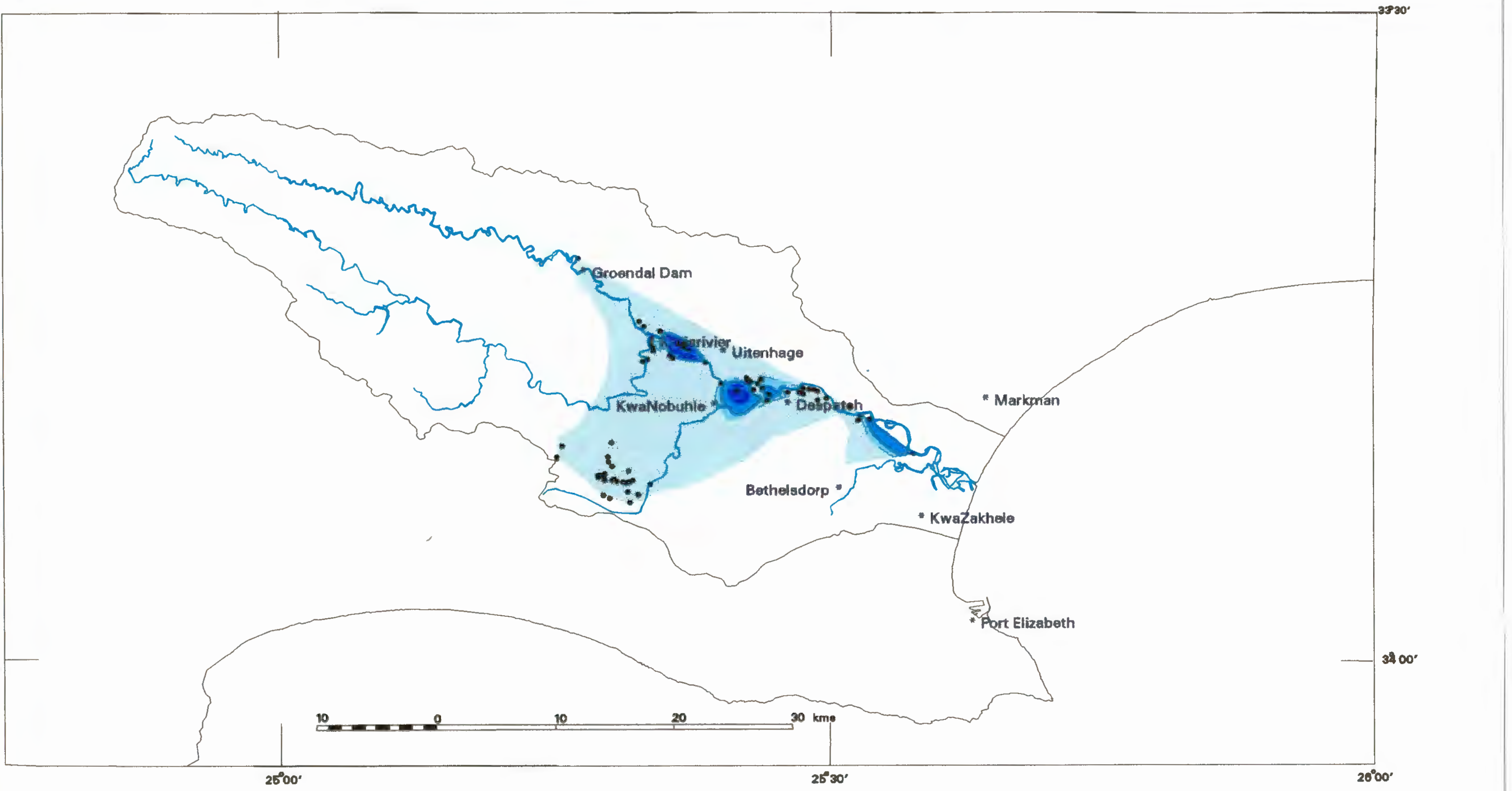


Figure 24 : POTASSIUM CONTOUR MAP

▨ 0-50 mg/l ▨ 50-200 mg/l ▨ 200-800 mg/l ■ > 800 mg/l ☐ no data

• Sampling points

Wool-pulling process

The major effect of this process on the shallow alluvial aquifer below the PWP evaporation dams, is the raising of the seepage water salinity in the immediate vicinity of the evaporation dam, and to a lesser extent the salinity of the monitoring borehole (Figure 25). The monitoring borehole's (G40039) water type is the same as that of the pollution source (Perseverance) on Figure 23, although the salinity varies significantly, with the pollution source having the highest salinity. The salinity difference is considered to be an effect of the proximity of borehole G40039 to the Swartkops River (about 30m, Orthophoto 10), and the daily interaction between the river and alluvial aquifer due to the tidal influence in this area of the River. This would result in a significant diluting effect on the leachate generated below PWP, which would explain the dramatic reduction in K concentration from >10 000mg/ℓ in the evaporation dams to <100mg/ℓ in the monitoring borehole.

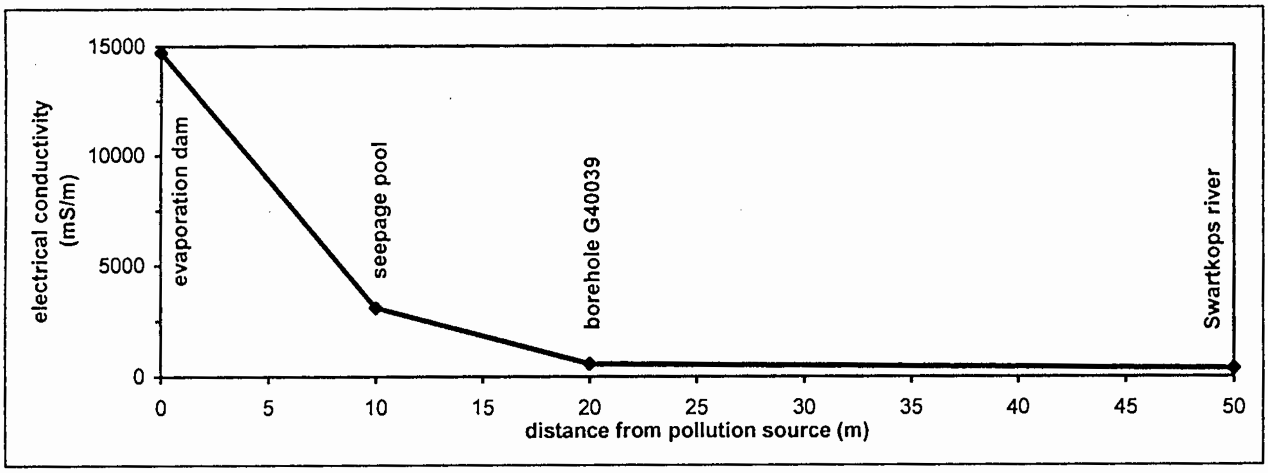


Figure 25: The effect of a pollution source on water quality - Perseverance Wool Pullery.

16.7. Nitrate Pollution

Following the discovery of relatively high sampled nitrate values from surface pollution sources (reported by Maclear, 1993) a concern existed regarding the effect of surface NO_3 pollution on groundwater in the SRAA. The following land-use practices are also considered by the author to be potential sources of NO_3 pollution:

- Small-scale irrigation of vegetables in the Elands and Kwa-Zunga River valleys.
- Extensive irrigation of vegetables, pasture and lucerne occurs (Orthophoto 2, and boreholes G40034 + G40035), with associated application of fertiliser to the agricultural lands, in the upper reaches of the Swartkops River, specifically in the Kruisrivier area.
- A chicken feedlot - Grahams Poultry (GHP), Good Hope farm - in the northern Kruisrivier area (Orthophoto 1, and Borehole G40033).

The most common contaminant identified in groundwater is dissolved nitrogen in the form of nitrate. Nitrate is very mobile in groundwater and moves in the phreatic zone with little transformation or retardation (Freeze and Cherry, 1979). The agricultural application of fertilisers and manure results mainly in NO_3 pollution of groundwater (documented in Tredoux, 1993), as well as increased levels of P and K.

Nitrogen in soil primarily originates from organic and inorganic fertilisers applied either directly to the land or via the irrigation water (fertigation) and from wet and dry decomposition of organic matter. The nitrogen in the soil is used by the crops and removed by denitrification processes and downward leaching through the vadose zone to the groundwater, where it becomes one of the most significant contaminants of groundwater resources (Van den Brink and Zaadnoordijk, 1995).

Monitoring boreholes G40034 and G40035 were sited in the Kruisrivier area (Orthophoto 2) to determine the effect, if any, of fertiliser application on the NO_3 content of the groundwater in the alluvial aquifer underlying this area. Borehole G40033 (Orthophoto 1) was sited down-drainage of the poultry farm evaporation dams to determine whether there was any groundwater pollution occurring, and surface water samples were taken downstream of the poultry farm to determine the nitrate content of water draining from the fields, which are fertilised with chicken manure and irrigated.

Borehole G40038 (Orthophoto 8) was sited on the Swartkops River flood-plain below Despatch, and G40040 (Orthophoto 11) on the banks of the Swartkops River estuary next to Redhouse, to ascertain whether any contaminated water was entering the alluvial aquifer from domestic sources such as leaking sewers.

16.7.1. Discussion of Results

Chicken farm

Sample KS1 (Appendix B) was taken from the non-perennial stream that originates at the Good Hope chicken farm, and has a high NO_3 (15mg/ℓ) together with high Na, Mg and Cl concentrations. This indicates typical "barnyard" pollution where considerable amounts of nitrogenous organic wastes concentrate in places where large numbers of animals are confined (Hem, 1970), such as in a chicken battery. The fertilisation of the poultry-farm fields with chicken manure further explains the high NO_3 values. Results from the sampling runs on G40033 show an average of 4.6mg/ℓ NO_3 in the groundwater down-drainage of the evaporation dams (Figure 26). This is the highest average NO_3 value obtained for the groundwaters sampled from the SRAA monitoring network, and is definite indication of unnatural contamination of this groundwater. The analyses of the Grahams Poultry evaporation dams (Appendix C), however, show that the expected pollution source has very low NO_3 values (below detection limits). It is thus proposed that the observed high NO_3 of the borehole is a function of seepage from the fields up-drainage of the borehole, where chicken manure is applied as fertiliser.

Evidence that seepage is in fact occurring from the evaporation dams was obtained in the field, when the salinity of the stream draining the valley in which the dams are located was measured immediately down-drainage of the dams. The water upstream of the point of seepage entry was clear and had a low salinity (35mS/m), whereas that below the point of seepage entry to the stream was discoloured and highly saline (800mS/m). In conclusion, it does not appear that leachate from the evaporation dams is affecting the monitored groundwater quality at G40033, since these waters are very different from each other (Figure 27). The hydrochemistry of the groundwater (G40033) is a function rather of natural salinity from seepage from the Kirkwood Formation which bounds the valley in which the borehole occurs, and the borehole water seems to be derived mostly from seepage from the bedrock rather than the thin, partially saturated overburden (lithological log, Appendix F).

Agricultural application of fertiliser.

No significant concentrations of NO_3, PO_4, K or NH_4 (indicator parameters for fertiliser application) were sampled in the monitoring boreholes (G40034 and G40035) below the Kruisrivier farming area. Borehole G40035 has a hydrochemistry very similar to river water (Figure 19) and is the least mineralised of all the monitored boreholes.

G40034 has a naturally high salinity, considered by Maclear (1995) to be a function of the relatively thin, poorly sorted, basal alluvial layer forming the "aquifer" in this area (Plate 9), as well as the thick clayey overburden. These factors would reduce recharge rates and increase residence time of infiltrating water, thereby increasing the time available for ion-exchange reactions to occur.

Residential sources of nitrate

The indicator parameters for general effluent, that can be expected to originate from residential areas, are EC, Na and SO_4 (DWA&F, 1993c). Boreholes G40038 and G40040, sited to monitor for potential pollution to the SRAA from domestic sources, have a hydrochemical suite indicative of natural salinity (Section 16.11), with no apparent anomalous concentrations of any of the indicator parameters.

The relatively low, yet significant, concentrations of NO_3 for these boreholes (Figure 26), however, are considered relevant. The only possible source of NO_3 in these areas is from domestic sources, and it is thus proposed that leaking sewer pipes and leaking conservancy tanks in the Despatch and Redhouse areas, respectively, explains the elevated NO_3 values. The elevated SO_4 and NH_4 of G40040 (Appendix C) are also considered to be significant, since the only possible natural source of SO_4 below Redhouse is from sea-water, and yet the observed concentrations in the groundwater are almost double that of sea-water (Appendix C). It is suggested that the concentrations of these parameters are monitored during future sampling runs for any observable trends.

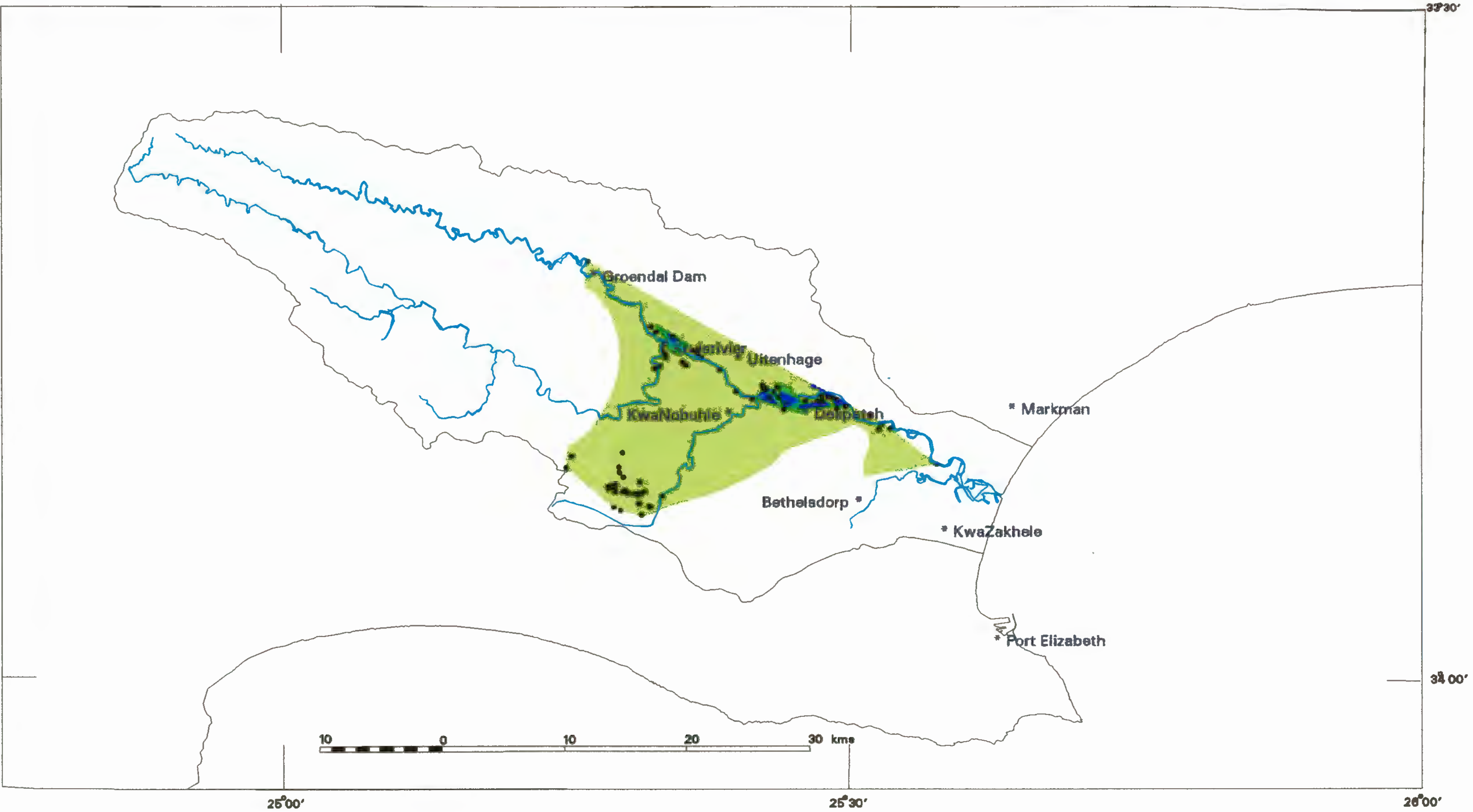


Figure 26 : NITRATE CONTOUR MAP

🟩 0-3 mg/l
🟩 3-6 mg/l
🟩 6-10 mg/l
🟦 > 10 mg/l
☐ no data

• Sampling points

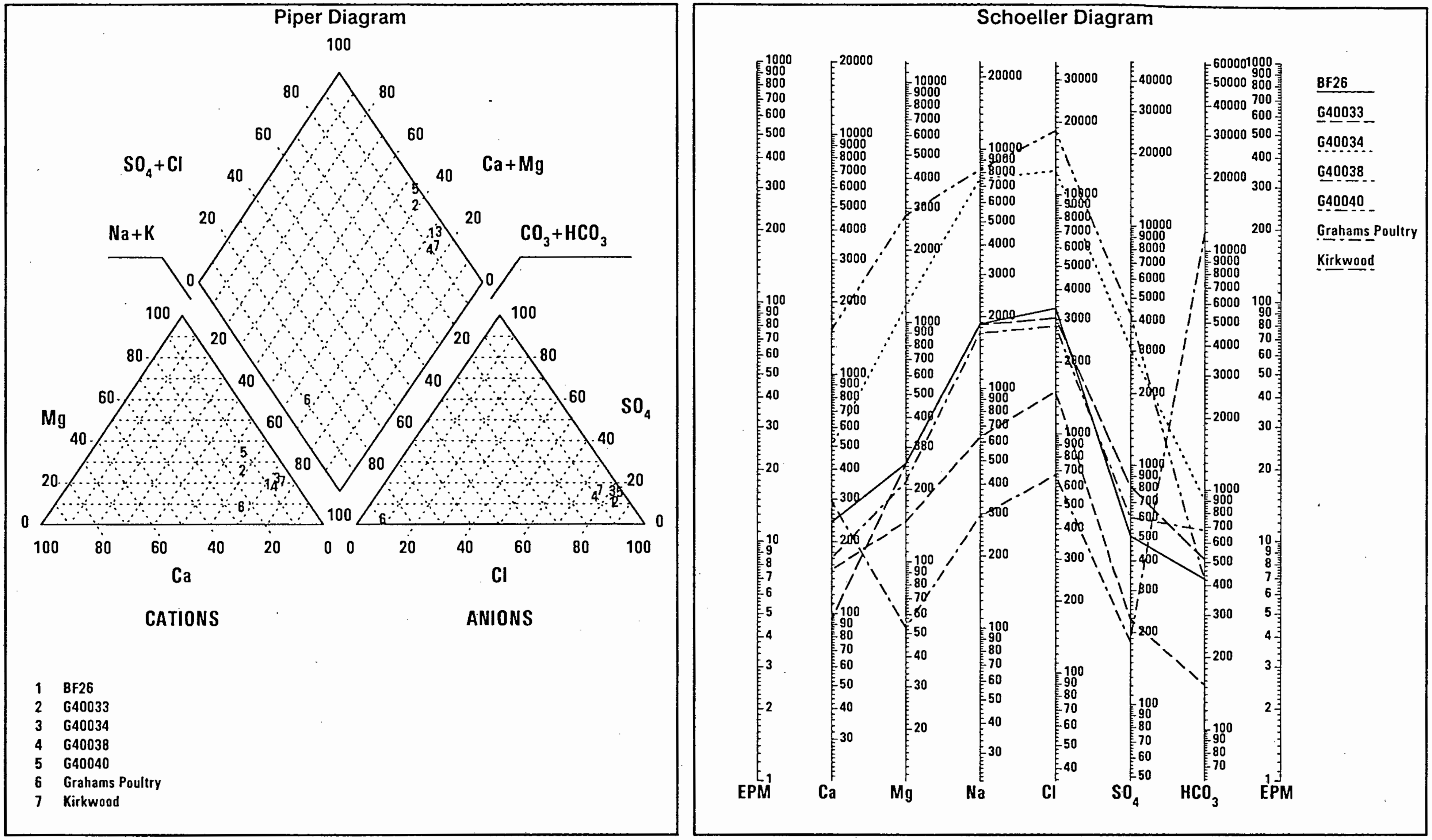


Figure 27: Farming and residential effect on hydrochemistry.

16.8. Sewage Treatment and Disposal

Maclear (1995) identified unlined maturation ponds and sewage treatment dams as potential pollution sources at the Uitenhage and Despatch, and to some extent KwaNobuhle, sewage works. Treated sewage effluent is "polished" through microbial breakdown and UV degradation in these maturation dams (Vosloo, pers. comm., 1996) which were considered as a source of contamination since they are unlined. The conservancy tanks system of sewage disposal at Redhouse was also considered as a pollution source (discussed in Section 16.7.1) and the groundwater monitoring network was thus designed to cover these points.

The risk of groundwater contamination from on-site sanitation and treatment of sewage is significant, and the risk of contamination from nitrates is of primary concern in drinking water, causing methaemoglobinaemia in infants and stomach cancer in adults. A literature review by Fourie and van Reyneveld (1993) indicated that it is not clear to what extent nitrate can be denitrified in the soil to produce nitrogen gas, which is released. The extent to which groundwater can be polluted by NO_3 from the sewage treatment process is, therefore, not fully understood. This form of pollution is, however, significant and warrants special attention.

Sanitary wastes are a combination of human excreta and sullage or "grey water", i.e. domestic waste-water from bathing, washing, laundry, etc. The constituents of sanitary wastes of primary concern to water quality (therefore indicator parameters) are: suspended solids (sludge causing anaerobic conditions), biodegradable organics (oxygen depletion if discharged untreated into the environment), nutrients, e.g. P (stimulates growth of undesirable aquatic life - Plate 16), and dissolved inorganic solids especially NO_3, SO_4 and to a lesser extent Ca and Na.

Dissolved organic and inorganic chemicals are not removed by wastewater treatment processes, and effluents from conventional sewage treatment plants contain significant concentrations of viruses and bacteria. The effluent is, therefore, unsuitable for discharge to freshwater bodies, where those water bodies are used for domestic water supplies or hands-on recreational purposes by downstream users.

16.8.1. Discussion of Results

Anomalously high concentrations of PO_4 and NH_4 were sampled in G40037 at the Despatch sewage works (DSW), in similar concentrations to that of the sampled water in the maturation dam. Since these parameters are considered as classic pollution indicators for effluent from the sewage treatment process (DWA&F, 1993c), the observed high concentration of these parameters in the groundwater at the DSW site (Orthophoto 9), are considered to be a definite indicator of pollution occurring to the SRAA as a result of the sewage works. The similarities in hydrochemical plotting positions of G40037 and DSW (Schoeller Diagram, Figure 28) provides further evidence of the effect of the sewage works' maturation dam and sludge lagoon water on the alluvial aquifer water. In contrast, the maturation ponds situated below the Uitenhage sewage works (Orthophoto 7) do not appear to be affecting the hydrochemistry of the groundwater in the SRAA, with borehole G40041's hydrochemistry being indicative of natural salinity in the alluvial aquifer, i.e. NaCl character and highly mineralised (Figure 28 and Section 16.11).

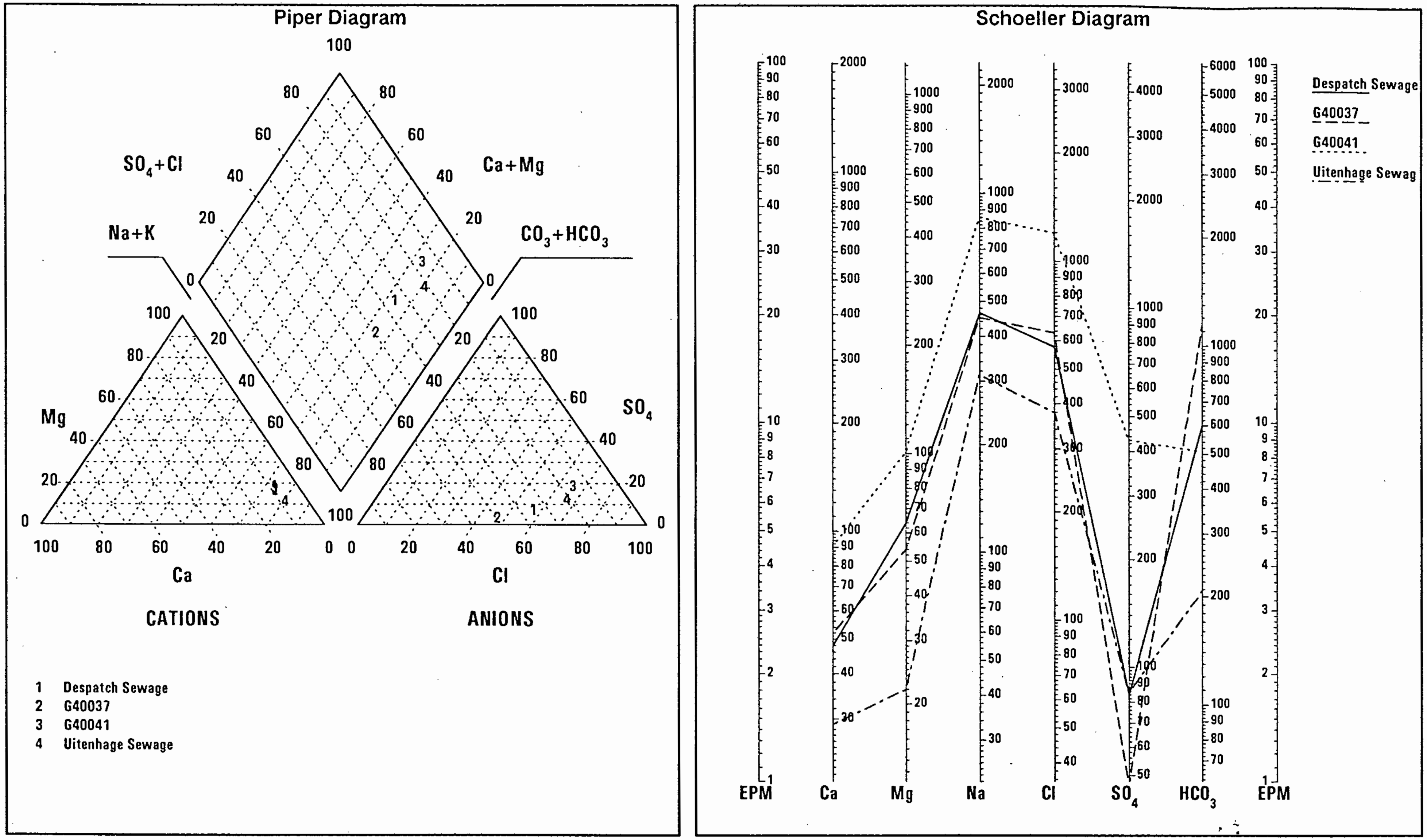


Figure 28: Sewage works related hydrochemistry.

16.9. Pollution Volume Estimations

One aim of this study (Section 1.2) was to provide an initial estimate of the volume of leachate-contaminated water which was entering the shallow hydrological system. The contaminated water enters the SRAA and thereby flows as base-flow into the Swartkops River. The identified pollution sources of concern in the Swartkops River Basin are detailed in Appendix H and shown in Orthophotos 1-11.

Estimations of volumes were made using Darcy's method (in Fetter, 1988) for calculating groundwater flux (Equation 4) and using the data presented in Table 8. For the purposes of this exercise the following were assumed:

- the aquifer hydraulic parameters are constant along the whole wetting front,
- the hydraulic parameters for the SRAA, derived in Maclear (1995), could be extrapolated to apply to areas of similar geology, based on observed lithology from the borehole logs, and
- no impeding artificial liners were present beneath the pollution sources identified as "unlined" (this is considered to be a safe assumption since the information on the liners was derived from field observations and confirmed with the land-owners),

Equation 4: Simplified Darcy equation for calculation of groundwater flow.

$$\boxed{\begin{aligned} Q &= T \times i \times w \\ Q &= K \times b \times i \times w \end{aligned}}$$

where: Q = groundwater flow or flux (m^3/day)
T = transmissivity (m^2/day)
K = conductivity (m/day)
b = aquifer thickness (m)
i = hydraulic gradient (dimensionless)
w = width of aquifer/wetting-front (m)

16.9.1. Discussion of Results

The relative contributors by volume, to the SPL of the SRAA can be readily seen from Table 8. The largest annual groundwater flow volume is derived from the residential village of Redhouse. This volume, however, is not significant since the water sampled from the monitoring borehole G40040 (Appendix C) only shows a small degree of contamination (moderate NO_3 and NH_4). This contamination is considered to be derived from the leaks in the conservancy tanks system of sewerage disposal in the area, the reason why the site was chosen for a monitoring borehole. The high salinities and very similar concentrations of the major ions and trace metals (especially Sr and B) to that for sea water indicates a sea-water origin of the water from the borehole. This is supported by the proximity of the monitoring borehole to the tidal influence of the Swartkops River estuary, where the aquifer will alternately gain and lose water due to fluctuating head conditions induced by the tides.

Table 8: Relative pollution load contribution from various sources in the Swartkops River Basin (refer to Equation 4 for definition of terms).

Pollution source	Surface area (1000m^2) *	w (m)	b (m) **	Cross-section area $w \times b$ (m^2)	K (m/day) ***	Velocity $K \times i$ (m/day) ****	Q (m^3/day)	Q (m^3/year)
GP	17	150	1.0	150	25	0.06	8.6	3 150
G&I	179	1 300	3.0	3 900	50	0.12	448.5	163 700
ECT	95	100	0.5	50	5	0.01	0.6	210
USW	22	150	3.0	450	50	0.12	51.8	18 890
CGH	171	300	2.5	750	25	0.06	43.1	15 740
DSW	33	300	3	690	50	0.12	103.5	37 780
PWP	41	350	3	1 050	5	0.01	12.1	4 410
RH	8 285	1 270	6	7 620	50	0.12	876.3	319 850

GP = Grahams Poultry farm, G&I = Gubb & Inggs wool washers, ECT = East Cape Tanning, USW = Uitenhage sewage works, CGH = Cape of Good Hope wool washers, DSW = Despatch sewage works, PWP = Perseverance wool pullery, RH = Redhouse.

* surface area of unlined source of pollution.

** saturated aquifer thickness (*b*) from lithological logs and water-level measurements in Maclear (1995), as shown in Appendix F.

*** hydraulic conductivities (*K*) derived from aquifer tests in Maclear (1995), and extrapolations made for areas of similar geology.

**** hydraulic gradient (*i*) for the water-table in the SRAA = 0.0023 from Maclear (1995).

The high Fe concentration is possibly a function of corrosion of plumbing pipes and underground tanks under the oxidising conditions of the alkaline sea-water which dominates the hydrology of the area underlying Redhouse. Further sampling runs would enable confirmation of this observation.

The major contributor of pollution to the SRAA is the set of Gubb & Inggs evaporation dams (Table 8). The dominance of this source over the other pollution sources in the study area is a function of its long wetting front and the relatively high hydraulic conductivity (*K*) of the alluvial gravel underlying the site (G40036, Appendix F). The highly contaminating nature of the effluent stream, which is piped to the evaporation dams and leaches into the SRAA and thereby into the Swartkops River (Section 16.6, and Appendix C) - indicates the significance of this source as a **major** contributor to the pollution load of the Swartkops River (see Figure 21).

The sludge lagoons and maturation ponds at the Despatch and Uitenhage sewage works and the Cape of Good Hope evaporation dams are the next highest contributors by volume of leachate to the hydrological system of the SRAA. From the hydrochemical analyses presented in Appendix C it can be seen that these sources are not as significant with respect to pollution load as, for example, the G&I evaporation dams, although the observed groundwater chemistry is saline. The anomalous and extremely high NH_4 of monitoring borehole G40037, and TAL and K of borehole G40042 (down-gradient of the Despatch sewage works and the Cape of Good Hope evaporation dams respectively), however, indicate a definite impact of these pollution sources on local groundwater chemistry (Sections 16.6 and 16.8).

Relative to the other pollution sources in the study area, the PWP and ECT evaporation dams contribute the least volume of contaminated water to the hydrological system. Using these two sites as an example, it can be seen that the surface area of the pollution source is unimportant in the calculation of the volume of flow of groundwater per unit time issuing from below the sites. The significant parameters are instead the short length of the wetting front and thin saturated aquifer thickness in the case of the ECT site, and the low *K* in the case of both sites.

In conclusion, there is significant contribution of the various pollution sources to the pollution loading of the Swartkops River, with relative contributions being dependent on site-specific factors such as size and shape of the source as well as the geohydrology of the aquifer underlying and down-gradient of the source. When analysing the results presented here, it should be noted that the estimates of *Q* in Table 8 are considered to be conservative for the following reasons:

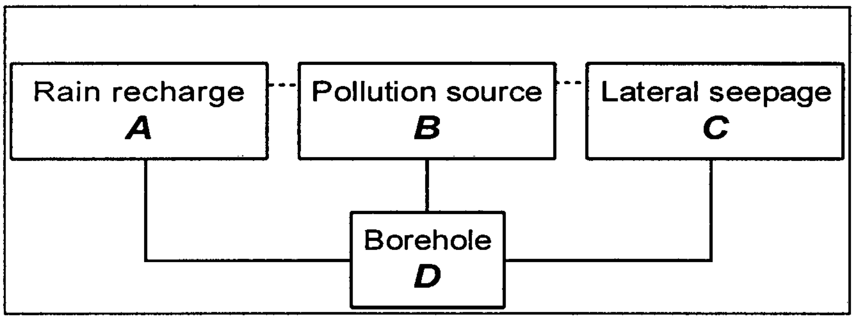
- In the case of local surface water impoundments, the hydraulic gradients are site-specific and will depend on the head of water present in, for example, the evaporation dam. This head will differ at irregular intervals (Section 13.5), but in all cases will produce a localised steeper gradient than that derived by Maclear (1995) for the whole SRAA. This will result in higher flow velocities and, ultimately, larger volumes of flow per unit time. Since it was logistically unfeasible to derive an average hydraulic head for each pollution source, a single figure for *i* was used. This is, however, considered acceptable for purposes of standardisation and comparison.
- The groundwater flow lines were assumed to be perpendicular to the wetting front and no dispersion of the pollution plume, generated from the leachate source, was considered to occur. In reality there will, however, be a degree of plume dispersion as a function of the dominant flow regime present down-gradient from the pollution source. This dispersion will result in a broadening of the plume wetting front with flow away from the pollution source towards the Swartkops River - the local drainage base of the groundwater in the SRAA. As the front broadens, a larger cross-sectional area of the aquifer will be affected by the pollution.

16.10. Chemical Mixing Exercise

An attempt was made to determine the relative hydrochemical contributions of the various potential sources of water input to the SRAA, based on the conceptual model of the hydrological system illustrated in Figure 22 and Figure 29. It was hypothesised that the observed chemistry of the groundwater (sampled at the monitoring boreholes) is proportionally accounted for to differing extents by the various chemical inputs to the system.

The data from the sampling runs carried out on the groundwater monitoring network and pollution sources, analyses from Maclear (1993) and rain-water samples taken for this study were processed with a linear optimisation method, using the "Mixer" computer program. The program is a general purpose least squares approximation routine for calculating mixing equations, modified from the "LSPX" program written by Bryan, Finger and Chayes*. A 4x7 matrix (4 variables and 7 chemical elements) of linear formulae was optimised for each pollution site to determine the best chemical mixing solution of the inputs to approximate the observed chemistry of the borehole water.

Figure 29: Conceptual chemical mixing model.



The following expression was optimised for each pollution site, using the major ions Ca, Mg, Na, K, $CaCO_3$, SO_4 and Cl as the input elements:

$$xA + yB + zC = D(calc)$$

where:

- *A, B* and *C* are the independent variables, i.e. the analysed chemistry of the inputs to the hydrological system (recharging rain water, effluent from pollution source and lateral seepage from the Kirkwood Formation),
- *D(obs)* and *D(calc)* are the dependent variables, i.e. the observed (analysed borehole water quality, Appendix C) and calculated chemistry of the output, and
- *x, y,* and *z* are the mixing coefficients.

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* in *Science* (1969), **163**, 926-927.

The optimisation routine solved for *x*, *y*, and *z*, and compared *D(calc)* to *D(obs)* for error estimation. No weighting vector was applied to the input variables in order to avoid any subjectivity entering into the iteration process. A summary of the results of the optimisation exercise is shown in Table 9.

Table 9: Chemical mixing exercise for the hydrological system, SRAA.

Site name	Mixing coefficient *		
	Rain recharge *x*	*Pollution source* *y*	*Lateral seepage* *z*
G&I	100	0	0
CGH	95	3	2
ECT	97	0	3
GP	96	0	4
DSW	82	18	0
USW	91	8.5	0.5
PWP	99	0	1

G&I = Gubb & Inggs wool washers, CGH = Cape of Good Hope wool washers, ECT = East Cape Tanning, GP = Grahams Poultry farm, DSW = Despatch sewage works, USW = Uitenhage sewage works, PWP = Perseverance wool-pullery.
* mixing coefficient normalised and expressed as percentage.

Table 9 shows that the chemistry of the rainfall recharge, with the exception of the DSW site, accounts for more than 90% of the observed borehole chemistry, with the influence of lateral seepage from the bounding Kirkwood Formation accounting for only a small proportion (<5%) of the groundwater chemistry. According to the optimisation exercise, the pollution sources generally have little to no influence on the hydrochemistry of the groundwater in the Swartkops River alluvial aquifer.

The anomalously high mixing coefficient, apportioned by the optimisation program to the pollution source at the DSW site, is possibly a function of a high degree of hydraulic connectivity between the monitoring borehole (G40037) and the maturation dams and sludge lagoons at the sewage works, as well as the proximity of the borehole to these structures (Orthophoto 9). This would allow little chance for dilution or attenuation of the seepage from these dams by the groundwater, before being intercepted by the monitoring borehole. The chemistry of the borehole water would therefore reflect that of the pollution source to a considerable degree.

On first appraisal, the results of the optimisation exercise appear to contradict what would naturally be expected, given the results of the sampling runs on the network of monitoring boreholes (Appendix C), i.e. that the pollution sources account for the observed borehole chemistry. On consideration though, all groundwaters - excepting juvenile water - originate from rain water recharge, which in turn is derived ultimately from evaporation and precipitation of sea water (hydrological cycle). The hydrochemistry of rain water (Figure 30), therefore, will have the over-riding effect on the hydrochemistry of the shallow groundwater in the SRAA.

A further factor of significance is that of scale. All the pollution sources, though termed diffuse sources of pollution on a local scale, e.g. the immediate area around the pollution site, are point pollution sources on a larger regional scale, e.g. the catchment area to the alluvial aquifer. Processes of dilution, attenuation and dispersion of contaminants in the groundwater therefore become significant, and the groundwater chemistry correctly indicates the dominance of the global recharge component on its hydrochemical facies.

The results presented above should not be taken as an indication by parties which are guilty of polluting the SRAA that there is no effect of their contaminating practices on the aquifer. It has been clearly shown in the preceding sections (16.5 to 16.8) that there are definite local effects of unnaturally occurring mineralisation of the groundwater as a result of pollution!

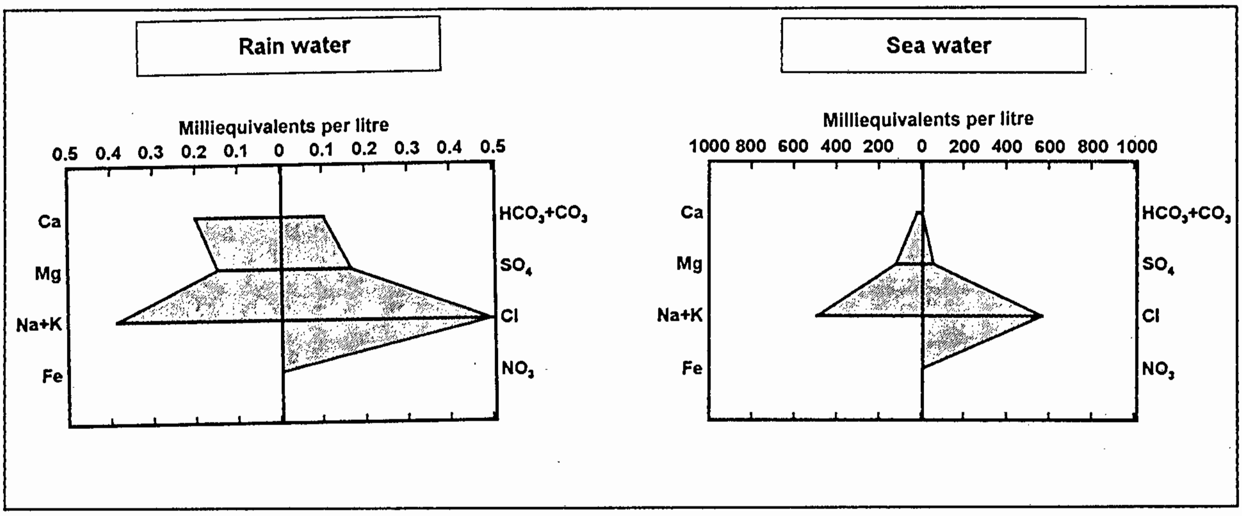

Figure 30: Rain and sea-water hydrochemistry.

16.11. Natural Salinity

There are localised occurrences of high salinities in the groundwater of especially the shallow SRAA, as a result of pollution to the aquifer. Within the parts of the study area underlain by Uitenhage and Bokkeveld Group sediments, however, there is a predominance of natural salinity in the groundwater, as detailed in sections 5.1 and 11.2.4. Figure 27 clearly shows the similarity in hydrochemistry of groundwaters originating from saline lithologies (compare "BF26" - Bokkeveld Group borehole and "Kirkwood" - a seepage issuing from the Kirkwood Formation).

With reference to Figure 31, the EC contours at the Brakkefontein cadastral farm, in the south-central portion of the study area illustrate an occurrence of natural salinity, with an average EC for this area of 180mS/m (from Maclear, 1993) and a NaCl-type water (Figure 8). The perched alluvial aquifer below Despatch (Plate 4) has very high salinities (av. 980mS/m from Maclear, 1993) as a result of the clayey nature of the overburden to this aquifer (Section 13.1.3) and slow movement of groundwater, and limited recharge area.

The bank seepage (groundwater sample ST1 - Appendix B) immediately south of the Spoornet workshop near Despatch (Orthophoto 8) has a high salinity (high EC and TDS as well as high concentrations of the major inorganic salts, i.e. Na, Cl and Mg), but is low in the organic pollutants. This can be attributed to the natural high salinity of the groundwater associated with the mudstones and siltstones of the Kirkwood and Sundays River Formations (Sections 5.1 and 8). The high SO_4 value is most likely due to a) the organic constituent of these sedimentary rocks (documented in Table 1 to be rich in plant, animal and marine fossils), which would yield large amounts of sulphates through oxidation (Freeze and Cherry, 1979), and/or b) as a residuum from palaeo seawater incursions.

In the eastern parts of the study area, the groundwater salinity generally exceeds 300mS/m (Figure 31) in the sampled boreholes. This is again attributable to the naturally high salinities of the seepage water in the Uitenhage Group sediments underlying most of these regions, where by way of example, brine is pumped from borehole FF2 (Map 5, Appendix A) for salt production. The occurrence of salt pans (Map 3) in the eastern areas gives further evidence of the existence of natural salinities in these formations.

Dug-wells in the shallow alluvial aquifer in the Perseverance area (av. EC of 660mS/m from Maclear, 1993) and borehole G40040 drilled at Redhouse into shelly sand estuarine deposits (EC of 4800mS/m, and F and Sr concentrations similar to sea water, Appendix C) indicate the effect of sea-water salinity introduced tidally to these areas (Section 16.9).

There are numerous trace metal hydrochemical indicators of naturally occurring "contamination" from geological deposits. Trace metal data of groundwaters in the study area are available in quantity only from the sampling runs carried out on the SRAA monitoring network, reported on in Maclear (1995). The analyses of significance (in Appendix C) with respect to naturally occurring concentrations are:

- **Iron and Manganese** - abundant and widespread in rocks and soils and closely related in chemical behaviour. The high Fe and Mn content of the groundwater sampled in the SRAA monitoring network is probably a function of the oxygenated condition of the recharging water (shallow water-table) which will attack any reduced iron and manganese elements present in the sedimentary deposits, to yield ferrous iron and ions of Mn (Hem, 1970).
- **Strontium** - Strontium is a common element in minor amounts especially in sedimentary rocks (Hem, 1970). Its occurrence in the groundwater samples from borehole G40040 (Redhouse) in concentrations similar to that of sea-water, provides a useful indicator of natural salinisation of the aquifer occurring at this point.

The fact that the trace metal concentrations of significance are almost always higher for Sampling Run 1 than Runs 2 and 3 (Appendix C), is a function of the acid preservation of the borehole samples from Run 1, with associated limitations to interpretation (Section 17). By way of example, the acidification of the water sample during Run 1 produced ferric iron, and thus the reported high Fe concentrations; whereas the equilibrium conditions of the SRAA groundwater (pH 7-8) would only produce low concentrations of ferrous iron, and hence the low Fe values for Sample runs 2 and 3.

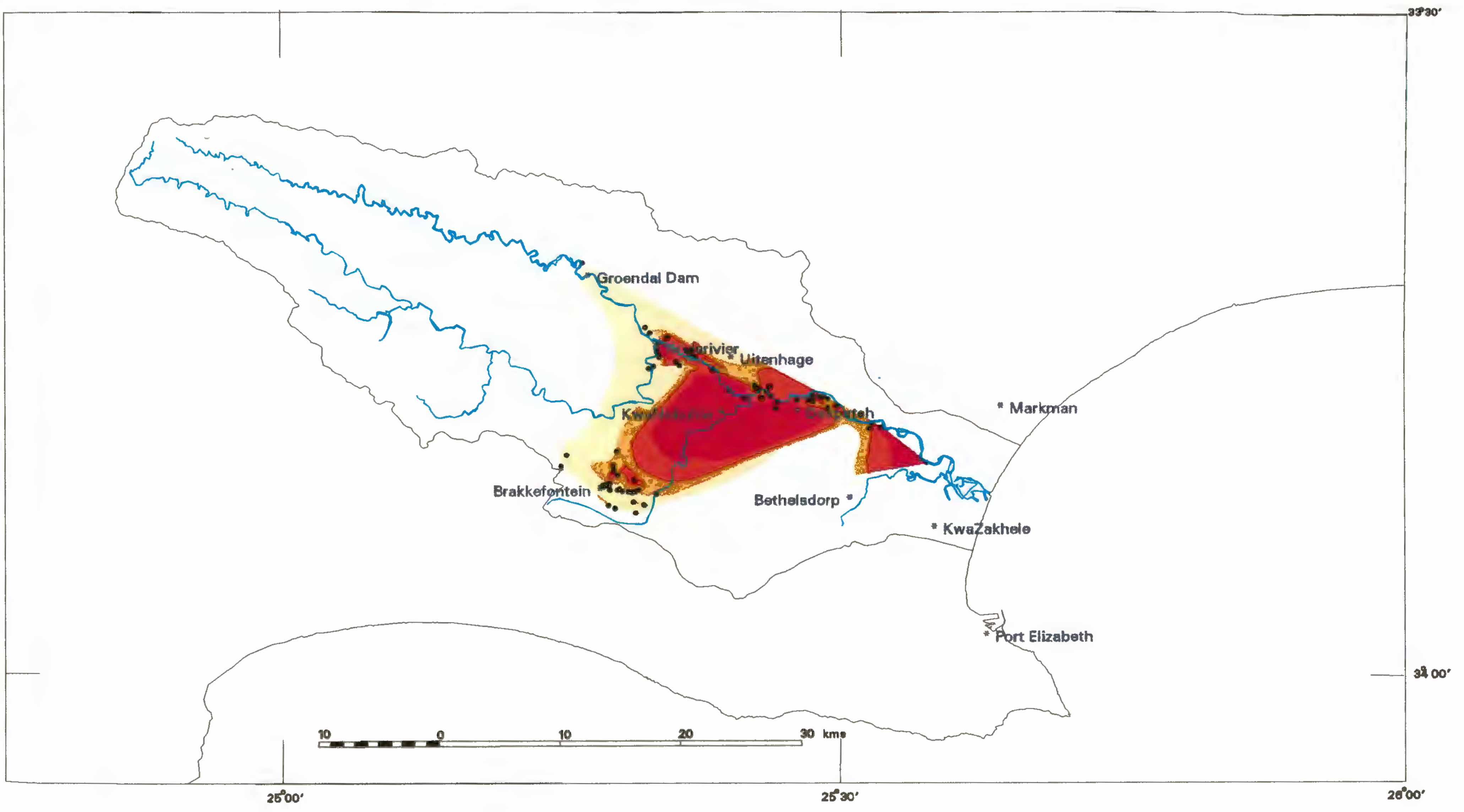

Figure 31 : EC CONTOUR MAP

17. PROJECT LIMITATIONS

- The groundwater hydrocensus was carried out in two separate sampling runs, i.e. start of the 1992 wet season, and the end of the 1993 dry season, due to various reasons. Variations in water quality should thus be viewed in the light of temporal differences in water level fluctuations and recharge.
- Some of the information obtained for the sample points surveyed during the hydrocensus was dependent on the owner's memory and is thus subjective. Where uncertainty existed regarding the borehole depth and geology, it was difficult to determine which aquifer the borehole was exploiting since the lithology penetrated was unknown. In cases where the owner was unavailable for the census, reasonable assumptions had to be made or a "?" entered on the data sheet as reflected in Appendix A.
- In cases where the sample point was not being used for abstraction purposes and therefore not equipped with a pump, purging of the borehole was not possible since a transportable pump was not available. A grab sample of stagnant water was instead taken, which is not necessarily representative of the natural groundwater occurring below that point or in the adjacent formation.
- Dug-well yields were generally very low, making the time required for complete purging of the well by the installed pump excessive. Most of these points, however, were being used on a continual basis, e.g. for garden irrigation purposes, and thus it was assumed that most of the dug-wells' samples were representative.
- Due to the poor spread of the sampled points over the whole study area, the groundwater level and hydro-chemical contouring of the data points using *Arc/Info* GIS resulted in an understandable degree of extrapolation between points in areas of data scarcity.
- The groundwater contour plot should be viewed only as broadly representative of rest water levels, since shallow and deep boreholes and dug-well rest water levels were combined in a single database for manipulation purposes. A further consideration is that a small percentage of the water levels were measured during pumping, during recovery or were purely rest water levels, with no groundwater artesian pressures being recorded. Anomalies will thus occur, but the data presentation is considered useful for areal comparison purposes, general trends are identifiable from the maps, and groundwater flow lines can be relatively accurately deduced.
- Borehole depths alone could not be used as an accurate representation of the aquifer type being "tapped" for groundwater provenance estimations, since many of the borehole casings, especially in the Kruisrivier area, have rusted. The rusted casing is ineffective in sealing off the Cretaceous formations and shallow alluvial groundwater, and this groundwater would leak into the borehole and mix with the deeper aquifer groundwater, producing a hydrochemically mixed sample as well as irregular water level readings.
- Following on from above, a few of the sites were sampled while groundwater was being pumped from the borehole / dug-well or immediately after the pump was shut down, i.e. during the period of water level recovery. This pumped sample represents a mixture of

groundwaters across the vertical section of an aquifer and usually consists of the most readily available groundwater in the system, i.e. the groundwater in the most transmissive rock layer or fracture zone. Edmundson (1980) states that pumped samples are important with respect to supply and yield estimations, but are useless for efficient and representative groundwater quality evaluation, unless the exact hydraulic conditions are known. The ionic concentrations occurring in the study area samples are useful, however, for comparison purposes and give definite trends.

- Water samples from the initial hydrocensus submitted for macro analysis were not preserved to prevent bacterial activity in the sample during the time period between sampling and analysis. The pH and inorganic nitrogen thus do not accurately represent field conditions. A study by Grobler et al. (1978), showed that concentration changes in an unpreserved sample vary from 2% for potassium to 95% for nitrate as a result of ageing of the sample before analysis. Schoonraad (pers. comm., 1993), however, states that these differences in the reported nitrogen values, are only of significance in concentrations typically less than 0.05mg/ℓ and that high concentrations (in tens of milligrams per litre), of relevance in this study, will be relatively unaffected, remaining similar to or the same as concentration conditions existing during the time of sampling.
- Analytical ionic imbalances occur. These, however, are to be expected as the cation and anion sums are seldom equal because of unavoidable variations in analyses and hydrochemical reactions which occur between time of sampling and time of analyses. Inequality thus increases as ionic concentrations increase. It should be noted, however, that accredited analytical laboratories of the DWA&F's Institute for Water Quality Studies (IWQS) and the CSIR were used for all the reported hydrochemical analyses, and ionic balance errors rarely exceeded 5% for the suite of water samples analysed for this study.
- The first sampling run carried out of the SRAA monitoring boreholes and pollution sites used HNO_3 to preserve the samples for trace metal analyses, whereas the samples from the next two sampling runs were unpreserved. This resulted in anomalies (in the trace metal results for different sampling runs) due to the leaching/digesting of the acid soluble fraction of the sediments in suspension, on preservation of the sample with acid. Most of the samples submitted were highly polluted and not clear, indicating the high suspended sediment load of the sample. The ultimate result is that the acid preservation increased the metal concentrations above "normal" expected levels. Since the aim of the sampling is to determine the quality of the groundwater in the SRAA under equilibrium and undisturbed conditions, the acid-preserved samples are generally discounted for the purposes of discussion of results.
- Hydrocensus samples were analysed for inorganic constituents only, thus bacterial and thermal pollution inputs were not indicated such as raw sewage discharge, with resulting high levels of *E. Coli* bacteria, OA and DOC.

18. SUMMARY AND CONCLUSIONS

The Swartkops River Basin is geohydrologically complex and lies within South Africa's largest artesian basin, centred on the industrial city of Uitenhage. Two aquifer types of significance occur, *viz.* a deep fractured secondary aquifer and an unconfined shallow alluvial aquifer. The Swartkops River Basin is structurally subdivided into two main aquifer units, *viz.* the Coega Ridge Aquifer and the Swartkops Aquifer, to the north and south of the Coega Fault respectively. The Swartkops Aquifer Unit is further sub-divided into the Kruisrivier and Bethelsdorp Compartments and the Swartkops River Alluvial Aquifer.

The primary alluvial aquifer is thin and only covers a relatively minor area within the river basin. It is, however, significant as an aqueduct of leachate, generated from surface pollution sources, to the river, by means of baseflow. The aquifer consists of a basal lag deposit of medium to coarse sand and gravel overlying an impermeable bedrock of Uitenhage Group sediments, and overlain by a semi-confining overburden of sandy soil and clayey silt. The aquifer hydraulic conductivity is sedimentologically controlled and variable within the river basin, and is a function of the grading of the alluvium as well as the overburden thickness.

The groundwater in the alluvial aquifer has a sodium-chloride character as a function of the hydrochemical facies of the rainfall recharge. Quality varies in response to the occurrence of natural saline seepage inputs from the bounding Uitenhage Group sediments and overlying clayey silt, as well as leachate from surface pollution sources. The localised effects of diffuse pollution sources on the hydrochemistry of the alluvial aquifer in places, down-gradient of the pollution input, is readily apparent. Chemical indicator parameters were very effectively used to identify the source of contamination to the groundwater in the alluvium. Estimations made on volumes of contaminated water entering the groundwater system show that the quality of the alluvial aquifer is generally not influenced by pollution, except in the central regions of the Swartkops River Basin, around Uitenhage and Despatch.

More effective control of pollution inputs into the hydrological system of the Swartkops River Basin is essential if the future sustainability of this resource is to be ensured. Polluters should be made aware of the effect of their contaminating waste disposal practices and should be encouraged to co-operate in ensuring a reduction of effluent inputs to the vulnerable alluvial aquifer.

The secondary aquifer is confined to semi-confined and consists of quartzites and sandstones of the Table Mountain Group in the northern and western areas, and sandstones and conglomerates of the Table Mountain and Uitenhage Groups in the central and southern regions. Artesian to sub-artesian conditions exist in places where the secondary aquifer is overlain by impermeable confining siltstones and mudstones of the Uitenhage Group, generally in the central and eastern regions of the river basin. The thickness of the confining layers increases eastward along the strike of the pre-Cretaceous Uitenhage Basin, making drilling for groundwater uneconomical in these area.

The groundwater is generally fresh, unpolluted and of good quality in the secondary aquifer and has a sodium-chloride character due to the proximity of the river basin to the sea. The seepage groundwater in the argillaceous Uitenhage and Bokkeveld Group sediments is generally highly saline, of a connate origin and is unusable for most purposes. The salinity of the groundwater in the Swartkops River Basin increases from west to east as it moves from recharge to discharge areas.

Groundwater is abstracted on a large scale from the secondary aquifer for irrigation in the Kruisrivier and Coega Ridge areas, as well as for residential supply to Uitenhage and Despatch from the Uitenhage Springs. Smaller-scale abstraction from boreholes and dug-wells occurs, for rural domestic and stock-watering purposes mostly in the southern and western farming areas of the catchment. Drilling for water in the Swartkops River Basin, mainly along the Coega Ridge and in the Kruisrivier areas in the first half of the century, has resulted in significant declines in water-levels and piezometric levels as well as reductions in yields of individual boreholes and springs, as abstraction exceeded recharge. This illustrates the vulnerability of the groundwater system to over-exploitation and resulted in controls on abstraction being imposed by means of a declaration of a government groundwater control area. As a result, a generally increased resource-awareness occurred amongst the groundwater users in the area, with a consequent small reduction in groundwater exploitation. Co-operation from all users will, however, be necessary to ensure that the exploitation potential of this valuable groundwater resource is maintained in the future, for the benefit of the region as a whole.

19. RECOMMENDATIONS

19.1. Further Investigations

The following additional studies are recommended:-

- Only two rainfall samples were used to determine the concentrations of Cl used in the Cl-mass balance equation to determine recharge (Section 15). Since the Cl input concentration from rainfall is an essential requirement for determination of recharge using this method, it is recommended that additional rainwater samples are obtained and analysed from different parts of the study area for different climatic events, in order to obtain a more accurate estimation of recharge.
- Analysis of groundwater samples from borehole G40041 for hydro-carbon contamination in order to conclusively identify the source of the smell and colour (noticed in Maclear, 1995) during the aquifer tests carried out on this site (Section 19.3).
- Additional aquifer tests carried out at selected sites to improve the existing understanding of the hydraulic parameters over the whole aquifer area, as well as to increase the confidence level for the parameters presented in this study (Section 13.2).
- Installation of additional boreholes to determine the polluting effect of known pollution sources as yet uncovered by the monitoring network, e.g. the Kat Canal, on the alluvial aquifer.
- The installation of a water level recorder on borehole G40038 (Despatch chimney) to monitor response of the phreatic water table to rainfall events, specifically the magnitude of water level fluctuations and speed of response in fluctuations to different rainfall events. The information gained would be valuable for recharge calculations. Borehole G40038 is considered suitable for this type of study since: a) it is relatively isolated from habitation which will reduce the chances of vandalism, b) its water level will not be influenced by changing water levels in surface impoundments such as evaporation dams, and it is located about 350m south of the Swartkops River and therefore will not be influenced by river stage, and c) the borehole intersected a relatively thick alluvium package (3m).
- On-going quantification of the movement and effect of contaminants on the groundwater and surface water resources of the Swartkops River flood-plain by monitoring and modelling, as well as assessing the cost and impact of the pollution.
- Use of environmental isotopes for improving the conceptual aquifer models.

19.2. Pollution Management Recommendations

- ***Prevention is better than Cure!***
- The disposal of industrial effluent to evaporation ponds, as a method of “treatment”, is undesirable due to the problems of sludge disposal, odours and groundwater pollution. On-site pre-treatment is, therefore, essential prior to disposal to evaporation dams.

- Industries should be motivated to reduce water-intake, recycle and effectively manage their waste-water disposal. Co-operation should be encouraged between the government and the public sectors to address this matter.
- The DWA&F's receiving water quality objectives (RWQO) approach to manage water quality and minimise risk to the environment should be enforced, to ensure that effluent is returned to the water body in concentrations which do not exceed the long-term assimilative capacity of the water resource.
- A differentiated protection policy (DWA&F, 1991) should be implemented to maintain groundwater in a pristine condition where possible. Stricter site-specific requirements should be set, according to the aquifer and uses of the groundwater from the aquifer, to maintain fitness for use.
- There should be a ***much stricter*** enforcement by the DWA&F of the "polluter pays" principle, to encourage the control of the pollution problem at source, and to link the polluter and the impact.
- And most importantly, effective design and management practices, for existing as well as new developments, should be prescribed to curb groundwater contamination and pollution, since these are much easier to control at the inception and operation stage than by the monitoring of effluent streams.

19.3. Groundwater Monitoring Recommendations

Recommended parameters to be monitored are the following :-

- groundwater quality: pH, EC and DO (field measurements), full macro and trace metal (laboratory analysis),
- pollution sources water quality: full macro and trace metal (laboratory analysis),
- river water quality: data obtainable from DWA&F - WQM (Port Elizabeth office),
- groundwater levels.

The following monitoring frequency is suggested :

- quarterly groundwater and pollution sources quality,
- monthly water levels.

If no accountable trends or anomalies are noticed in water quality variations with time, it is suggested that the monitoring frequency as well as monitored parameters be revised and adjusted after the first year of monitoring and once the hydraulic parameters are better understood. This will save on analytical expenses and reduce unnecessary monitoring. It should be noted that the quality of tannery and wool-washing waste waters tends to vary greatly over relatively short time periods. Care must thus be taken to ensure that the samples are representative when sampling these process waste waters. It is further suggested that the groundwater samples from the monitoring boreholes be analysed for organic constituents in areas of suspected microbiological leaching, e.g. sewage works.

19.4. General Aquifer Management

Since groundwater from the Swartkops River Basin is an important supply of water for domestic and large-scale irrigation purposes, it is vital that a groundwater resource awareness is initiated and encouraged to ensure water conservation in the future.

Abstraction from the Coega Ridge and Swartkops Aquifer Units should be planned, and carried out on the advice of geohydrological specialists, for the ultimate benefit of the groundwater users and the community dependent on this resource. The antipathy of groundwater consumers, and particularly the groundwater polluters, with respect to co-operating with control measures could be overcome by involving them with local management. In order to implement management schemes with minimal upset, it will be necessary to involve the groundwater users directly in the development, management, and distribution of the groundwater resource. In this way the responsibility for resource management will be shared co-operatively between the users and the controlling body, i.e. DWA&F, in the interest of the whole community.

In 1916 the Sandfontein borehole was drilled in the Coega Ridge aquifer unit and an artesian yield of 8ℓ/s was obtained. This borehole was allowed to flow to waste on surface for 12 years until 1928, when it was re-equipped and the artesian flow only then controlled! In 1954 the steel borehole casing rusted through, allowing good quality groundwater to flow to waste under pressure into the Cretaceous sediments. This borehole was eventually grouted by the DWA&F only in the 1980's! Wasteful practices such as these must not be allowed to re-occur in the future.

The major aims of the declaration of the Uitenhage subterranean government water control area in 1957 were to maintain the artesian character of the Uitenhage artesian basin and especially the Coega Ridge aquifer unit, in order to ensure the long-term sustainability of the groundwater resource. If uncontrolled abstraction of groundwater is allowed to occur in the future, as occurred in the period 1910-1960, there will be a further trend of decreases in the number of free-flowing artesian boreholes, as a result of regional lowering of piezometric surfaces in the aquifer. Every effort must be made to avoid such a situation, so that the viability of the groundwater resource, as a strategic supply in the region, is maintained.

In summary, all groundwater users in the UAB should be made aware of the importance of their resource and its vulnerability to mismanagement and pollution. Close co-operation between all users and controlling bodies will be essential in the future, to ensure that groundwater resource utilisation goes hand-in-hand with fair distribution, and that resource over-exploitation is avoided.

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MAP REFERENCES

SA 1 : 10 000 orthophoto map series :-
3325CB 21-22, 3325CD 2-5, 3325CD 9-10, 3325DC 1, 3325DC 6-8, 3325DC 12-13.

SA 1 : 50 000 topo-cadastral map series sheets :-
3324DB (2nd ed.), 3325CA (2nd ed.), 3325CB (2nd ed.), 3325CD + 3425AB (2nd ed.), 3325CC (2nd ed.), 3325DA (3rd ed.), 3325DC+DD + 3425BA (4th ed.).

SA 1 : 250 000 topographical sheet 3324 (3rd ed.).

SA 1 : 250 000 geological series sheet 3324.

SA 1 : 250 000 topo-cadastral series sheet 3324.

PLATES

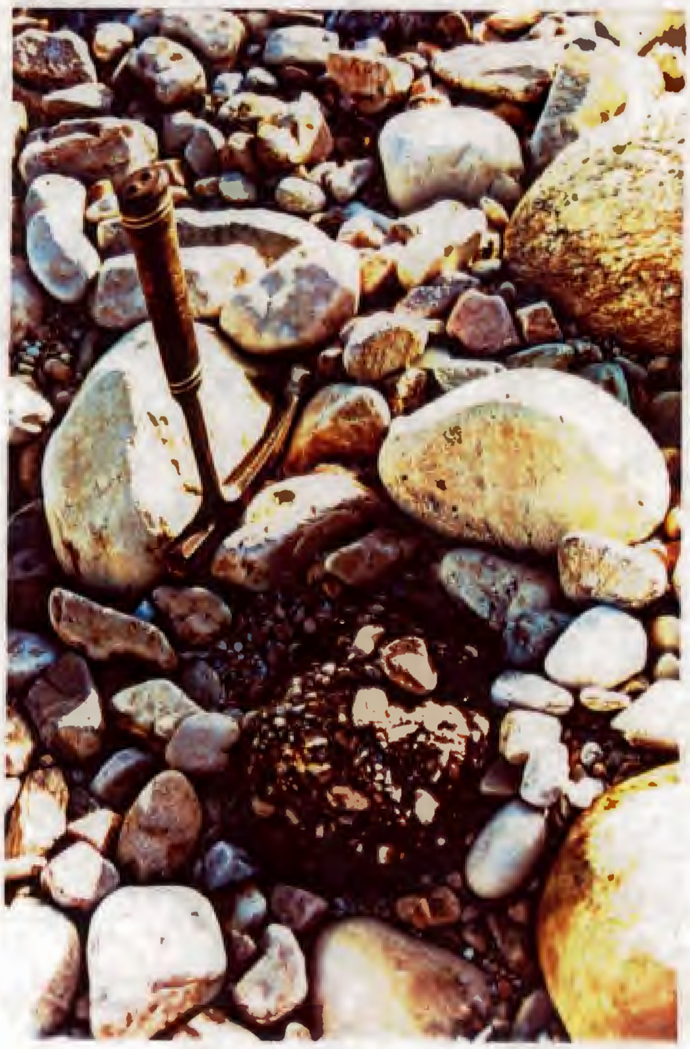


Plate 1: TMS boulder and cobble alluvium in the Kwa-Zunga River. Reworked Enon conglomerate in the foreground. Hammer point indicates upriver direction.

Plate 2: Layered Kirkwood Formation mudstones and siltstones. View south over Swartkops River towards Redcliff from Nic Classen bridge.

Plate 3: Coquinite of the Alexandria Formation near the R75 highway bridge over the Swartkops River.

Plate 4: Fluvial terrace gravel deposit. View south from railway towards Genot Str. - Despatch. Note gravel filled palaeo-channels incised into semi-consolidated sandstone of the Sundays River Formation to far left and immediate right of figure.

Plate 5: Fault breccia in Peninsula Formation quartzite - Coega Kop quarry.

Plate 6: Highly sheared Peninsula Formation in Coega Fault zone - north wall Groendal Dam.

Plate 7: Plateau deposit of Bluewater Bay Formation unconformably overlying calcareous sandstone of the Alexandria Formation - Algoa Group. Motherwell Canal.

Plate 8: Eye 2 - Uitenhage Springs. Note borehole casing immediately below figure.

Plate 9: Basal cobble to boulder lag deposit forming transmissive horizon of alluvial aquifer in this area. Note clayey soil overburden - Moreson, Kruisrivier.

Plate 10: View north over valley containing East Cape tanning ponds - Uitenhage industrial area visible in the distance.

Plate 11: Seepage below East Cape tanning pond. Note ephemeral drainage feature to right of seepage.

Plate 12: Dried sludge residue - view north over Cape of Good Hope wool-washers evaporation dam.

Plate 13: Borehole purging prior to sampling - borehole G40036, Gubb & Inggs. Note black colour of groundwater.

Plate 14: Borehole purging prior to sampling - borehole G40042, Cape of Good Hope. Note brown colour of groundwater and frothing on aeration.

Plate 15: Residual sediment deposit at base of old exposed evaporation dam - Gubb & Inggs.

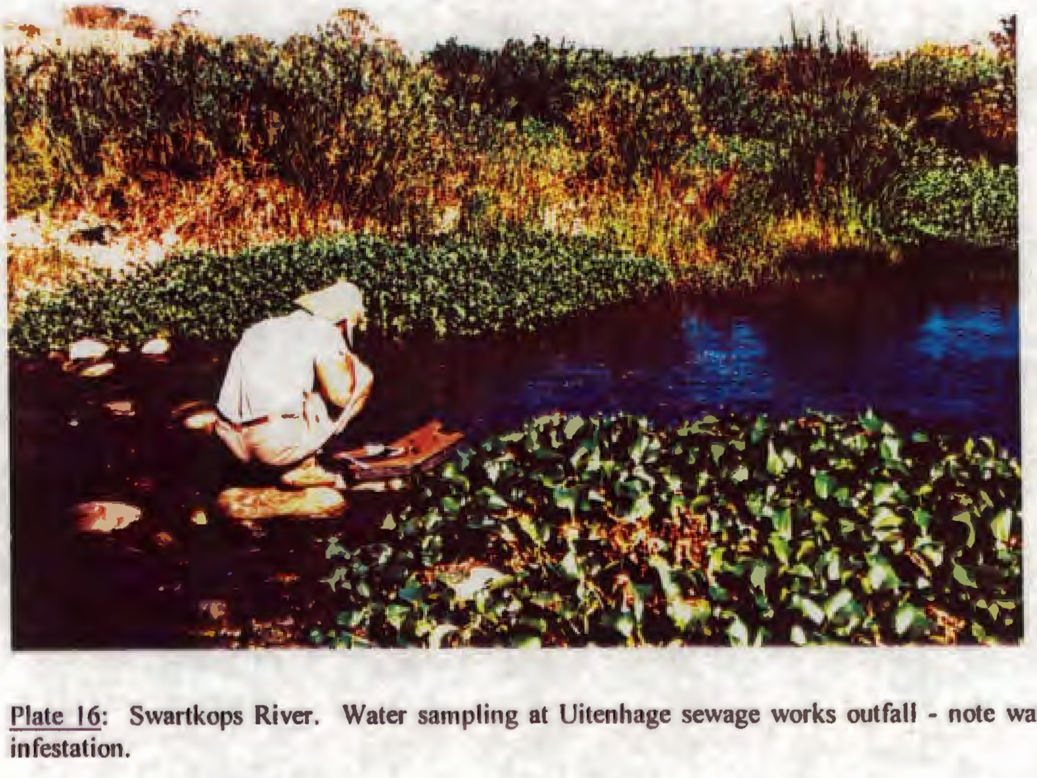


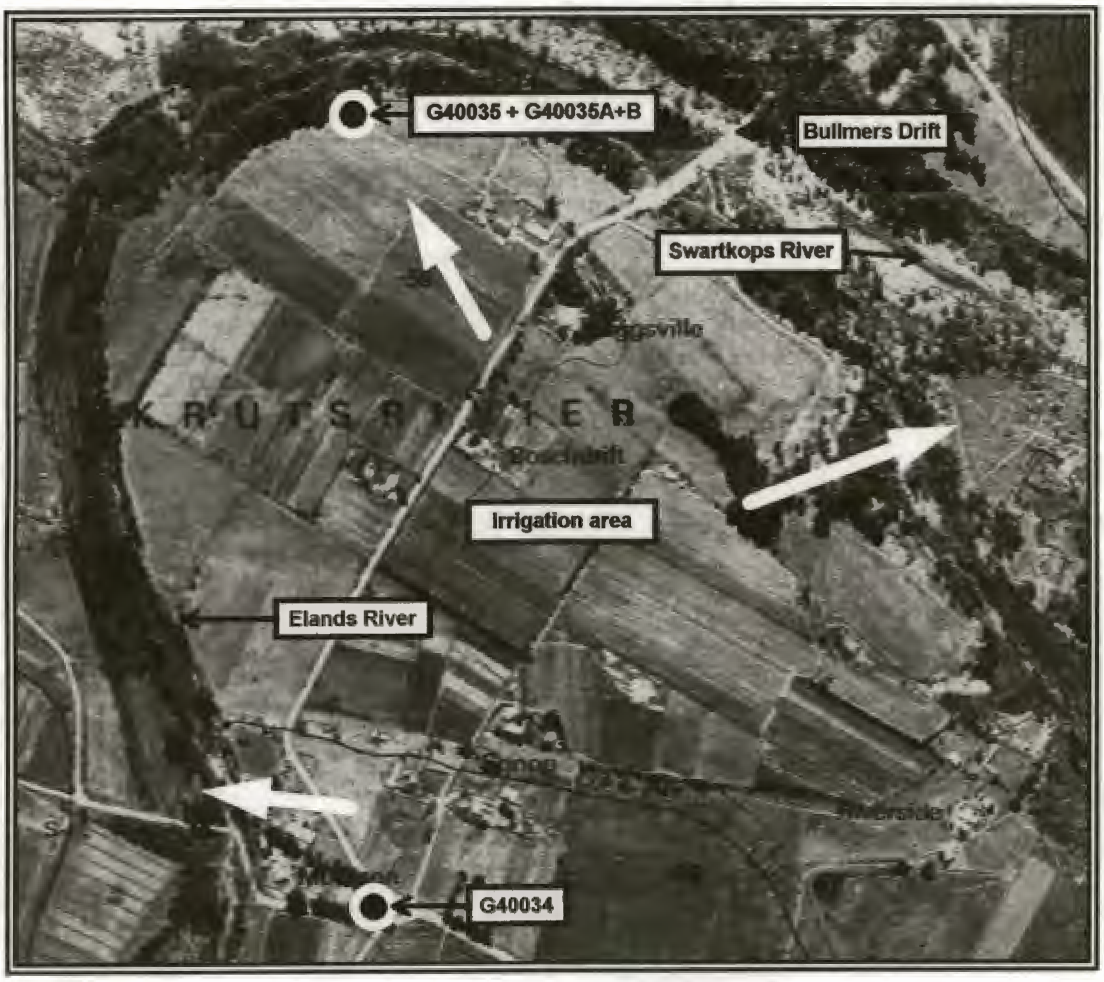
Plate 16: Swartkops River. Water sampling at Uitenhage sewage works outfall - note water hyacinth infestation.

ORTHOPHOTOS

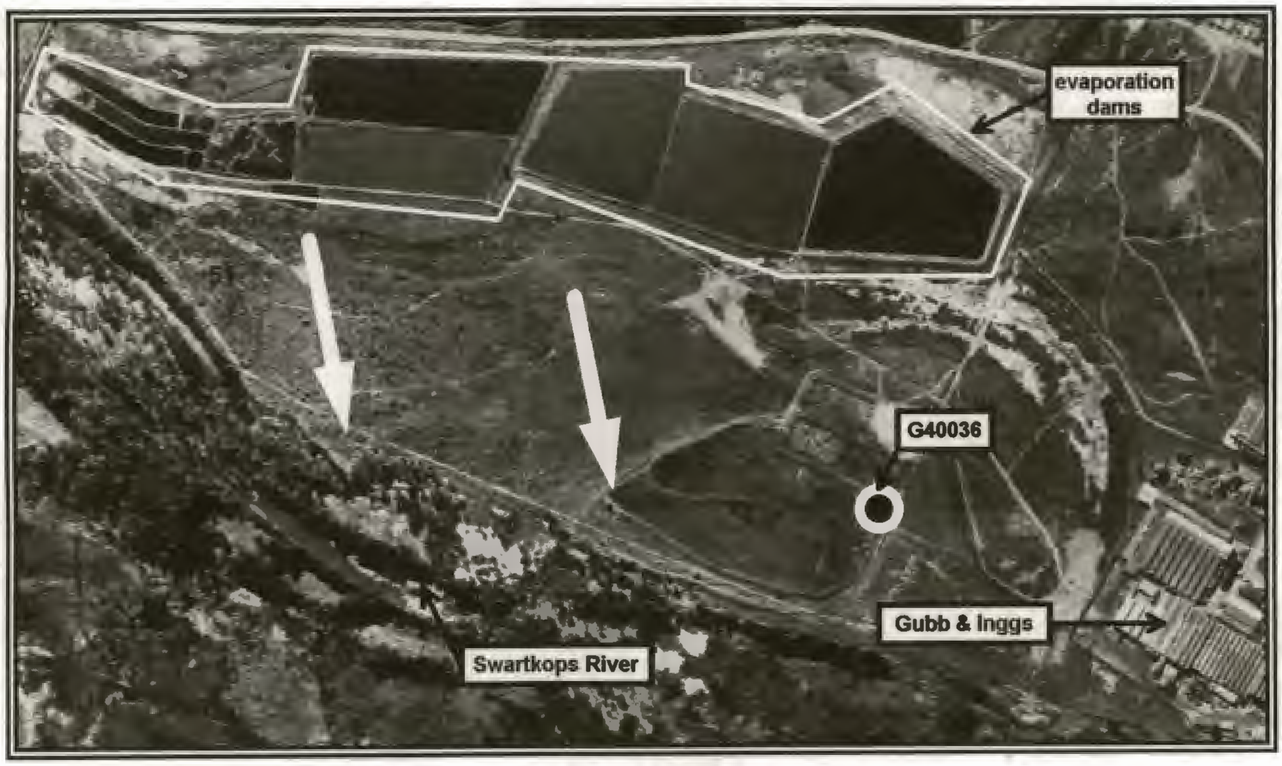
Relative locations - boreholes and pollution sources.

- Images scanned from orthophoto map series published by Chief Directorate: Surveys and Land Information, Mowbray, RSA. Map numbers are indicated in brackets.
- All images scale = 1 : 10 000.
- Thick white arrow indicates groundwater flow direction.

Orthophoto 1: Grahams poultry farm - Good Hope (3325CB22+CB23).



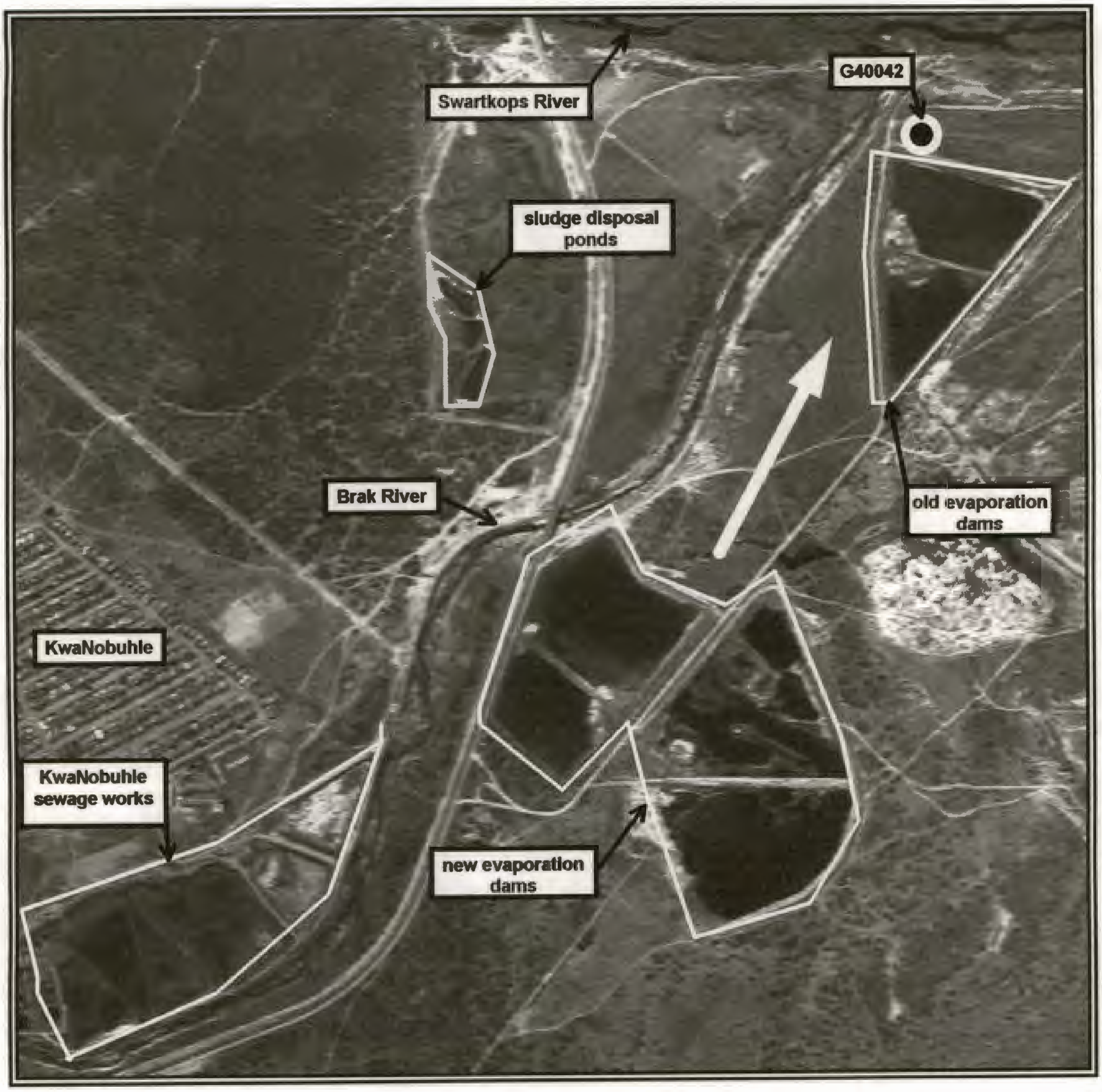
Orthophoto 2: Kruisrivier irrigation area (3325CD2).



Orthophoto 3: Gubb & Inggs wool-washers (3325CD3).

Orthophoto 4: Cape Road industrial area (3325CD3).

Orthophoto 5: East Cape Tanning and old Municipal waste site (3325CD3).



Orthophoto 6: Cape of Good Hope wool-washers evaporation dams, KwaNobuhle sewage works and Uitenhage sludge disposal ponds (3325CD4+CD9).

Orthophoto 7: Uitenhage sewage works (3325CD4).

Orthophoto 8: Despatch residential area (3325CD5).

Orthophoto 9: Despatch sewage works (3325CD5+CD10).

Orthophoto 10: Perseverance wool pullery (3325DC6).

Orthophoto 11: Redhouse residential area (3325DC7).

APPENDIX A:

SWARTKOPS RIVER BASIN HYDROCENSUS DATA - GROUNDWATER ABSTRACTION POINTS

(from Maclear, 1993)

LEGEND

Site Number :	(#) -	original number from previous reports in brackets
Site type :	BH -	borehole
	DW -	dug-well
	S -	spring
Coordinates :	DMS -	degrees minutes seconds
Elevation :	m amsl -	metres above mean sea level (inferred from 1 : 10 000 ortho-photos)
Water Use :	Br -	brick manufacture
	C -	chicken farm
	D -	domestic
	Da -	dairy farm
	G -	garden
	I -	irrigation If : fruit Il : lucerne In : nursery Iv : vegetables
	M -	municipal supply
	N -	none
	Na -	salt production
	Nc -	nature conservation
	P -	swimming pool
	S -	stock watering
Pump Type :	C -	centrifugal
	M -	mono
	P -	piston
	S -	submersible
	T -	turbine
	W -	wind-pump
Yield[1] :	past -	past (original) yield date uncertain
Abstraction :	rounded off to the nearest 10 m^3/a	
E.C. :	electrical conductivity in milli-Siemens per metre at 25° Celsius. Shaded values exceed the SABS (1984) maximum allowable limit for drinking water.	
Geology :	alvm -	alluvium (silt, sand, river gravel, boulders)
	mdsn -	mudstone
	qrtz -	quartzitic
	shle -	shale
	snds -	sandstone (qrtz snds = TMS)
Water Level :	mbs	- metres below surface
	?	- pump installed in hole + casing capped making measurement impossible
Date :	date of site visit or date of last water level measurement	

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[1] The present or reported yield is not necessarily a true reflection of the yield of the borehole / dug-well, but is instead the yield which the installed pump is capable of delivering.

SITE NO.	SITE TYPE	OWNER FARM NAME (PORTION) /ADDRESS	LATITUDE (D M S)	LONGITUDE (D M S)	ELEVN. (mamsl)	WATER USE	PUMP TYPE	YIELD (l/s)	ABSTRACT -ION (m3/yr)	E.C. (mS/m)	GEOLOGY	WATER (mbs)	LEVEL (mamsl)	BH DEPTH	DATE
AK1	BH	INDUSTEX (PTY) LTD Alexander Park Plot 7402 (Uitenhage)	33 47 10	25 25 30	32	N	N	10	105 120 (planned)	446	alvm + mdsn	1.96	30.04	13.5	92-8-25
AK2	BH	INDUSTEX PTY LTD Alexander Park Plot 7402 (Uitenhage)	33 47 02	25 25 26	33	N	N	?	0	159	alvm + mdsn	2.53	30.47	5.4	92-8-25
BE1	BH	BLOM Boschoogte (3)	33 48 09	25 20 58	106	D S	M	3.8 (1992) 0.4 (1976)	0	?	mdsn + qrtz snds	54.86 (1976)	51.14	214.88	93-07
BF1	BH	GIBELLO Brakkefontein (416)	33 51 36	25 16 58	319	D S	S	0.3	440	33	qrtz snds	45.67	273.33	?	93-3-25
BF2	BH	BRAUN High View Estate Brakkefontein (416)	33 51 29	25 17 08	281	D I	S	0.06 (1993) 0.7 (1992)	1 860	44	?	23.87	257.13	84	93-3-25
BF3	BH	CARTER Blue Mountain Brakkefontein (31)	33 51 21	25 16 56	273	G I	S	0.9 (1993) 1.3 (past)	27 590	?	shle + snds	30	243	173	93-3-26
BF4	BH	CARTER Blue Mountain Brakkefontein (31)	33 51 27	25 17 13	277.5	I	S	0.9 (1993) 1.3 (past)	27 590	?	shle + snds	?	?	182	93-3-26
BF5	BH	CARTER Blue Mountain (nursery) Brakkefontein (31)	33 51 25	25 16 50	279	D	S	0.9 (1993) 1.1 (past)	27 590	?	shle + snds	25 while pumping	254	34	93-3-26
BF7	BH	HUGO Brakkefontein	33 50 55	25 17 56	237.5	S	M	1	1 970	975	?	?	?	110	93-4-7
BF8	BH	NEW OWNER Uitkyk Brakkefontein	33 50 41	25 17 54	241	D S	S	0.8	26 280	436	?	11.5	229.5	>36	93-4-7
BF9	BH	LEITH Brakkefontein	33 51 08	25 18 08	217	G D	S	0.8 (1993) 1.7 (past)	420	517	?	25	192	65	93-4-7
BF10	BH	PRIDEHUY Klipkuil Brakkefontein (67)	33 51 32	25 17 29	273	G D S	S	0.5	1 350	57.2	?	14.64	258.36	30	93-4-7
BF11	BH	KOCK Brakkefontein (67)	33 51 34	25 17 21	284	D S I	S	0.5	16 210	47.3	?	13	271	55	93-4-7

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BF12	BH	VOS Joyce Brakkefontein	33 51 39	25 17 23	289	G D	S	0.6 (1993) 0.4 (past)	730	45	?	?	?	30	93-4-7
BF13	BH	VAN DER MERWE Rapsie Brakkefontein (39)	33 51 29	25 17 43	262.5	D S	S	0.08 (1993) 0.14 (past)	170	78.2	?	35	227.5	55	93-4-7
BF14	BH	BALFOUR Brakkefontein	33 51 37	25 17 41	263	G D	S	0.9	2 300	63	?	9.7	253.3	20	93-4-7
BF15	BH	HURTER Brakkefontein (145+155)	33 51 52	25 17 39	304.5	D	S	0.3	210	32	?	32.9	271.6	54	93-4-14
BF16	BH	HURTER Brakkefontein (145+155)	33 51 47	25 17 43	279	D	S	0.1 (1993) 0.3 (past)	100	55	?	?	?	40	93-4-14
BF17	BH	SUNDERBANK Brakkefontein	33 52 29	25 17 39	324	D	W	0.1 (1993) 0.3 (past)	4 380	72	?	?	?	120	93-4-14
BF18	BH	DORFLING Brakkefontein	33 51 47	25 18 08	265	D S I	M	0.2	2 070	49.4	?	?	?	?	93-4-14
BF19	BH	MARTIN Brakkefontein	33 51 50	25 18 23	271	D S I	M	0.01	60	52.3	?	?	?	60	93-4-14
BF20	BH	CHARLEWOOD Rocklands Poultry Farm Brakkefontein	33 51 52	25 18 43	264	C S	S	0.6	17 960	56.6	qrtz snds	?	?	>100	93-4-14
BF21	BH	CHARLEWOOD Rocklands Poultry Farm Brakkefontein	33 51 44	25 18 14	262	D C	S	0.6	18 400	47.9	qrtz snds	10	252	>100	93-4-14
BF22	BH	ROSE La Rochelle Brakkefontein (145)	33 52 19	25 18 59	257	D	S	0.4	2 430	71.8	?	15.32	241.68	42	93-4-14
BF25	BH	MOSTERT Arbeidsgenot Brakkefontein	33 51 47	25 19 15	230	D S	C	0.1 (1993) 0.7 (past)	910	241	?	?	?	56	93-4-15
BF26	BH	LEUSCHER Von Wildenau Brakkefontein (68)	33 51 21	25 19 01	239	D	S	0.6 (1993) 1.5 (past)	110	1016	?	?	?	96	93-4-15
BF27	BH	LIEBENBERG Brakkefontein (102)	33 52 37	25 18 00	265	D P	S	0.1 (1993) 0.8 (past)	20	66.8	?	11.24	253.76	25	93-4-15

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BF28	BH	BEZUIDENHOUT Rocky Ridge Brakkefontein (46)	33 51 54	25 18 54	247	D	S	0.4	1 220	66	?	18 during recovery	229	137	93-4-16
BF29	BH	VERMEULEN Brakkefontein	33 52 49	25 19 06	260	D Iv C	S	0.4	4 210	66.6	?	6	254	35	93-4-20
BF30	BH	FOURIE Windgat Vlakte Brakkefontein	33 52 28	25 19 33	246	D S If	S	3.8 (1993) 7.5 (past)	7 020	80	mdsn + snds	8.9	237.1	36.5	93-4-16
BF31	BH	LITTLE Lamedos Brakkefontein (204)	33 52 26	25 19 32	245	P S C	S	0.5 (1993) 0.8 (past)	1 240	86.9	?	?	?	55	93-4-16
BF32	BH	COETZEE Heideveld Brakkefontein	33 52 37	25 16 48	285	D S If	S	1.5	1 000	52	qrtz snds	7.78	277.22	40	93-4-20
BF33	BH	VAN DER BERG Brakkefontein (184)	33 52 45	25 16 58	274	D Iv	W	0.6	~ 2 200 wind dependent	160	?	12	262	36	93-4-20
BF34	BH	FULLER Brakkefontein	33 52 51	25 17 17	269	D S I	S	0.6 (1993) 1.0 (past)	11 010	124	mdsn + shle + snds	9	260	53	93-4-20
BF35	BH	WEBSTER Kilreiny Brakkefontein	33 52 51	25 17 19	264	D G	S	0.3	3 290	115	?	12	252	36.6	93-4-20
BF36	BH	RICHARDS Brakkefontein	33 53 07	25 17 41	257	D S C	S	0.08 (1993) 0.1 (past)	1 310	97	mdsn + snds	15.25	241.75	50	93-4-20
BF37	BH	VERMEULEN Brakkefontein	33 52 52	25 19 00	253	D Iv C	S	0.4	4 210	64	?	17	236	65	93-4-20
BF38	BH	MCDONALD CRICHTON Athlone Union Cotton Mills Brakkefontein	33 53 02	25 18 06	252	D C If	M	0.6 (1993) 5.6 (1980)	4 160 20 800 planned	54	qrtz snds	10.25	241.75	60	93-4-26
BF39	BH	RYAN Pearson Vale Brakkefontein	33 53 18	25 18 00	257	G D S	S	0.5 (1993) 0.6 (1983)	560	65	?	?	?	50	93-4-26
BF40	BH	MYBURGH Trentham Brakkefontein (84)	33 52 53	25 18 13	263	D	S	0.7	150	119	?	13	250	45	93-4-26

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BF41	BH	BREDENKAMP Brakkefontein	33 53 04	25 18 48	241	C S	S	2.8	29 200	77	qrtz snds	?	?	40	93-4-26
BF42	BH	BREDENKAMP Brakkefontein	33 52 50	25 18 33	267	N	S	0	0	82	mdsn	13.4	253.6	55	93-4-26
BF43	BH	JUKEL Brakkefontein (82)	33 52 47	25 17 58	272	D S P	S	0.4 (1993) 0.6 (past)	1 370	67	?	?	?	60	93-4-26
BF44	BH	MARX Brakkefontein (178)	33 53 09	25 18 26	242	D S I	M	0.6	10 030	87	qrtz snds	?	?	20	93-4-26
BH1	BH	WRIGHT Paardehoek (395)	33 48 57	25 19 39	94.5	D S	M	0.8 (1993) 1.1 (past)	730	710	alvm + mdsn + qrtz snds	?	?	100	93-4-27
BH2	BH	VAN ZYL Lelagh (395)	33 50 27	25 20 29	236	D S	S	1.0 (1993) 1.3 (1975)	220	642	?	?	?	60	93-4-27
BH3	BH	MDANYANA Bosch Hoogte (327)	33 49 49	25 21 33	183	D S	S	0.3	760	730	?	?	?	?	93-3-25
BH4	BH	VAN DEN BERG Burchley Hills (8)	33 50 02	25 20 43	225.5	D	S	0.7	2 840	404	shle + qrtz snds	55	170.5	103	93-4-27
BN1	BH	FATMAN Boschfontein (390)	33 50 12	25 15 24	276	N	N	0	0	33.8	qrtz snds	9.75	266.25	?	93-3-25
BN2 (KR72)	BH	OUTSPAN INTERNATIONAL Buffelsfontein (52)	33 46 26	25 19 35	66	I	S	11.4 ('92) 12.9 ('83)	70 670	33.8	mdsn + qrtz + snds	27.2	38.8	200	92-9-24
BN3	BH	DE LANGE Boschfontein Boschfontein (390)	33 49 52	25 16 06	261	N	S	0	0	?	?	?	?	?	93-3-25
BS1	BH	VAN DYK Windmill (42)	33 53 21	25 19 44	236	D S	S	0.2 (1993) 2.5 (past)	510	210	?	7	229	60	93-4-27
BS2	BH	VAN DYK Windmill (42)	33 53 21	25 19 42	240	D	P	0.1 (1993) 2.5 (past)	30	500	?	8.55	231.45	60	93-4-27
CD1	BH	SCHEEPERS Cotswold Elands River Valley	33 38 09	24 55 58	480	D I	N	2.5 (1993) 12.6 (1982) blow yield	79 650	10.6	mdsn + snds	artesian	480	122	93-3-16
DH3	BH	JANSE V RENSBURG 3 Van Riebeeck St. Plot 6004 (Despatch)	33 48 05	25 26 34	47.5	N	N	0	0	2500	mdsn	2.36	45.14	140	92-9-17
DN1	BH	DEPARTMENT OF EDUCATION Longmore Camping Ground Downton (421)	33 52 24	25 15 17	347	D	S	0.9	1440	132	?	75 while pumping	272	150	93-4-20

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DT1	BH	HUMAN De Rust (Kruisrivier)	33 45 30	25 20 12	62	D S I	T	5.7 (1983)	134 820 (1983)	169	mdsn+snds	9	53	183	92-8-26
EI1 (KR17)	BH	PITOUT Elandsdraai (93)	33 46 44	25 19 57	68	D S I	S	6.3 ('92) 10.3 ('83)	196 390	?	mdsn+snds	15	53	182	92-9-24
FF2	BH	SWARTKOPS SEESOUT Swartkops (PE)	33 50 48	25 34 22	4	Na	S	5.7 ('92) 12.6 ('77)	800 000	?	mdsn	3.4	0.6	79.3	77-2-19
FK1 (KR13)	BH	HARBRON Fonteinshoek (92)	33 46 44	25 20 03	78	N	N	1.0 (1983)	3 380 ('83)	41.2	mdsn+snds	43.95	34.05	91.44	92-9-24
FK2 (KR53)	BH	JANSE V VUUREN Fonteinshoek (36)	33 46 49	25 19 27	82.5	D S I	S	3.3 (1983)	52 030 ('83)	44	mdsn+snds	?	?	91.44	92-9-24
GD1 (KR56)	BH	UITENHAGE MUNICIPALITY Greylands (117)	33 46 01	25 21 55	45.5	N	N	?	0	?	?	closed	?	?	92-8-27
GI1	BH	GUBB & INGGS Uitenhage	33 45 26	25 21 30	49	N	N	0	0	dry	alvm+mdsn	dry	?	3	93-6-7
GI2	BH	GUBB & INGGS Uitenhage	33 45 28	25 21 46	47	N	N	0	0	1270	alvm+mdsn	3.47	43.53	4	93-6-7
GI3	BH	GUBB & INGGS Uitenhage	33 45 32	25 21 58	45	N	N	0	0	1320	alvm+mdsn	1.67	43.33	4	93-6-7
GI4	BH	GUBB & INGGS Uitenhage	33 45 37	25 22 02	46	N	N	0	0	816	alvm+mdsn	1.12	44.88	3	93-6-7
GI5	BH	GUBB & INGGS Uitenhage	33 45 27	25 22 07	45	N	N	0	0	1016	alvm+mdsn	1.13	43.87	5	93-6-7
GI6	BH	GUBB & INGGS Uitenhage	33 45 48	25 22 15	44	N	N	0	0	996	alvm+mdsn	1.83	42.17	6	93-5-10
GL2	BH	UITENHAGE MUNICIPALITY Groendal (Bosreservaat)	33 41 29	25 16 16	198	N	N	0.3	10 950	28.6	qrtz snds	artesian	198	240	92-8-19
GS1 (KR66)	BH	THOMPSON Greenacres (Rooiland)	33 46 00	25 19 55	60.5	G D	S	0.9 (1983)	1 540	57.1	mdsn+snds	?	?	150	92-8-26
KL1	BH	KWANOBUHLE MUNICIPALITY Klipkuil (323)	33 49 57	25 24 08	71	S	N	?	?	800	? drilled 1956	artesian	71	?	93-4-29
KL2	BH	KWANOBUHLE MUNICIPALITY Klipkuil (323)	33 50 19	25 24 12	82	S	N	?	?	690	? drilled 1960	artesian	82	?	93-4-29
KM1	BH	KEMP Kastaiing Boom	33 46 17	25 19 48	64	D S Il If	S	9.5 ('92) 11.4 ('85)	57 280	37.2	mdsn+snds	27	37	>78	92-9-24
KR50	BH	FERREIRA Meldon (113)	33 46 08	25 21 26	54.5	D	S	0.8 (1983)	2 100	65.2	qrtz snds	11.9	42.6	182	92-8-27

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KR9A	BH	LE ROUX Repos Alleurs (79)	33 45 23	25 20 01	57	N	N	?	0	?	mdsn + snds	closed	?	?	92-8-27
LE1 (KR16)	BH	JANSE V VUUREN Langlaagte (51/61)	33 46 39	25 19 55	65	D Iv	S	8.8 ('92) 6.5 ('83)	381 870	30.6	alvm + mdsn + snds	37	28	176	92-9-24
ME1 (KR32)	BH	VAN HEERDEN Marizane (97)	33 46 22	25 21 15	84	S I	S	1.3 (1982)	31 820	1340	qrtz snds	38.8	45.2	152	92-8-27
MN1	BH	VAN VUUREN Melkhoutboom Elands River Valley	33 37 42	24 52 02	573	D S I	N	1.0 (1993) 2.0 (past)	31 540	12	snds	0.01 artesian	572.99	136	93-3-16
MN2	BH	VAN VUUREN Melkhoutboom Elands River Valley	33 38 44	24 51 36	600	D S I	N	0.8	0	43.7	snds	1 artesian	599	168	93-3-16
MN3	BH	SCHEEPERS Melkhoutfontein Elands River Valley	33 39 00	24 52 21	622	S	C	1.5	?	39.8	snds + shle	?	?	120	93-3-16
MN4	BH	SCHEEPERS Melkhoutfontein Elands River Valley	33 37 25	24 53 48	552	D S	N	0.5	15 770	15.4	?	artesian	552	120	93-3-16
MS1	BH	SWARTKOPS SEESOUT Missionvale (PE)	33 51 54	25 32 32	41	Na	N	0.6	0	?	mdsn	1.7	39.3	40	92-10-7
MW3	BH	FROST Mimosadale West (329)	33 47 49	25 19 00	78	S	P	0.2 ('93) 0.3 ('82)	40	114	snds	11.77	66.23	50	93-4-27
MW3A	BH	SEARL Wincanton (Mimosadale)	33 47 02	25 19 46	67.5	D S I	M	10	29 160	87	snds	19	48.5	122	93-4-27
MW8	BH	FROST Mimosadale West (329)	33 48 15	25 20 08	89	S Br	P	0.2 ('93) 0.4 ('82)	1 960	61	?	24	65	369	93-3
PE1	BH	PERSEVERANCE WOOL PULLERY Mountain View	33 48 59	25 31 33	7	N	N	?	0	273	?	artesian	7	?	92-9-8
RD1	BH	ELS Rooiland (74)	33 46 08	25 20 03	65	G D	M	2.1	1 070	78.2	mdsn + snds	30	35	73.2	92-9-24
RD2	BH	SWANEPOEL Rooiland	33 46 11	25 20 03	67	G D	S	0.9	1 840	33.4	mdsn + shle + snds	25	42	132	92-9-24
RL1	BH	VAN DER TOUW Patcor Quarries Rietkuil (396)	33 52 11	25 21 41	227	D	S	1.3	3 290	169	qrtz snds	35.44	191.56	160	93-4-29

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RL2	BH	VAN DER TOUW Patcor Quarries Rietkuil (396)	33 52 09	25 21 27	231	D	S	1.3	19 710	364	qrtz snds	60 during recovery	171	180	93-4-29
RL3	BH	VAN DER TOUW Patcor Quarries Rietkuil (396)	33 52 06	25 21 19	180	D	S	0.3 (1993) 1.3 (past)	370	201	snds	3.06	176.94	100	93-4-29
RM1	BH	LANDMAN Ruimte (Kruisrivier)	33 45 47	25 20 22	70	N	N	2.5	138 280	60.7	mdsn	37.99	32.01	177	92-8-26
SP1	BH	WELGEMOED Sonop (Kruisrivier)	33 45 38	25 20 19	64	D S lv	S	6.7 (1982)	158 470	34.5	mdsn+snds	52.19	11.81	107	92-8-26
TR1	BH	POTGIETER Totteridge Park	33 48 21	25 31 05	6	N	N	?	0	110.1	mdsn+snds	artesian	6	?	92-9-1
UT1	BH	ANDERSON Uitkomst (Kruisrivier)	33 46 00	25 21 16	55.5	N	N	?	0	41.5	mdsn	4.12	51.38	?	92-8-27

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BF6	DW	MARAIS Ranger Hills Brakkefontein	33 50 02	25 18 06	157	S	C	0.4	11 830	198	?	4.32	152.68	8.55	93-4-7
BI1	DW	PRETORIUS Bosvlei (Kruisrivier)	33 44 25	25 19 36	61	S I	C	?	4 980	32.8	alvm	1.8	59.2	5.13	92-8-26
CR1	DW	UITENHAGE MUNICIPALITY Cuyler Manor (320)	33 47 06	25 26 14	31	N	N	?	0	1122	alvm+mdsn	11.06	19.94	12.2	92-9-1
DH11	DW	ROSSOUW 11 Pienaar St., Despatch	33 47 47	25 26 40	33.5	G P	C	?	20	1330	alvm+mdsn	5.33	28.17	6.62	92-9-3
DH12	DW	BOTHA 12 Havenga St., Despatch	33 47 31	25 28 33	19	G	C	?	?	281	alvm+mdsn	6.41	12.59	6.68	92-9-2
DH147	DW	GERBER 147 Boom St., Despatch	33 48 03	25 29 20	13.5	G P If	C	0.004	1 940	268	alvm+mdsn	1.75	11.75	3.8	92-9-8
DH1472	DW	FIRNS Plot 147, Despatch	33 47 38	25 29 20	14.5	G Iv	C	?	1 800	579	alvm	4.38	10.12	5.1	92-9-2
DH17	DW	KOERTZEN 17 Schoeman St.,Despatch	33 47 42	25 28 20	20.5	G	N	?	0	1224	alvm	5.28	15.22	5.48	92-9-2
DH20	DW	LOMBAARD 20 Fourie St., Despatch	33 47 46	25 28 33	18	G	C	?	20	586	alvm	5.44	12.56	5.75	92-9-3
DH51	DW	LOMBAARD 51 Boom St., Despatch	33 47 34	25 29 07	14.5	D	C	0.02	730	620	alvm	4.72	9.78	5.53	92-9-2
DH823	DW	SCHEEPERS 12 Boom St. Plot 823 (Despatch)	33 47 33	25 28 52	17	G	C	?	?	1560	alvm	5.5	11.5	7	92-9-3
KG1	DW	TALJAARD Kreutsberg Plot 1736	33 47 35	25 25 50	29	G	S	?	?	830	alvm	2.73	26.27	4.4	92-8-27
MK1	DW	JANSE V. VUUREN Melbrook (Uitenhage)	33 47 12	25 25 39	29.5	N	N	?	0	593	alvm	3.22	26.28	?	92-8-27
MK2	DW	JANSE V. VUUREN Melbrook (Uitenhage)	33 47 14	25 25 36	30.5	N	N	?	0	932	alvm	1.67	28.83	?	92-8-27
PE2	DW	SUMCAY CAMP Perseverance	33 48 55	25 32 19	5	N	C	?	0	1600	alvm	5	0	5.9	92-9-8
TE1	DW	HOPGOOD Tollgate The Meadows	33 47 18	25 26 04	28	D S	W	?	?	243	alvm	3.33	24.67	5	92-8-27
TM1	DW	TAIT 69 Pienaar St., Despatch	33 47 31	25 26 19	28.5	N	N	?	0	2090	alvm	1.38	27.12	3.18	92-9-3
VE1	DW	RENS Vrede (Kruisrivier)	33 44 40	25 19 51	55	D S I	C	?	?	33.4	alvm	1.7	53.3	4.68	92-8-26

SITE NO.	SITE TYPE	OWNER FARM NAME (PORTION) /ADDRESS	LATITUDE (D M S)	LONGITUDE (D M S)	ELEVN. (mamsl)	WATER USE	PUMP TYPE	YIELD (l/s)	ABSTRACT -ION (m3/yr)	E.C. (mS/m)	GEOLOGY	WATER (mbs)	LEVEL (mamsl)	BH DEPTH	DATE
BF23	S	ROCKLANDS SUPERMARKET Brakkefontein	33 51 52	25 19 04	244	Nc	N	flowing	0	53.4	snds	surface	244	NA	93-4-15
BF24	S	STEYN Brakkefontein Oos Brakkefontein	33 51 58	25 20 12	164.5	Da I	M+C	11	262 800	78.4	?	surface	164.5	NA	93-4-15
BN2	S	FATMAN Boschfontein (390)	33 50 42	25 15 06	380	G D S	N	0.6	?	33.8	qrtz snds	?	?	?	93-3-25
BN4	S	DE LANGE Boschfontein Boschfontein (390)	33 50 47	25 15 19	355	G D S	N	0.1	?	38	qrtz snds	?	?	?	93-3-25
BN5	S	NIEMAN Holrivier Boschfontein (390)	33 51 17	25 15 00	340	D	N	?	? gradient flow	40	qrtz snds	?	?	?	93-3-25
DS1	S	BETHELSDORP MUNICIPALITY Bethelsdorp	33 52 14	25 27 13	79	N	N	?	0	231	?	flowing	79	NA	93-4-29
KL3	S	KWANOBUHLE MUNICIPALITY Klipkuil (323)	33 50 32	25 24 25	89	S	N	?	?	1378	?	flowing	89	NA	93-4-29
SD2	S	RENS Springfield (339)	33 44 02	25 19 22	67	D S I	C	?	?	30.8	alvm	seepage pit	67	0	92-8-26
SP1 (US)	S	UITENHAGE MUNICIPALITY The Springs Sandfontein (291)	33 42 00	25 26 17	175	M	N	45	1 400 000	14.5	qrtz snds	flowing	175	NA	93-2-25
WN1	S	BETHELSDORP MUNICIPALITY Bethelsdorp	33 52 52	25 28 23	149	N	N	?	0	186	?	flowing	149	NA	93-4-29

APPENDIX B:

SWARTKOPS RIVER BASIN HYDROCENSUS DATA - HYDROCHEMICAL ANALYSES

(from Maclear, 1993)

LEGEND

Site type	:	BH	- borehole
		D	- waste and / or storm water drainage canal or non-perennial stream
		DW	- dug-well
		P	- pipe
		R	- river
		S	- spring

NH_4	-	ammonium as N
NO_3+NO_2	-	nitrate and nitrite reported as equivalent molecular nitrogen (N) where 1 mg/ℓ N = 4.5 mg/ℓ NO_3
PO_4	-	ortho-phosphate (inorganic) as P
TAL	-	total alkalinity as $CaCO_3$
TDS	-	total dissolved salts.

All values in mg/ℓ (ppm) except :

E.C.	-	electrical conductivity in milli-Siemens per metre at 25° Celsius
pH	-	logarithm of the inverse of the hydrogen ion concentration.

- The shaded values exceed the maximum allowable limit[1] for water used for domestic purposes.
- Average sea-water hydrochemistry values[2] included for comparative purposes.

IWQS DETECTION LIMITS - 1996

Macro Constituents:

Element	Accuracy*	Reproducibility	Lld**
Ca	1%	0.1%	1.0 mg/l
Cl	1%	0.1%	3.0 mg/l
EC	1%	0.1%	1mS/m
F	2%	0.2%	0.1 mg/l
K	1%	0.1%	0.3 mg/l
Mg	1%	0.1%	1.0 mg/l
Na	1%	0.1%	2.0 mg/l
NH_4 - N	1%	0.1%	0.04 mg/l
NO_3+NO_2 - N	1%	0.1%	0.04 mg/l
pH	1%	0.1%	0.01 pH units
PO_4 - P	1%	0.1%	0.005 mg/l
Si	1%	0.1%	0.4 mg/l
SO_4	2%	0.2%	4.0 mg/l
TAL as $CaCO_3$	2%	0.1%	4 mg/l

* Accuracy at Mid range. Accuracy at Lld is by definition 50%, or 2 sigma RSD (relative standard deviation).

** Lld = lower limit of detection.

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[1] Water quality limits from:
- DWA&F (1993a),
- SABS (1984), and
- Kempster, P.L., Hattingh, W.H.J. and van Vliet, H.R. (1980). Summarised Water Quality Criteria. DWA&F technical report TR 108, IWQS, Pretoria.

[2] Sea-water chemistry from:
- Driscoll, F.G. (1986). Ground Water and Wells (2nd ed.). Johnson Division, St. Paul, Minnesota, and
- Hem (1970).

SITE NO.	SITE TYPE	DATE SAMPLED	H NUMBER	pH	EC	TDS	NH4 N	NO3+NO2 N	F	TAL CaCO3	Na	Mg	Si	PO4 P	SO4	Cl	K	Ca
SABS MAX.				5.5-9.5	300	2000	2	10	1.5	650	400	100	25	0.2	600	600	800	400
SEA WATER				8.2	4400	35000	0.5	0.2	1	120	10500	1350	1	0.01	2650	19500	400	400
AK1	BH	92-8-25	92425124	7.9	446	2779	<0.04	<0.04	0.7	271	765	88	9.7	0.025	446	1063	6	80
AK2	BH	92-8-25	92425136	8.3	159	926	4.74	1.2	0.5	230	238	36	<0.4	0.009	49	291	10.4	9
BF7	BH	93-4-7	93005167	8	975	6430	0.11	<0.04	1.1	381	1734	263	5	0.005	434	3263	33.1	237
BF8	BH	93-4-7	93005179	7.7	436	2538	0.05	<0.04	0.8	225	720	72	8.8	<0.005	163	1216	6.2	86
BF9	BH	93-4-7	93005180	7.7	517	3002	0.06	<0.04	0.6	153	824	114	14.2	0.009	159	1601	5.9	109
BF10	BH	93-4-7	93005192	7.8	57.2	279	<0.04	0.47	0.2	6	82	11	4.4	0.005	11	158	0.6	6
BF11	BH	93-4-7	93005209	7.5	47.3	232	<0.04	0.41	0.1	8	67	9	4.4	0.005	11	127	0.5	6
BF12	BH	93-4-7	93005210	7.2	45	213	<0.04	0.56	0.1	7	63	8	4.3	<0.005	1	116	0.4	5
BF13	BH	93-4-7	93005222	8.1	78.2	521	<0.04	<0.04	0.1	162	83	11	9.1	<0.005	17	148	8.6	57
BF14	BH	93-4-7	93005234	7.8	63	319	<0.04	1.99	0.1	20	84	11	4.4	<0.005	13	163	1.7	13
BF16	BH	93-4-14	93005246	7.2	55	286	0.05	0.45	0.3	8	82	11	4.4	0.008	14	160	0.6	6
BF17	BH	93-4-14	93005258	6.8	72	368	0.08	0.04	0.1	5	109	15	2	0.007	19	212	0.5	6
BF18	BH	93-4-14	93005260	6.6	49.4	253	<0.04	0.33	0.1	32	68	9	4.1	0.006	8	121	0.7	5
BF19	BH	93-4-14	93005271	7.2	52.3	265	<0.04	0.33	0.1	11	75	11	4.3	0.006	12	145	0.4	7
BF20	BH	93-4-14	93005283	7.3	56.6	287	<0.04	0.58	0.1	6	82	11	4.3	0.005	13	162	0.4	8
BF21	BH	93-4-14	93005295	7.1	47.9	240	<0.04	0.7	0.1	5	71	9	4.3	0.005	11	134	0.4	6
BF22	BH	93-4-14	93005301	7.1	71.8	374	<0.04	0.92	0.1	8	113	14	4.4	0.005	16	209	0.4	7
BF25	BH	93-4-15	93005337	7.6	241	1319	0.06	<0.04	0.4	114	355	46	13.7	0.008	73	641	5.6	59
BF26	BH	93-4-15	93005349	8.1	1016	6685	0.06	<0.04	0.8	349	1871	257	7.8	0.006	507	3347	35.4	241
BF27	BH	93-4-15	93005350	7.2	66.8	338	0.05	0.78	0.2	9	104	10	4.1	0.005	26	179	0.6	4
BF28	BH	93-4-16	93005362	7.2	66	331	<0.04	3.63	0.1	13	92	13	4.3	<0.005	16	169	0.4	1
BF29	BH	93-4-16	93005374	7.1	66.6	333	<0.04	<0.04	0.1	13	97	12	3.8	0.005	17	182	0.4	8
BF30	BH	93-4-16	93005386	7	80	397	<0.04	0.34	0.1	5	114	16	4.1	<0.005	13	233	0.4	11
BF31	BH	93-4-16	93005398	7	86.9	434	<0.04	0.11	0.1	9	120	19	4.6	0.005	20	249	0.4	14
BN1+2	BH	92-9-24	92426580	5.4	33.8	168	<0.04	0.07	0.2	5	44	6	4	<0.005	19	87	0.9	4
CD1	BH	93-3-16	93005453	7	10.6	47	<0.04	<0.04	0.1	<4	13	2	4.7	0.013	5	22	0.5	1
DH3	BH	92-9-18	92426566	7.5	2500	18244	0.36	0.39	0.6	80	5328	513	2.2	0.016	638	10875	88.2	703
DT1	BH	92-8-26	92425185	7.2	169	873	<0.04	0.05	0.2	75	214	29	2.6	0.005	41	442	7.8	47
FK1	BH	92-9-24	92426621	5.5	41.2	205	<0.04	0.04	<0.1	<4	52	8	4.2	<0.005	27	106	1.3	6
FK2	BH	92-9-24	92426610	7.5	44	237	<0.04	0.06	0.1	10	66	7	4.2	<0.005	24	120	0.7	6

SITE NO.	SITE TYPE	DATE SAMPLED	H NUMBER	pH	EC	TDS	NH4 N	NO3+NO2 N	F	TAL CaCO3	Na	Mg	Si	PO4 P	SO4	Cl	K	Ca
SABS MAX.				5.5-9.5	300	2000	2	10	1.5	650	400	100	25	0.2	600	600	800	400
SEA WATE		.		8.2	4400	35000	0.5	0.2	1	120	10500	1350	1	0.01	2650	19500	400	400
GI2	BH	92-12-07	92430480	8.6	1270	13500	28.7	0.1	0.8	6284	1367	127	2.7	0.18	517	728	2963.4	97
GI3	BH	92-12-07	92430491	9.1	1320	14788	21.9	0.42	1.9	6711	1727	86	3.5	0.98	550	949	3228.5	29
GI4	BH	92-12-07	92430508	9.1	816	7680	0.6	1.4	1.3	3249	873	71	5	2.44	208	754	1772.2	25
GI5	BH	92-12-07	92430510	8.8	1016	10045	0.2	0.14	1.3	4304	1662	293	8.6	0.59	440	1228	1137.8	33
GI6	BH	92-12-07	92430521	8.6	996	10124	30.1	1.14	3.24	4064	1105	134	6.4	3.38	965	657	2165.2	86
GL2	BH	92-8-19	92425112	7.9	28.6	186	<0.04	<0.04	1.2	89	42	3	4.2	0.021	<4	18	4.8	5
GS1	BH	92-8-26	92425148	7.3	57.1	280	0.08	<0.04	0.2	16	79	10	4.1	0.009	25	140	1.6	5
KM1	BH	92-09-24	92426578	6.1	37.2	185	<0.04	0.11	0.4	9	48	6	4.2	0.006	19	93	1.5	4
KR50	BH	92-8-27	92425239	3.9	65.2	344	<0.04	0.05	0.3	5	89	12	3.7	0.031	65	157	2.5	12
LE1	BH	92-09-24	92426633	5.7	30.6	163	<0.04	0.04	<0.1	9	41	5	4.3	<0.005	19	81	1.1	4
ME1	BH	92-8-27	92425252	7.7	41.5	227	<0.04	<0.04	0.1	13	62	8	4.4	0.012	19	114	1.3	6
MN1	BH	93-3-16	93005416	7.1	12	53	0.19	<0.04	0.1	6	14	2	<0.4	0.01	<4	24	1.6	<1
MN2	BH	93-3-16	93005428	7.3	43.7	260	0.05	<0.04	0.3	52	60	5	3.5	0.018	9	103	2.8	18
MN3	BH	93-3-16	93005430	7.3	39.8	223	<0.04	<0.04	0.2	28	61	7	20.7	0.381	9	103	2.7	4
MN4	BH	93-3-16	93005441	7.1	15.4	74	0.04	0.17	0.1	5	18	3	4.2	0.065	5	37	0.7	3
PE1	BH	92-9-8	92425288	8.6	273	1692	<0.04	0.32	8.7	279	582	6	5.6	0.016	62	684	2.7	6
RD1	BH	92-9-24	92426608	7.8	78.2	436	<0.04	0.05	0.1	28	127	13	3.4	0.005	25	225	2.5	10
RD2	BH	92-9-24	92426591	6	33.4	171	<0.04	0.06	0.1	6	47	6	4.1	0.011	18	88	1.2	3
RM1	BH	92-8-27	92425276	4.3	60.7	294	<0.04	<0.04	0.2	4	73	11	4.3	0.017	39	150	5.2	10
SP1	BH	92-8-27	92425264	7.5	34.5	181	<0.04	<0.04	0.2	26	50	5	3.9	0.01	9	77	2.2	4
TR1	BH	92-9-1	92423309	8.9	110.1	832	<0.04	<0.04	3.9	373	239	2	6.2	0.029	17	113	1	2
UT1	BH	92-8-27	92425240	8	1340	8734	<0.04	0.47	0.1	275	2216	397	<0.4	0.014	166	5182	36.2	399

SITE NO.	SITE TYPE	DATE SAMPLED	H NUMBER	pH	EC	TDS	NH4 N	NO3+NO2 N	F	TAL CaCO3	Na	Mg	Si	PO4 P	SO4	Cl	K	Ca
SABS MAX.				5.5-9.5	300	2000	2	10	1.5	650	400	100	25	0.2	600	600	800	400
SEA WATER				8.2	4400	35000	0.5	0.2	1	120	10500	1350	1	0.01	2650	19500	400	400
GC	D	92-10-8	92427431	8	963	6207	0.13	4.56	0.7	302	1714	244	2.9	0.026	670	3002	60.8	128
GI	D	92-10-8	92427420	7.2	102.4	742	9.12	0.3	0.3	146	66	9	7.7	0.243	205	96	119.7	54
GP1	D	92-10-6	92427327	8	2260	17794	<0.04	72.42	1.7	555	5422	545	5.8	0.009	1742	8668	47.9	371
GX	D	92-10-8	92427443	7	80	505	0.06	0.05	0.3	115	115	8	4.1	0.035	87	124	7.3	23
KS1	D	92-10-6	92427340	8	729	4755	0.24	14.71	0.3	340	995	270	1.4	0.016	286	2417	66.7	239
NT1	D	92-10-6	92427339	7.5	610	3985	20.6	0.32	0.6	280	1082	166	4.8	1.742	301	1934	19.6	108
NT2	D	92-10-8	92427406	7.7	96.6	749	26.26	<0.04	0.3	309	156	6	8	6.486	5	131	15.7	4
NT3	D	92-10-8	92427418	8.2	448	2966	0.39	11.71	1	580	756	92	11.8	0.054	260	1002	21.6	74
ST1	D	92-9-25	92426645	8.6	960	6623	<0.04	<0.04	0.6	423	1859	258	<0.4	0.005	821	3048	26.2	95
ST2	D	92-9-25	92426657	7.5	60.7	480	0.05	<0.04	0.4	177	114	6	4.2	0.552	51	70	3.3	17
BF6	DW	93-4-7	93005155	7.1	198	1245	2.71	0.05	0.2	205	248	59	12	0.005	238	373	8.5	64
BI1	DW	92-8-26	92425161	7.2	32.8	153	0.06	0.19	0.1	17	41	6	2.6	0.005	7	73	0.8	4
CR1	DW	92-9-1	92423310	7.8	1122	7791	<0.04	2.34	0.9	450	2023	377	7.1	0.477	790	3758	45.3	236
DH11	DW	92-9-3	92423395	8	1330	9287	0.04	34.15	0.6	523	2036	446	7.8	1.157	959	4348	348.2	356
DH12	DW	92-9-2	92423346	7.8	281	1789	<0.04	1.17	0.3	137	319	92	5.3	0.01	287	752	13	154
DH147	DW	92-9-8	92425306	7.9	268	1555	0.13	0.84	0.4	201	341	70	5.7	0.117	140	650	11.6	94
DH1472	DW	92-9-2	92423322	8.1	579	3758	<0.04	27.39	0.5	450	892	128	8.4	0.019	389	1457	55.4	167
DH17	DW	92-10-14	92423358	7.7	1224	8499	<0.04	0.6	0.4	319	2333	360	5.2	0.011	1013	4062	50.7	288
DH20	DW	92-9-3	92423371	7.8	586	3734	<0.04	14.99	0.3	203	908	155	8.1	0.009	457	1701	29.9	168
DH51	DW	92-9-2	92423334	7.9	620	4099	0.11	17.51	0.5	379	973	173	6.9	0.013	475	1709	30.7	197
DH8231	DW	92-9-3	92423360	7.5	1560	11604	0.04	0.51	0.4	144	3073	239	4.4	0.011	1944	5410	24.1	735
DH8232	DW	92-9-3	92423383	7.8	849	5750	<0.04	10.08	0.4	233	1515	131	5	0.01	894	2536	16.6	329
KG1	DW	92-8-27	92425203	8.2	830	5744	0.09	15.95	0.9	784	1543	213	8.2	0.027	315	2482	29.6	134
MK1	DW	92-8-27	92425215	8.2	593	4372	<0.04	1.15	0.7	475	1221	139	<0.4	0.076	517	1791	27	90
MK2	DW	92-8-27	92425227	8.4	932	6745	0.04	8.7	0.6	1047	1744	266	8.1	0.719	738	2403	120.7	155
PE2	DW	92-9-8	92425290	7.6	1600	11190	13.11	1.21	0.7	676	3160	355	19.5	24.288	719	5577	230.7	226
TE1	DW	92-8-27	92425197	7.9	243	1535	<0.04	0.55	0.5	300	381	50	9	0.008	208	468	11.4	47
TM1	DW	92-9-3	92423401	8	2090	16387	<0.04	5.48	1.1	554	4444	668	8.2	0.036	1452	8541	130.9	450
VE1	DW	92-8-26	92425173	7.2	33.4	158	0.09	0.04	0.1	15	43	6	2.7	<0.005	7	79	1	4

SITE NO.	SITE TYPE	DATE SAMPLED	H NUMBER	pH	EC	TDS	NH4 N	NO3+NO2 N	F	TAL CaCO3	Na	Mg	Si	PO4 P	SO4	Cl	K	Ca
SABS MAX.				5.5-9.5	300	2000	2	10	1.5	650	400	100	25	0.2	600	600	800	400
SEA WATE				8.2	4400	35000	0.5	0.2	1	120	10500	1350	1	0.01	2650	19500	400	400
AA1	P	92-8-26	92423413	7.4	188	1220	0.05	4.32	0.6	161	338	23	5.1	1.115	151	435	20.1	34
SS1	R	92-10-6	92427250	7.4	30.8	150	<0.04	<0.04	0.1	14	40	5	2.2	0.01	9	74	0.6	4
SS2	R	92-10-6	92427261	7.2	44	223	<0.04	0.06	0.1	22	56	8	2.4	0.016	16	107	1.5	7
SS3	R	92-10-6	92427273	7.3	51	255	<0.04	<0.04	0.2	20	67	9	2.9	0.009	16	130	1	7
SS4	R	92-10-6	92427285	7.2	112.7	616	<0.04	<0.04	0.3	46	158	30	3	0.012	44	298	4	25
SS5	R	92-10-6	92427297	7.4	83.3	479	<0.04	<0.04	0.2	42	114	21	4.6	0.008	63	206	2.1	18
SS6	R	92-10-6	92427303	7.7	281	1625	<0.04	<0.04	0.2	109	369	82	2.9	0.007	119	836	8.8	77
SS7	R	92-10-8	92427352	8.2	403	3207	0.06	1.57	0.4	736	555	95	3.4	0.111	247	955	366.5	83
SS8	R	92-10-6	92427315	8.3	422	3216	<0.04	<0.04	0.3	497	636	98	3.1	0.008	492	1015	297.9	72
SS9	R	92-10-8	92427364	7.9	490	3424	<0.04	3.88	0.4	424	772	119	1.1	1.067	426	1260	227.8	82
SS10	R	92-10-8	92427376	7.9	474	3038	<0.04	1.03	0.5	397	674	104	2.2	1.246	380	1137	169	81
SS11	R	92-10-8	92427388	8.1	519	3417	<0.04	0.29	0.5	484	770	111	1.4	1.838	421	1261	172.4	85
SS12	R	92-10-8	92427390	7.9	608	3968	0.07	1.94	0.5	466	954	138	1.6	1.351	447	1609	150.7	88
BF23	S	93-4-15	93005313	7.3	53.4	331	<0.04	<0.04	0.1	86	67	10	<0.4	0.006	7	113	5.4	23
BF24	S	93-4-15	93005325	7.2	78.4	414	0.04	<0.04	0.1	13	122	15	4.6	0.006	18	233	0	1
SD2	S	92-8-26	92425150	7.3	30.8	146	0.24	0.09	0.2	18	39	6	2.1	0.005	<4	70	0.6	4
SP1 (US)	S	93-2-25	93004430	6	14.5	63	<0.04	<0.04	0.1	<4	17	2	5.3	0.03	7	33	<0.3	2

APPENDIX C:

HYDRO-CHEMICAL RESULTS FROM INITIAL SAMPLING RUNS - SWARTKOPS RIVER ALLUVIAL AQUIFER MONITORING NETWORK.

(from Maclear, 1995)

LEGEND

NH_4	-	ammonium as N
NO_3+NO_2	-	nitrate and nitrite reported as equivalent molecular nitrogen (N) where 1 mg/ℓ N = 4.5 mg/ℓ NO_3
PO_4	-	ortho-phosphate (inorganic) as P
TAL	-	total alkalinity as $CaCO_3$
TDS	-	total dissolved salts.

All values in mg/ℓ (ppm) except :

E.C.	-	electrical conductivity in milli-Siemens per metre at 25° Celsius
pH	-	logarithm of the inverse of the hydrogen ion concentration.

- The shaded values exceed the maximum allowable limit[3] for water used for domestic purposes.
- Average sea-water hydrochemistry values[4] included for comparative purposes.

IWQS DETECTION LIMITS - 1996

Macro Constituents:

Element	Accuracy*	Reproducibility	Lld**
COD	3%	0.3%	9.9 mg/l
DOC	2%	0.2%	0.2 mg/l

refer to Appendix B Legend for additional macro constituents detection limits.

Trace Elements:

Element	Accuracy*	Reproducibility	Lld**
Al	1%	0.1%	0.020 mg/l
As	1%	0.1%	0.050 mg/l
B	1%	0.1%	0.002 mg/l
Ba	1%	0.1%	0.002 mg/l
Cd	1%	0.1%	0.001 mg/l
Co	1%	0.1%	0.005 mg/l
Cr	1%	0.1%	0.003 mg/l
Cu	1%	0.1%	0.004 mg/l
Fe	1%	0.1%	0.003 mg/l
Mn	1%	0.1%	0.001 mg/l
Mo	1%	0.1%	0.006 mg/l
Ni	1%	0.1%	0.004 mg/l
Pb	1%	0.1%	0.020 mg/l
Sr	1%	0.1%	0.001 mg/l
V	1%	0.1%	0.003 mg/l
Zn	1%	0.1%	0.003 mg/l

* Accuracy at Mid range. Accuracy at Lld is by definition 50%, or 2 sigma RSD (relative standard deviation).

** Lld = lower limit of detection.

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[3] Water quality limits from:
- DWA&F (1993a),
- SABS (1984), and
- Kempster, P.L., Hattingh, W.H.J. and van Vliet, H.R. (1980). Summarised Water Quality Criteria. DWA&F technical report TR 108, IWQS, Pretoria.

[4] Sea-water chemistry from:
- Driscoll, F.G. (1986). Ground Water and Wells (2nd ed.). Johnson Division, St. Paul, Minnesota, and
- Hem (1970).

MONITORING BOREHOLES
Macro analysis

Borehole No.	SITE NAME	SAMPLE RUN *	E.C. (mS/m)	T D S (mg/L)	pH (Lab)	Na (mg/L)	Mg (mg/L)	Ca (mg/L)	F (mg/L)	Cl (mg/L)	NO3+NO2 as N (mg/L)	SO4 (mg/L)	PO4 as P (mg/L)	TAL as CaCO3 (mg/L)	Si (mg/L)	K (mg/L)	NH4 as N (mg/L)	Hardness (mg/L)	D O C (mg/L)	C O D (mg/L)
SABS max			300	2000	5.5-9.5	400	100	400	1.5	600	10	600	0.2	650	18	800	2	300	10	75
Sea water			4400	35000	8.2	10500	1350	400	1	19500	0.2	2650	0.01	120	6.4	400	0.5	6535	-	-
G40035	INGGSVILLE	1	90	421	7.1	119	18	9.4	<0.2	202	<0.1	46	<0.1	20	-	3	<0.1	97	4.2	16
		2	23	125	7.3	27	5	3	0.1	46	0.15	8	0.04	28	2.3	2.1	0.04	28	-	-
		3	26	121	7.3	32	5	3	0.1	54	0.19	6	0.019	16	2.5	2.5	0.04	28	-	-
G40034	MORESON	1	3650	26384	7.8	7386	1148	595	<0.2	13308	<0.5	3066	<0.1	608	-	139	0.6	6194	23	-
		2	3130	25683	7.6	7733	1198	404	0.1	11879	<0.04	3180	0.04	890	5.8	203	0.3	5922	-	-
		3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
G40033	GRAHAMS POULTRY	1	385	2172	7.5	495	112	125	<0.2	1014	10.6	157	<0.1	181	-	38	<0.1	772	9	79
		2	442	2866	7.2	573	143	143	0.2	1471	2	325	0.05	129	4	45	0.1	944	-	-
		3	675	3588	7.5	817	185	192	0.2	2035	1.17	206	0.065	69	4.4	63.1	0.08	1239	-	-
G40036	GUBB&INGGS	1	820	7532	7.8	752	96	107	2	650	<0.1	850	9.8	2863	-	1476	97	661	377	1249
		2	816	8277	7.9	779	8	22	2.1	1152	0.83	748	268.4	2200	9.8	1993.4	50.28	88	-	-
		3	1026	8978	8.2	1003	118	99	2.6	650	8.72	809	0.035	3600	7.5	1749.4	92.28	731	-	-
G40044	NIVANSDRIFT	1	180	1056	7.2	252	37	40	<0.2	424	<0.1	62	<0.1	186	-	16	<0.1	252	10	40
		2	326	1859	7.4	474	72	51	0.2	839	0.04	129	0.15	216	3.1	29.6	0.04	423	-	-
		3	395	2500	7.6	706	88	59	0.3	1159	..04	143	0.376	251	3.2	38.3	0.05	508	-	-
G40043	E.C.T.P.	1	4350	30597	7.5	9648	1019	427	1.6	16472	<0.1	1536	<0.1	1156	-	81	1.3	5245	31	-
		2	2870	22165	7.8	6974	569	225	1.1	11751	0.04	1340	0.04	978	6.4	110.2	0.98	2895	-	-
		3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
G40042	C.G.H.P.	1	1260	13204	8	2426	336	183	1	1595	<0.1	282	<0.1	5840	-	1230	27	1835	192	3478
		2	1127	10264	8.4	2313	197	35	0.5	1496	0.31	38	78	4259	8.8	738.7	9.67	895	-	-
		3	1300	14614	8	3015	316	58	0.5	1627	0.1	645	0.578	6348	5	1208.7	0.46	1441	-	-
G40041	U.S.W.	1	540	3424	9.4	909	111	104	0.5	1304	<0.1	454	<0.1	433	-	14	0.5	715	17	79
		2	436	3066	7.5	793	98	86	0.5	1147	0.04	413	0.045	420	9.8	15.4	0.49	617	-	-
		3	459	3138	8.1	876	93	84	0.6	1154	0.04	426	0.005	399	10.7	16.4	0.36	591	-	-
G40038	CHIMNEY	1	920	6036	7.5	1610	210	175	<0.2	2583	2.2	620	0.5	648	-	44	1.3	1299	11	87
		2	874	6234	7.7	1658	227	170	0.3	2846	1.34	632	0.08	527	6.6	50.9	1.2	1356	-	-
		3	1101	6594	8.1	1877	211	168	0.3	3039	1.26	570	0.033	507	6.8	104.2	0.12	1285	-	-
G40037	D.S.W.	1	375	2618	7.4	430	59	58	<0.2	617	<0.1	37	35	952	-	65	155	387	20	103
		2	371	2746	7.5	439	55	51	0.2	650	0.04	48	32.5	958	16.7	60.8	135.9	353	-	-
		3	429	2685	7.5	485	47	46	0.3	631	0.09	55	36	878	17.3	64.9	135.5	308	-	-
G40039	P.W.P.	1	580	3614	7.7	1005	98	88	<0.2	1508	<0.1	296	<0.1	424	-	95	6	622	13	79
		2	513	3513	7.8	934	92	76	0.3	1523	0.04	276	0.11	422	4.4	89.2	6.18	567	-	-
		3	542	3667	8.2	1038	83	72	0.3	1639	0.04	232	0.17	416	4.5	95.6	0.37	520	-	-
G40040	REDHOUSE	1	5000	37144	7.8	10688	1361	961	2.3	18942	2.3	4383	<0.1	359	-	365	3.3	7983	22	-
		2	3900	30441	7.8	10967	1400	853	1	11938	0.46	4416	0.1	407	7.7	360	5.38	7873	-	-
		3	5550	42016	7.5	3015	5626	2783	0.9	24586	0.16	4167	0.033	280	6.1	1484	9.42	30024	-	-

* SAMPLE RUN 1: dates sampled = 95.05.23 to 95.05.24, dates analysed 95.06.06 to 95.06.12, sample preserved HgCl2, laboratory = CSIR Stellenbosch.

* SAMPLE RUN 2: dates sampled = 95.09.27 to 95.09.28, dates analysed = 96.02.16, sample unpreserved, laboratory = IWQS - Pretoria.

* SAMPLE RUN 3: dates sampled = 95.11.20 to 95.11.21, dates analysed = 96.02.16, sample unpreserved, laboratory = IWQS - Pretoria.

POLLUTION SOURCES
Macro analysis

Sample No.	SITE NAME	SAMPLE RUN *	E.C. (mS/m)	T D S (mg/L)	pH (Lab)	Na (mg/L)	Mg (mg/L)	Ca (mg/L)	F (mg/L)	Cl (mg/L)	NO3+NO2 as N (mg/L)	SO4 (mg/L)	PO4 as P (mg/L)	TAL as CaCO3 (mg/L)	Si (mg/L)	K (mg/L)	NH4 as N (mg/L)	Hardness (mg/L)	D O C (mg/L)	C O D (mg/L)
SABS max			300	2000	5.5-9.5	400	100	400	1.5	600	10	600	0.2	650	18	800	2	300	10	75
Sea water			4400	35000	8.2	10500	1350	400	1	19500	0.2	2650	0.01	120	6.4	400	0.5	6535	-	-
337UI/R1	BULLMERS DRIFT	1	70	360	7.3	100	14	12	<0.2	153	0.2	50	0.03	36	-	1.7	0.1	87	4	20
		2	49.8	265	7.2	69	11	7	0.1	111	0.15	25	0.016	32	1.4	2.8	<0.04	63	-	-
		3	40.3	222	8.4	60	9	6	<0.1	93	0.09	13	0.019	29	2.3	4.2	1.62	52	-	-
337UI/D1	GRAHAMS POULTRY	1	2350	19351	7.8	517	83	551	<1	1230	<1	350	60	19351	-	2090	3000	1718	9420	39970
		2	77	533	7.2	70	23	39	0.2	118	<0.04	18	4.833	190	4.5	8.5	8.35	192	-	-
		3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
337UI/D3	GUBB&INGGS	1	2200	24601	9.3	2530	85	84	<1	1500	<1	200	52	11140	-	6610	34.4	559	2090	10183
		2	2060	14319	8.6	969	66	12	0.9	323	0.18	40	0.611	10500	5.7	102.6	0.46	301	-	-
		3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
UI/D4	E.C.T.P.	1	6400	53403	9.5	19170	245	10	<1	23840	<1	100	8	8220	-	245	1.8	1030	260	1711
		2	5160	37894	8.5	1998	250	16	0.6	25735	0.23	65	188.9	7400	3.9	224.1	1.14	1065	-	-
		3	1026	8978	8.2	1003	118	99	2.6	650	8.72	809	0.035	3600	7.5	1749.4	92.28	731	-	-
UI/D2	C.G.H.P.	1	1400	14046	8.8	1406	71	66	<1	1400	<1	250	20.5	5840	-	3700	78.9	456	1420	9409
		2	1212	11882	8.5	1072	36	19	0.6	948	0.12	50	372.8	4400	7.9	3227.2	16.37	195	-	-
		3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
UI/D1	U.S.W.	1	200	1066	7.7	295	25	33	<0.2	400	0.2	111	7.4	158	-	24	3.02	185	13	84
		2	178	1016	7.2	299	22	29	0.3	295	0.09	58	14.8	195	5	27.4	1.97	163	-	-
		3	164	1180	7.2	345	19	26	0.4	444	<0.04	87	12.8	158	6.6	26.9	0.37	143	-	-
567UI/D1	D.S.W.	1	285	1831	8	2426	409	67	<0.2	520	0.2	122	42.4	484	-	43	37.2	1844	18	116
		2	287	2057	7.5	450	58	48	0.4	665	<0.04	78	33.3	488	11.9	49.2	8.9	358	-	-
		3	338	2090	7.7	466	64	48	0.2	576	<0.04	84	47.6	493	14.8	59.2	36.8	382	-	-
PE/D1	P.W.P.	1	18500	255795	9.9	83100	2340	100	<1	124500	<1	1800	34	23800	-	17200	25	9844	430	19145
		2	10940	167980	8.8	100000	72	29	<0.1	4484	0.46	143	309.8	25000	0.7	10000	0.67	368	-	-
		3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

* SAMPLE RUN 1: dates sampled = 95.07.04 to 95.07.05, dates analysed 95.07.11 to 95.07.13, sample preserved HgCl2, laboratory = CSIR - Stellenbosch.
* SAMPLE RUN 2: dates sampled = 95.09.27 to 95.09.28, dates analysed = 96.02.16, sample unpreserved, laboratory = IWQS - Pretoria.
* SAMPLE RUN 3: dates sampled = 95.11.20 to 95.11.21, dates analysed = 96.02.16, sample unpreserved, laboratory = IWQS - Pretoria.

MONITORING BOREHOLES
Trace metals

Borehole No.	SITE NAME	SAMPLE RUN *	Al (mg/L)	Ba (mg/L)	Cd (mg/L)	Cr (mg/L)	Cu (mg/L)	Fe (mg/L)	Mn (mg/L)	Mo (mg/L)	Ni (mg/L)	Pb (mg/L)	Sr (mg/L)	V (mg/L)	Zn (mg/L)	As (mg/L)	Co (mg/L)	B (mg/L)
SABS max			0.5	1	0.02	0.2	1	1	1	0.1	0.5	0.1	none	0.5	5	0.3	0.5	2
Sea water			0.01	0.03	0.00011	0.00005	0.003	0.01	0.002	0.01	0.002	0.00003	8	0.002	0.01	0.003	0.0005	4.6
G40035	INGGSVILLE	1	0.33	<0.03	<0.005	<0.03	<0.03	0.5	0.05	<0.01	<0.03	<0.03	0.03	<0.03	<0.03	<0.005	<0.03	<0.1
		2	0.076	0.007	<0.002	<0.003	<0.002	0.05	0.003	<0.005	<0.006	<0.015	0.038	<0.002	0.006	<0.05	-	-
		3	<0.02	0.015	<0.002	<0.003	<0.002	0.008	<0.001	<0.005	<0.006	<0.015	0.045	<0.002	<0.004	<0.05	-	-
G40034	MORESON	1	0.81	0.09	0.03	<0.03	0.04	16.7	18.4	0.07	0.09	0.33	11.4	0.03	<0.03	<0.005	0.06	4
		2	<0.02	0.034	<0.002	0.011	<0.002	<0.003	2.037	<0.005	<0.006	<0.015	7.105	<0.002	<0.004	<0.05	-	-
		3	<0.02	0.039	<0.002	<0.003	<0.002	<0.003	3.041	<0.005	<0.006	<0.015	10.193	<0.002	<0.004	<0.05	-	-
G40033	GRAHAMS POULTRY	1	0.62	0.23	<0.005	<0.03	<0.03	1.09	0.25	<0.01	<0.03	0.06	1.6	<0.03	<0.03	<0.005	<0.03	0.12
		2	<0.02	0.307	<0.002	<0.003	<0.002	<0.003	<0.001	<0.005	<0.006	<0.015	1.827	<0.002	<0.004	<0.05	-	-
		3	<0.02	0.546	<0.002	<0.003	<0.002	<0.003	<0.001	<0.005	<0.006	<0.015	2.431	<0.002	<0.004	<0.05	-	-
G40036	GUBB&INGGS	1	1.12	<0.03	0.007	0.04	<0.03	2.06	1.13	0.02	0.06	0.07	0.44	0.09	<0.03	0.626	<0.03	0.36
		2	0.131	0.035	<0.002	0.034	<0.002	0.781	0.931	<0.005	0.032	<0.015	0.436	0.077	0.01	0.363	-	-
		3	<0.02	<0.001	<0.002	0.027	<0.002	1.513	1.064	<0.005	0.015	<0.015	0.536	0.012	<0.004	<0.05	-	-
G40044	NIVANSDRIFT	1	0.1	0.07	<0.005	<0.03	<0.03	1.48	0.638	0.011	<0.03	0.03	0.49	0.03	<0.03	<0.005	<0.03	0.25
		2	<0.02	0.086	<0.002	<0.003	<0.002	<0.003	<0.001	<0.005	<0.006	<0.015	0.923	<0.002	<0.004	<0.05	-	-
		3	<0.02	0.15	<0.002	<0.003	<0.002	<0.003	<0.001	<0.005	<0.006	<0.015	1.177	<0.002	<0.004	<0.05	-	-
G40043	E.C.T.P.	1	4.43	0.08	0.034	0.04	0.05	2.02	2.88	0.08	0.14	0.35	9.07	0.05	<0.03	<0.005	0.08	4.42
		2	<0.02	0.009	<0.002	<0.003	<0.002	<0.003	<0.001	<0.005	0.012	<0.015	4.869	<0.002	<0.004	<0.05	-	-
		3	<0.02	0.041	<0.002	0.008	<0.002	<0.003	2.446	<0.005	0.043	<0.015	5.232	<0.002	<0.004	<0.05	-	-
G40042	C.G.H.P.	1	0.36	1.07	0.021	0.03	0.04	8.09	3.48	0.06	0.19	0.21	3.34	0.1	<0.03	0.035	0.08	0.9
		2	<0.02	0.269	<0.002	<0.003	<0.002	0.188	<0.001	<0.005	0.085	<0.015	2.058	0.075	<0.004	0.212	-	-
		3	<0.02	0.717	<0.002	0.038	<0.002	3.575	3.557	<0.005	0.108	<0.015	4.253	0.142	<0.004	0.272	-	-
G40041	U.S.W.	1	0.51	<0.03	0.007	<0.03	<0.03	6.54	0.88	0.03	0.05	0.1	1.16	<0.03	<0.03	0.02	<0.03	1.15
		2	<0.02	0.005	<0.002	<0.003	<0.002	<0.003	0.037	<0.005	<0.006	<0.015	1.128	<0.002	<0.004	<0.05	-	-
		3	<0.02	0.009	<0.002	<0.003	<0.002	<0.003	0.051	<0.005	<0.006	<0.015	1.059	<0.002	<0.004	<0.05	-	-
G40038	CHIMNEY	1	0.69	0.09	0.011	<0.03	<0.03	0.36	0.93	0.03	0.04	0.12	2.28	<0.03	<0.03	0.006	<0.03	1.89
		2	<0.02	0.091	<0.002	<0.003	<0.002	<0.003	0.616	<0.005	<0.006	<0.015	2.175	<0.002	<0.004	<0.05	-	-
		3	<0.02	0.125	<0.002	<0.003	<0.002	<0.003	0.85	<0.005	<0.006	<0.015	3.2	<0.002	<0.004	<0.05	-	-
G40037	D.S.W.	1	0.12	0.07	0.005	<0.03	<0.03	5.46	0.85	0.01	<0.03	0.03	0.38	<0.03	<0.03	0.013	<0.03	0.65
		2	<0.02	0.004	<0.002	<0.003	<0.002	0.009	0.392	<0.005	<0.006	<0.015	0.328	<0.002	<0.004	<0.05	-	-
		3	<0.02	<0.001	<0.002	<0.003	<0.002	<0.003	0.609	<0.005	<0.006	<0.015	0.517	<0.002	<0.004	<0.05	-	-
G40039	P.W.P.	1	1.27	0.33	0.006	<0.03	<0.03	10.6	1.2	0.02	<0.03	0.08	1.05	<0.03	<0.03	0.008	<0.03	0.66
		2	<0.02	0.19	<0.002	<0.003	<0.002	<0.003	<0.001	<0.005	<0.006	<0.015	0.795	<0.002	<0.004	<0.05	-	-
		3	<0.02	0.308	<0.002	<0.003	<0.002	<0.003	1.003	<0.005	<0.006	<0.015	0.869	<0.002	<0.004	<0.05	-	-
G40040	REDHOUSE	1	2.54	<0.03	0.041	<0.03	0.08	7.92	0.32	0.13	0.13	0.38	8.48	0.06	<0.03	<0.005	0.08	5.22
		2	<0.02	0.019	<0.002	<0.003	<0.002	<0.003	<0.001	0.082	<0.006	<0.015	8.136	<0.002	<0.004	<0.05	-	-
		3	<0.02	0.008	<0.002	<0.003	<0.002	<0.003	<0.001	0.042	<0.006	<0.015	11.084	<0.002	<0.004	<0.05	-	-

* SAMPLE RUN 1: dates sampled = 95.05.23 to 95.05.24, dates analysed = 95.06.06 to 95.06.12, sample preserved HNO3, laboratory = CSIR - Stellenbosch.

* SAMPLE RUN 2: dates sampled = 95.09.27 to 95.09.28, dates analysed = 96.02.16, sample unpreserved, laboratory = IWQS - Pretoria.

* SAMPLE RUN 3: dates sampled = 95.11.20 to 95.11.21, dates analysed = 96.02.16, sample unpreserved, laboratory = IWQS - Pretoria.

POLLUTION SOURCES
Trace metals

Borehole No.	SITE NAME	SAMPLE RUN *	Al (mg/L)	Ba (mg/L)	Cd (mg/L)	Cr (mg/L)	Cu (mg/L)	Fe (mg/L)	Mn (mg/L)	Mo (mg/L)	Ni (mg/L)	Pb (mg/L)	Sr (mg/L)	V (mg/L)	Zn (mg/L)	As (mg/L)	Co (mg/L)	B (mg/L)
SABS max			0.5	1	0.02	0.2	1	1	1	0.1	0.5	0.1	none	0.5	5	0.3	0.5	2
Sea water			0.01	0.03	0.00011	0.00005	0.003	0.01	0.002	0.01	0.002	0.00003	8	0.002	0.01	0.003	0.0005	4.6
337UI/R1	BULLMERS DRIFT	1	1.21	0.11	0.01	<0.03	0.12	2.66	0.09	<0.01	0.09	0.22	0.63	<0.03	0.23	<0.005	<0.03	1.34
		2	<0.02	0.036	<0.002	<0.003	<0.002	<0.003	<0.001	<0.005	<0.006	<0.015	0.144	<0.002	<0.004	<0.05	-	-
		3	<0.02	0.039	<0.002	<0.003	<0.002	0.034	0.012	<0.005	<0.006	<0.015	0.101	<0.002	0.006	<0.05	-	-
337UI/D1	GRAHAMS POULTRY	1	26.1	1.83	1.73	0.93	4.68	88.4	108	0.556	1.4	1.54	20.4	0.3	32.2	0.01	0.83	7.77
		2	<0.02	<0.001	<0.002	<0.003	<0.002	<0.003	0.371	<0.005	<0.006	<0.015	0.274	<0.002	0.008	<0.05	-	-
		3	0.103	1.648	<0.002	0.008	<0.002	0.089	0.051	<0.005	0.029	<0.015	0.419	<0.002	0.255	<0.05	-	-
337UI/D3	GUBB&INGGS	1	23.5	1.62	0.058	1.49	24	38.2	11.6	0.098	0.77	1.08	2.48	1.86	1.24	0.039	0.49	4.08
		2	<0.02	0.7	<0.002	0.256	<0.002	<0.003	1.279	<0.005	0.083	<0.015	0.469	0.377	<0.004	<0.05	-	-
		3	<0.02	1.005	<0.002	0.315	<0.002	<0.003	1.388	<0.005	0.109	<0.015	0.546	0.449	0.293	<0.05	-	-
UI/D4	E.C.T.P.	1	3.2	0.38	0.11	4.91	0.14	3.36	0.65	0.176	0.49	1.3	0.74	0.18	0.3	0.024	0.26	21.2
		2	<0.02	0.304	<0.002	0.548	<0.002	<0.003	<0.001	<0.005	<0.006	<0.015	0.216	<0.002	<0.004	<0.05	-	-
		3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
UI/D2	C.G.H.P.	1	43.1	1.69	0.086	0.83	0.42	126	12.8	0.195	0.51	2.4	1.93	1.09	1.08	0.017	0.36	1.67
		2	0.35	0.473	<0.002	0.093	<0.002	8.15	1.878	<0.005	<0.006	<0.015	0.38	0.138	0.09	<0.05	-	-
		3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
UI/D1	U.S.W.	1	0.64	0.12	0.039	0.04	0.1	4.33	0.48	0.131	0.13	0.17	1.44	<0.03	0.21	<0.005	0.03	2.61
		2	<0.02	<0.001	<0.002	<0.003	<0.002	0.15	<0.001	<0.005	<0.006	<0.015	0.282	<0.002	<0.004	<0.05	-	-
		3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
567UI/D1	D.S.W.	1	1.12	0.2	0.045	0.05	0.12	1.05	0.59	0.079	0.12	0.36	3.23	<0.03	0.29	<0.005	0.07	3.11
		2	<0.02	0.015	<0.002	<0.003	<0.002	0.024	<0.001	<0.005	<0.006	<0.015	0.585	<0.002	<0.004	<0.05	-	-
		3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
PE/D1	P.W.P.	1	4.54	1.53	0.124	0.83	0.51	27.4	0.44	0.35	1.18	1.88	7.12	1.37	0.95	<0.005	0.79	48.5
		2	<0.02	0.806	<0.002	<0.003	<0.002	<0.003	<0.001	<0.005	<0.006	<0.015	0.849	<0.002	<0.004	<0.05	-	-
		3	<0.02	0.997	<0.002	<0.003	<0.002	<0.003	<0.001	<0.005	<0.006	<0.015	0.755	<0.002	<0.004	<0.05	-	-

* SAMPLE RUN 1: dates sampled = 95.07.04 to 95.07.05, dates analysed = 95.07.11 to 95.07.13, sample preserved HNO3, laboratory = CSIR - Stellenbosch.

* SAMPLE RUN 2: dates sampled = 95.09.27 to 95.09.28, dates analysed = 96.02.16, sample unpreserved, laboratory = IWQS - Pretoria.

* SAMPLE RUN 3: dates sampled = 95.11.20 to 95.11.21, dates analysed = 96.02.16, sample unpreserved, laboratory = IWQS - Pretoria.

APPENDIX D:

RAIN WATER ANALYSES

Determinand (mg/*l*)	Groendal Dam GD1	Sea View SV1	SABS limit*	Sea water
K	1.4	2.7	800	400
Na	8	7	400	10500
Ca	4	8	400	400
Mg	1.8	1	100	1350
NH_4 as N	0.28	<0.04	2	0.5
SO_4	8	4	600	2650
Cl	17.5	8	600	19500
TAL (as $CaCO_3$)	5	35	650	120
$NO_3 + NO_2$	0.2	0.08	10	0.2
P	<0.1	0.02	0.2	0.01
F	<0.1	0.2	1.5	1
DOC	14.5	-	10	-
EC (mS/m)	9.4	9.9	300	4400
pH	6.4	7.8	5.5-9.5	8.2
TDS	60	75	2000	35000
Hardness	17	24	300	6535

* maximum limit for drinking water from SABS (1984).
- Dates analysed GD1 = 95/11/17, SV1 = 95/08/23,
- GD1 = preserved $HgCl_2$, SV1 = unpreserved,
- GD1 = analysed at CSIR laboratory - Stellenbosch, SV1 = analysed at IWQS - Pretoria.
- Location: GD1 = Groendal Dam 33°41'29" (S) 25°16'16" (E)
  SV1 = Sea View 34°00'06" (S) 25°20'01" (E).
- Weather details on sample dates (as supplied by Weather Bureau office - Port Elizabeth airport):
  GD1 = frontal rain, 11.5mm, wind SW(E) 30-50 knots, distant cumulo-nimbus cloud,
  SV1 = light drizzle/frontal rain, 12.2mm, wind SW 10-20 knots.

APPENDIX E:

ZWARTKOPS SPA BOREHOLE - DRILLING DETAILS

(from Brown, 1972)

Reason for drilling (*circa* 1908), according to the driller Mr. G.W. Smith, in Mountain (1955):

> *"The idea of putting down a deep bore to prove what lay under the surface was largely undertaken from a spirit of adventure, partly assisted by various vague rumours of traces of oil having been found at places in the Zwartkops River Valley..."*

Miscellaneous data:

borehole location	Lat. : 33°52'50" S	Long. : 25°36'45" E
drill rig	steam-driven percussion	
drill rods	11.5m long	
casing purchased	2.4km (high quality steel)	
drilling dates	30/4/1908-7/10/1909	
total project cost	£13 000	
major leak in casing	25mbs	
grouting dates	25/8/1969-8/12/1969 (grout = cement and sawdust mix)	

Borehole construction:

screen interval (m)	screen diameter (")
0-25	18
25-84	14
84-293	9
293-412	8
412-640	6
640-960	5
960-1103 (eoh)	open hole

Drilling rate:

drill rate (m/day)	depth (m)
4.3	0-975
2.4	975-1035
5.5	1035-1085
0	1103

Water strikes, non-thermal artesian :

depth	salinity
82	fresh
280	fresh
381	fresh
466	fresh
756	brine

Water strikes, thermal artesian :

depth	yield (ℓ/s)	temp(°C)	comments
1038	1.8	40.5	sulphur smell
1085	13.1	54.5	scalding thermal

ZWARTKOPS SPA BOREHOLE LOG

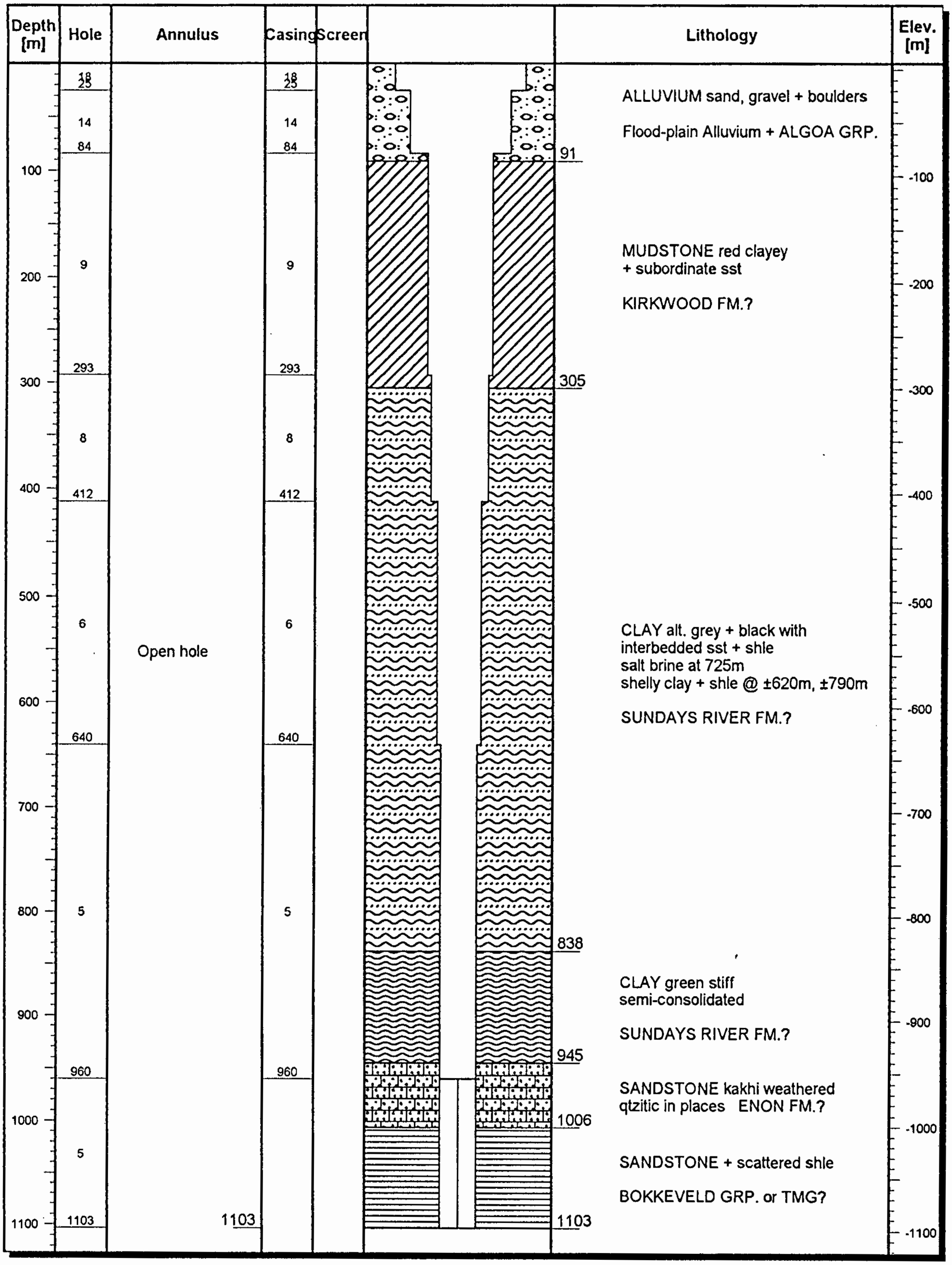
Well Log: Lithology & Construction

Well Ident	Zwartkops Spa	Name	Zwartkops Spa Borehole (disused)				
Drill. Method	Steam-driven percussion	Drill. Dates	27/7/1908-7/10/1909				
X	371681	Y	6250416	Z	5.0	Meas. Pt. Elev.	5.0

All measurements are in meters. Hole and casing diameters in inches.

Scales (1: xxx)

Water Level (m AMSL)	Vertical 5500.0	Horizontal



ZWARTKOPS SPA BOREHOLE - HYDROCHEMICAL DATA

(from Kent, 1969)

Borehole water classified as *chalybeatic.*

* all values in mg/ℓ unless indicated otherwise.

TDS	-	563
pH	-	6.9 (lab.)

Macro ions		**Trace elements**	
NH_4	0	Ba	nd
Li	nd	Al	2.8
Na	145.8	Fe	25
K	10.2	Mn	1
Mg	16.4	Br	0
Ca	10		
F	0.5		
Cl	237.9		
NO_3	0		
SO_4	33.6		
PO_4	0.4		
HCO_3	82.4		
CO_3	0		
SiO_2	18		

GAS

N_2 + He + Ar	85%
O_2	11.5%
CO_2	3.5%

APPENDIX F:

BOREHOLE LOGS - SWARTKOPS RIVER ALLUVIAL AQUIFER MONITORING NETWORK

(from Maclear, 1995)

LEGEND

- Logs extended to below end of hole to indicate extension of lithology.
- X+Y in UTM co-ordinate system (UTM zone 35).
- Concrete block scale representative for above surface only.

Well Log: Lithology & Construction

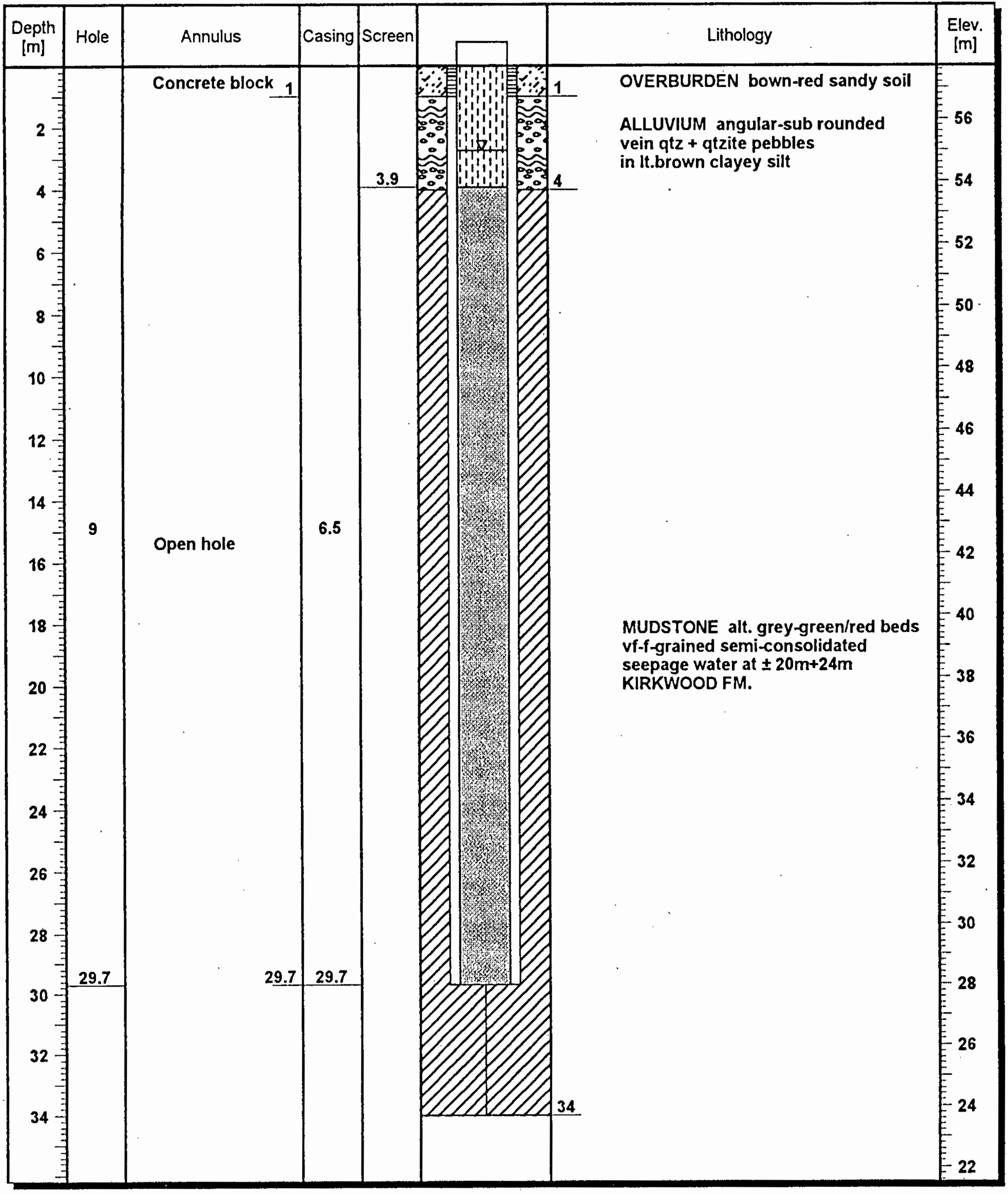
Well Ident	G40033
Name	GOOD HOPE
Drill. Method	Odex (air percussion)
Drill. Dates	09/29/94 - 10/05/94

X	346753.9	Y	6264773.6	Z	57.70	Meas. Pt. Elev.	58.50

All measurements are in meters. Hole and casing diameters in inches.

Scales (1: xxx)

Water Level (m AMSL)	55.00	Vertical	Horizontal
		200.0	



Depth [m]	Hole	Annulus	Casing	Screen	Lithology	Elev. [m]
		Concrete block 1			OVERBURDEN bown-red sandy soil	
				3.9	ALLUVIUM angular-sub rounded vein qtz + qtzite pebbles in lt.brown clayey silt	
	9	Open hole	6.5			
					MUDSTONE alt. grey-green/red beds vf-f-grained semi-consolidated seepage water at ± 20m+24m KIRKWOOD FM.	
	29.7	29.7	29.7			

Well Log: Lithology & Construction

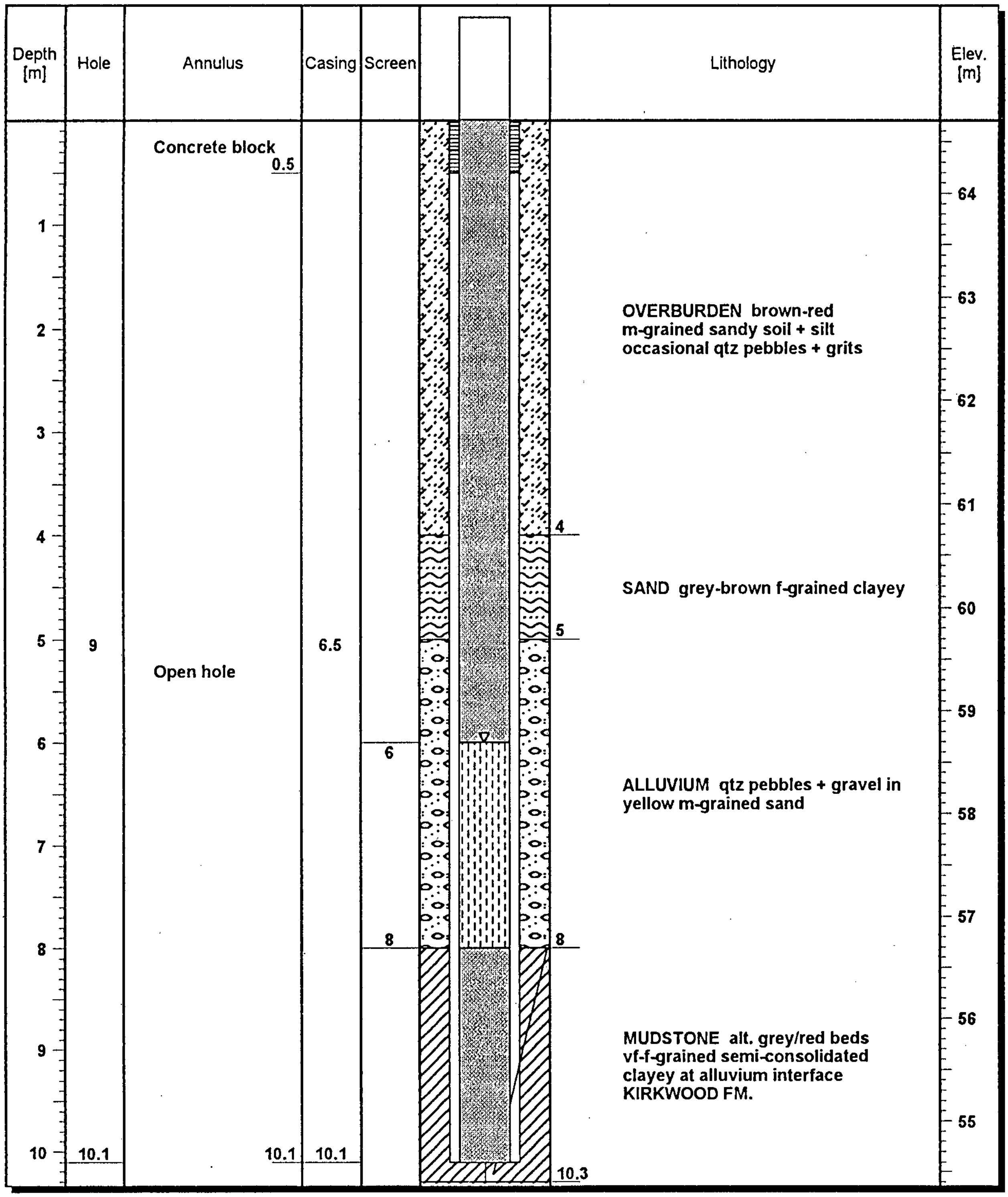
Well Ident	G40034
Name	MÔRESON
Drill. Method	Odex (air percussion)
Drill. Dates	10/11/94 - 10/11/94

X	Y	Z	Meas. Pt. Elev.
346107.7	6263346.0	64.70	65.70

All measurements are in meters. Hole and casing diameters in inches.

Scales (1: xxx)

Water Level (m AMSL)	Vertical	Horizontal
58.70	60.0	



OVERBURDEN brown-red m-grained sandy soil + silt occasional qtz pebbles + grits

SAND grey-brown f-grained clayey

ALLUVIUM qtz pebbles + gravel in yellow m-grained sand

MUDSTONE alt. grey/red beds vf-f-grained semi-consolidated clayey at alluvium interface KIRKWOOD FM.

Well Log: Lithology & Construction

Well Ident G40035	Name INGGSVILLE

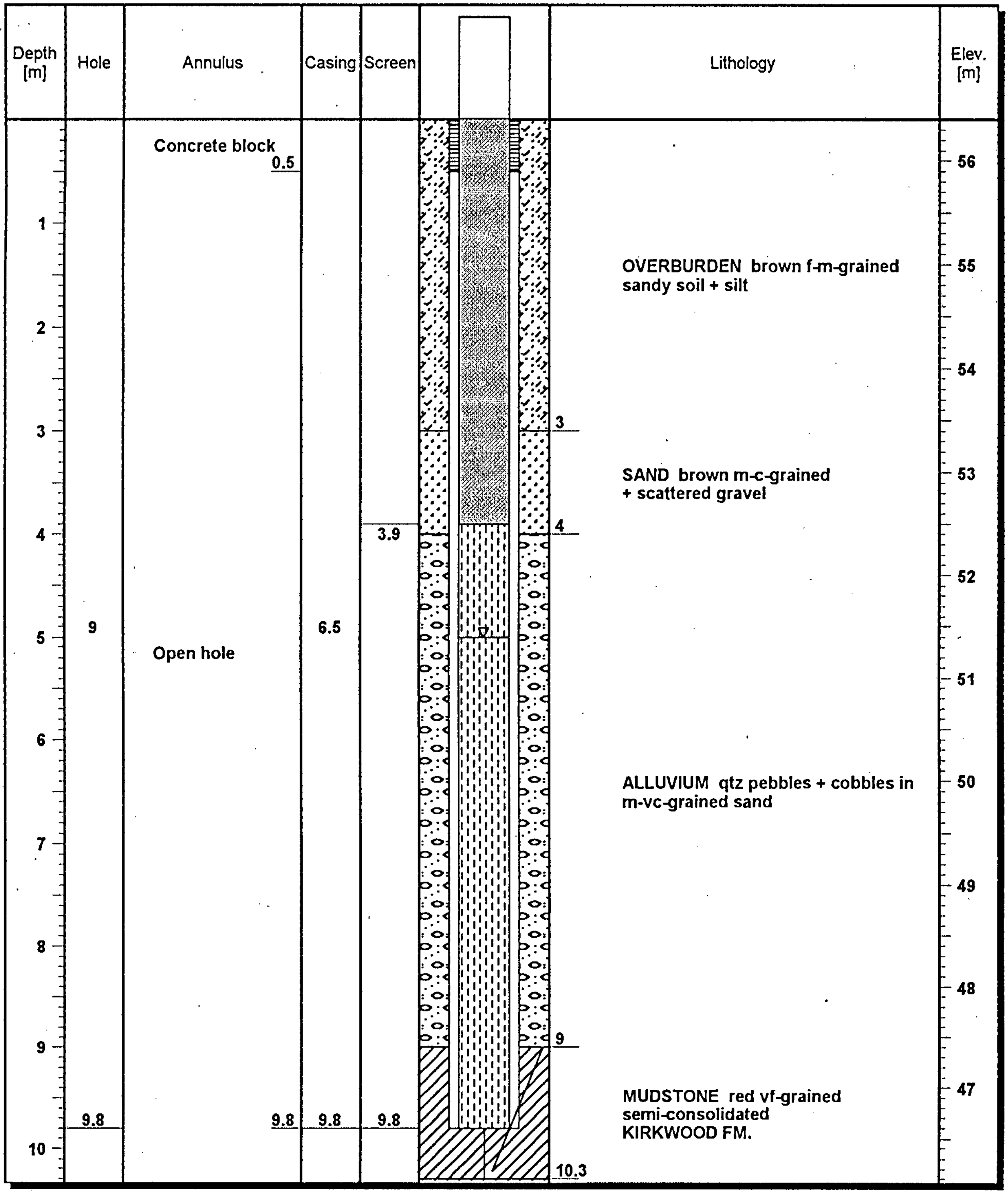
Drill. Method	Odex (air percussion)	Drill. Dates	10/12/94 - 10/20/94

X	346065.6	Y	6264362.0	Z	56.40	Meas. Pt. Elev.	57.40

All measurements are in meters. Hole and casing diameters in inches.

Scales (1: xxx)

Water Level (m AMSL) 51.40		Vertical 60.0	Horizontal



Well Log: Lithology & Construction

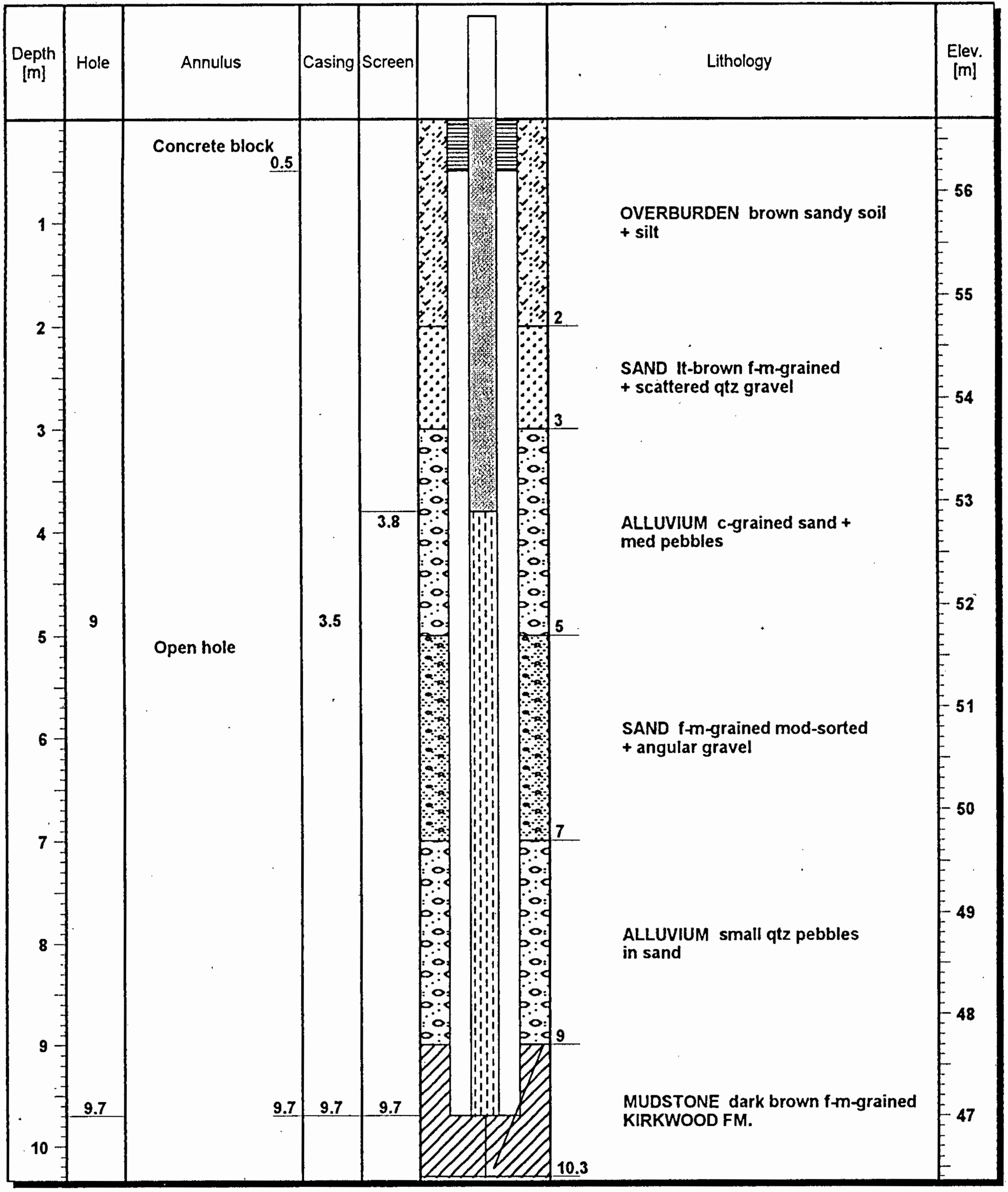
Well Ident	**G40035A**	Name	**INGGSVILLE**
Drill. Method	**Odex (air percussion)**	Drill. Dates	**10/24/94 - 10/01/94**

X	**346040.4**	Y	**6264330.8**	Z	**56.70**	Meas. Pt. Elev.	**57.70**

All measurements are in meters. Hole and casing diameters in inches.

Scales (1: xxx)

Water Level (m AMSL)		Vertical **60.0**	Horizontal



OVERBURDEN brown sandy soil + silt

SAND lt-brown f-m-grained + scattered qtz gravel

ALLUVIUM c-grained sand + med pebbles

SAND f-m-grained mod-sorted + angular gravel

ALLUVIUM small qtz pebbles in sand

MUDSTONE dark brown f-m-grained KIRKWOOD FM.

Well Log: Lithology & Construction

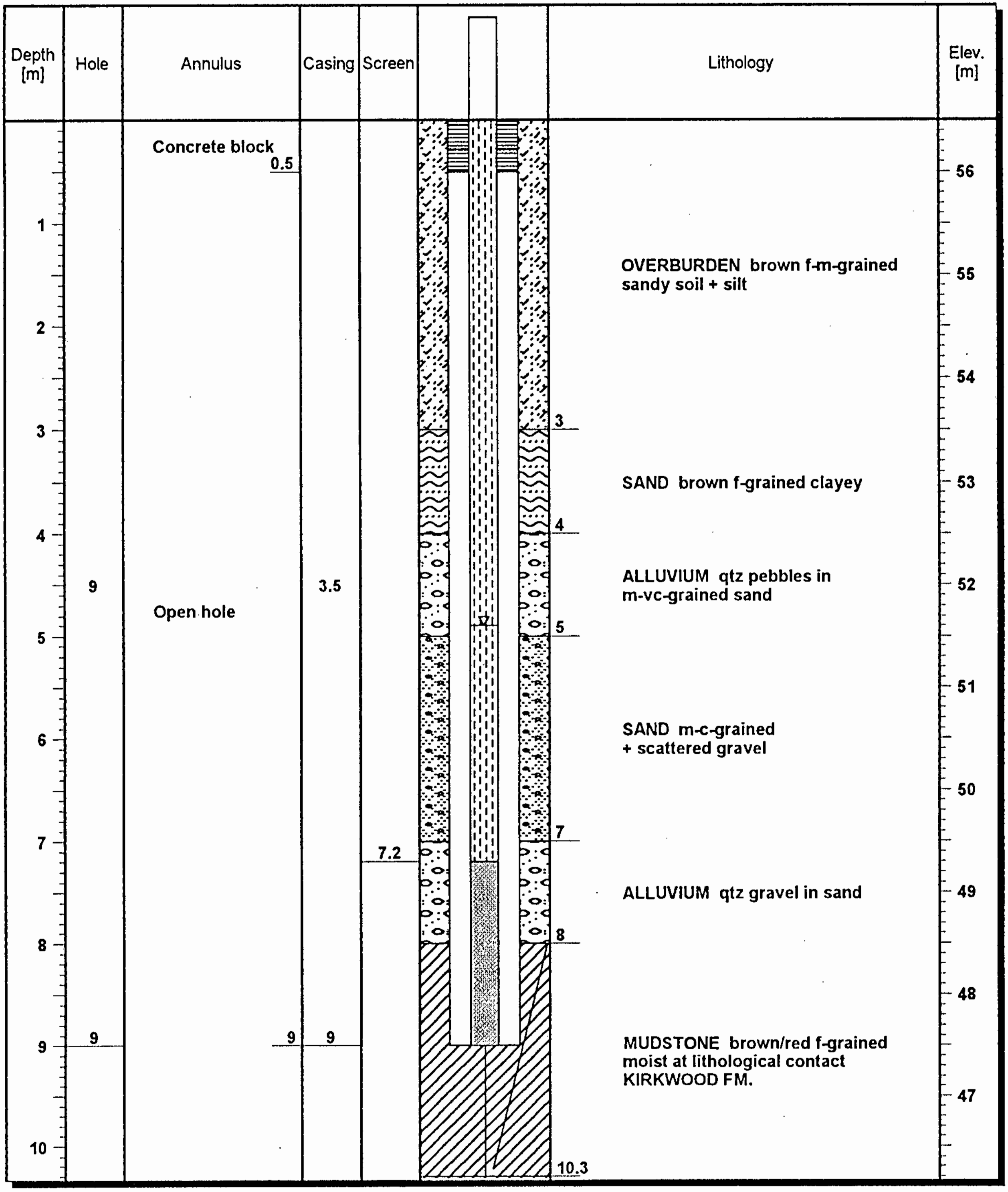
Well Ident G40035B	Name INGGSVILLE
Drill. Method Odex (air percussion)	Drill. Dates 11/02/94 - 11/02/94

X 346091.3	Y 6264362.4	Z 56.50	Meas. Pt. Elev. 57.50

All measurements are in meters. Hole and casing diameters in inches.

Scales (1: xxx)

Water Level (m AMSL) 51.60	Vertical 60.0	Horizontal



Well Log: Lithology & Construction

Well Ident	**G40036**
Name	**GUBB & INGGS**

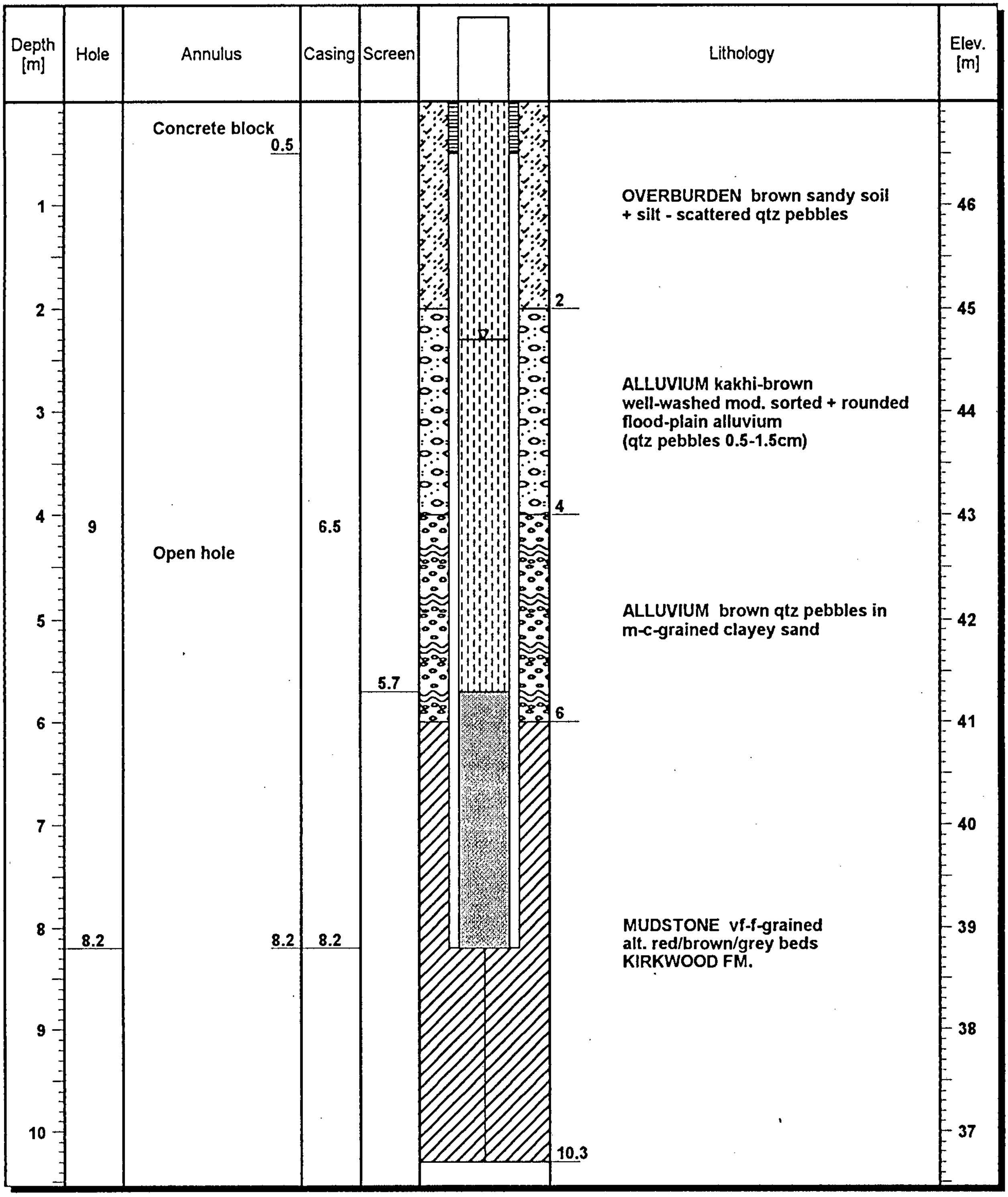
Drill. Method	**Odex (air percussion)**	Drill. Dates	**11/16/94 - 11/16/94**

X	**348784.9**	Y	**6263296.3**	Z	**47.00**	Meas. Pt. Elev.	**47.80**

All measurements are in meters. Hole and casing diameters in inches.

Scales (1: xxx)

Water Level (m AMSL)	**44.70**	Vertical	**60.0**
		Horizontal	



Well Log: Lithology & Construction

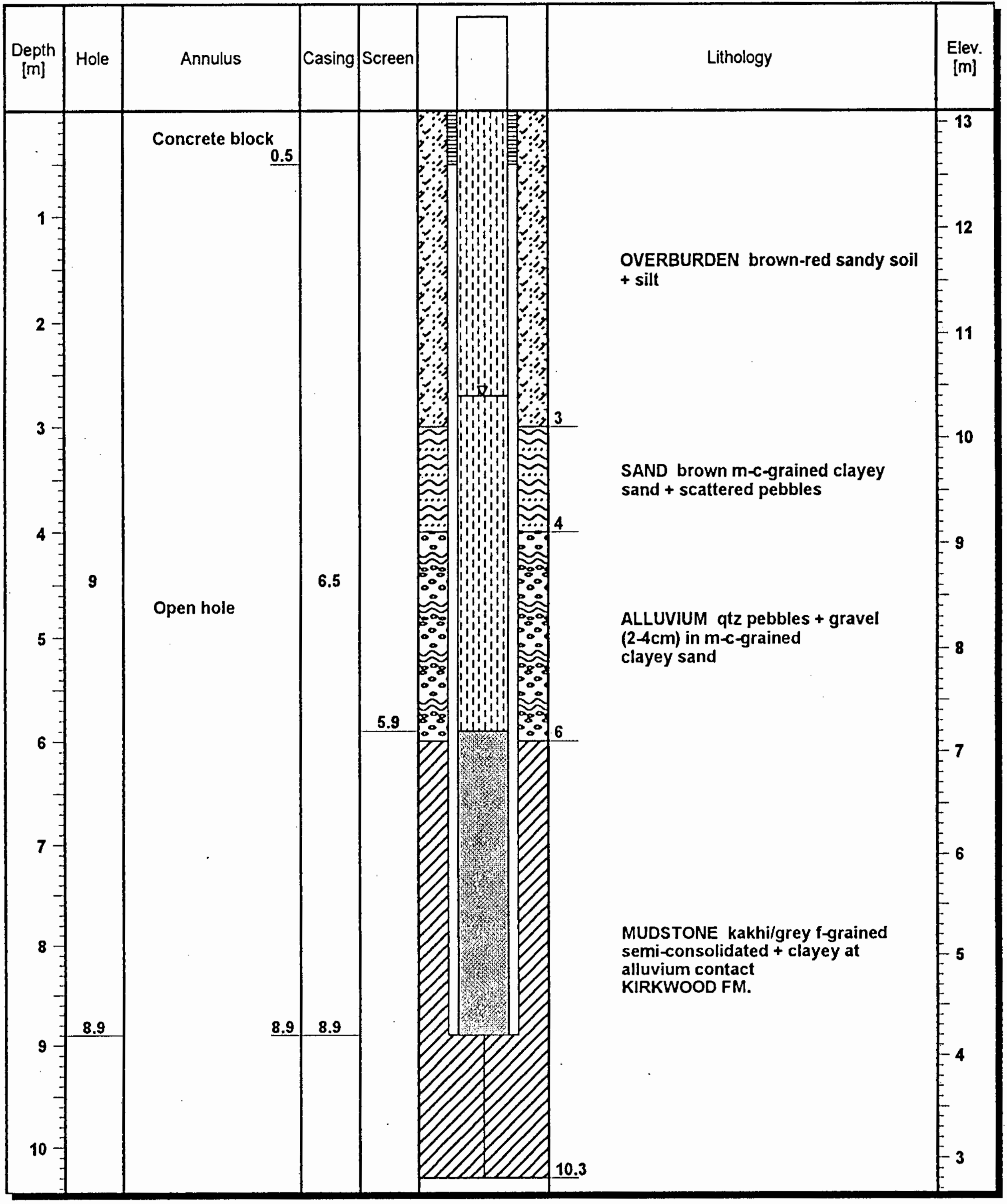
Well Ident G40037	Name	DESPATCH SEWAGE WORKS	
Drill. Method	Odex (air percussion)	Drill. Dates	11/17/94 - 11/18/94

X 360835.8	Y 6259258.9	Z 13.10	Meas. Pt. Elev. 14.00

All measurements are in meters. Hole and casing diameters in inches.

Scales (1: xxx)

Water Level (m AMSL)	10.40	Vertical 60.0	Horizontal



OVERBURDEN brown-red sandy soil + silt

SAND brown m-c-grained clayey sand + scattered pebbles

ALLUVIUM qtz pebbles + gravel (2-4cm) in m-c-grained clayey sand

MUDSTONE kakhi/grey f-grained semi-consolidated + clayey at alluvium contact KIRKWOOD FM.

Well Log: Lithology & Construction

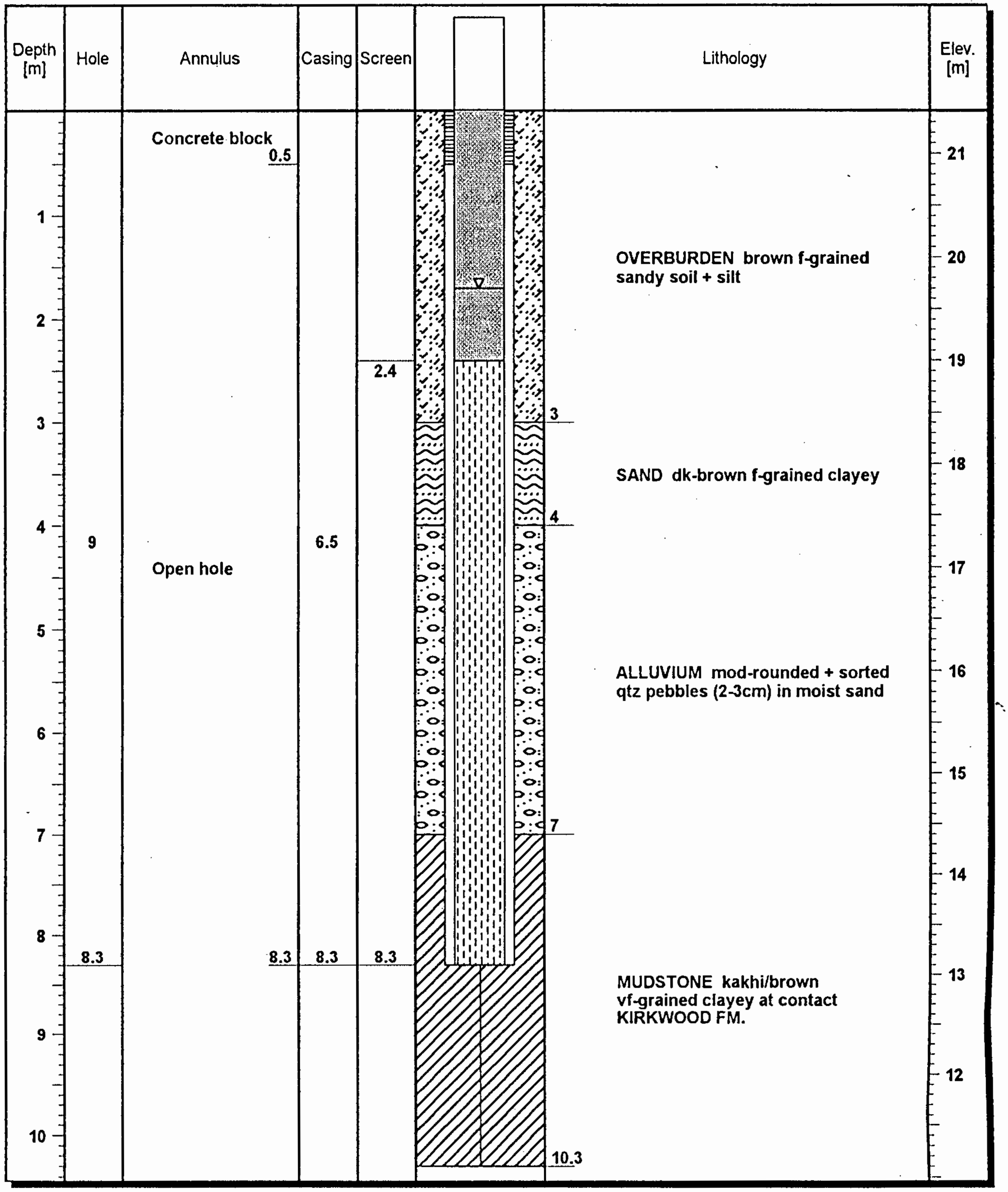
Well Ident G40038	Name DESPATCH CHIMNEY
Drill. Method Odex (air percussion)	Drill. Dates 11/30/94 - 12/01/94

X 357562.4	Y 6259703.5	Z 21.40	Meas. Pt. Elev. 22.30

All measurements are in meters. Hole and casing diameters in inches.

Scales (1: xxx)

Water Level (m AMSL) 19.70	Vertical 60.0	Horizontal



OVERBURDEN brown f-grained sandy soil + silt

SAND dk-brown f-grained clayey

ALLUVIUM mod-rounded + sorted qtz pebbles (2-3cm) in moist sand

MUDSTONE kakhi/brown vf-grained clayey at contact KIRKWOOD FM.

Well Log: Lithology & Construction

Well Ident G40039	Name PERSEVERANCE WOOL PULLERY

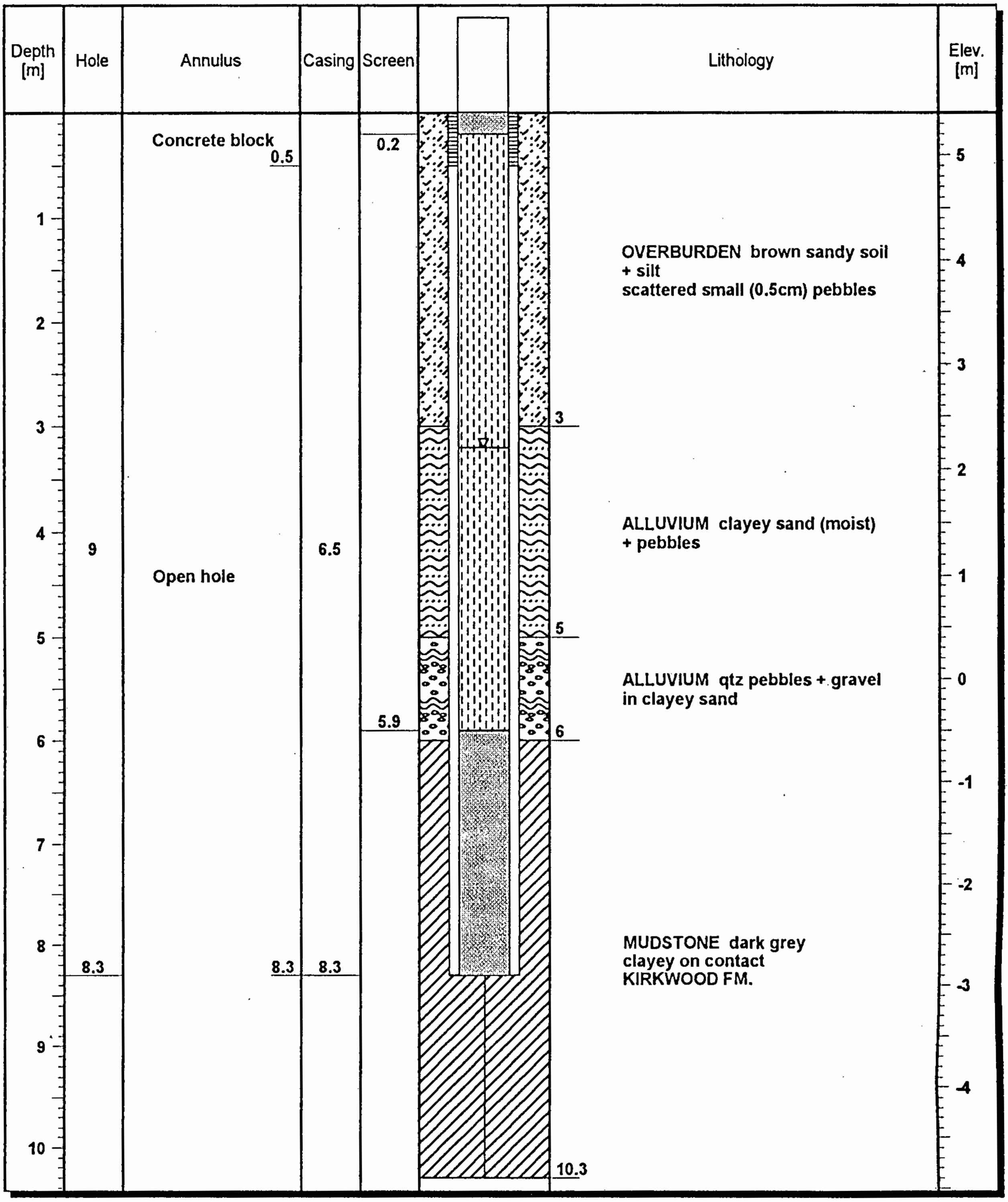
Drill. Method	Odex (air percussion)	Drill. Dates	12/05/94 - 12/05/94

X 363737.1	Y 6257822.1	Z 5.40	Meas. Pt. Elev. 6.30

All measurements are in meters. Hole and casing diameters in inches.

Scales (1: xxx)

Water Level (m AMSL) 2.20	Vertical 60.0	Horizontal



Well Log: Lithology & Construction

Well Ident	G40039A
Name	PERSEVERANCE WOOL PULLERY

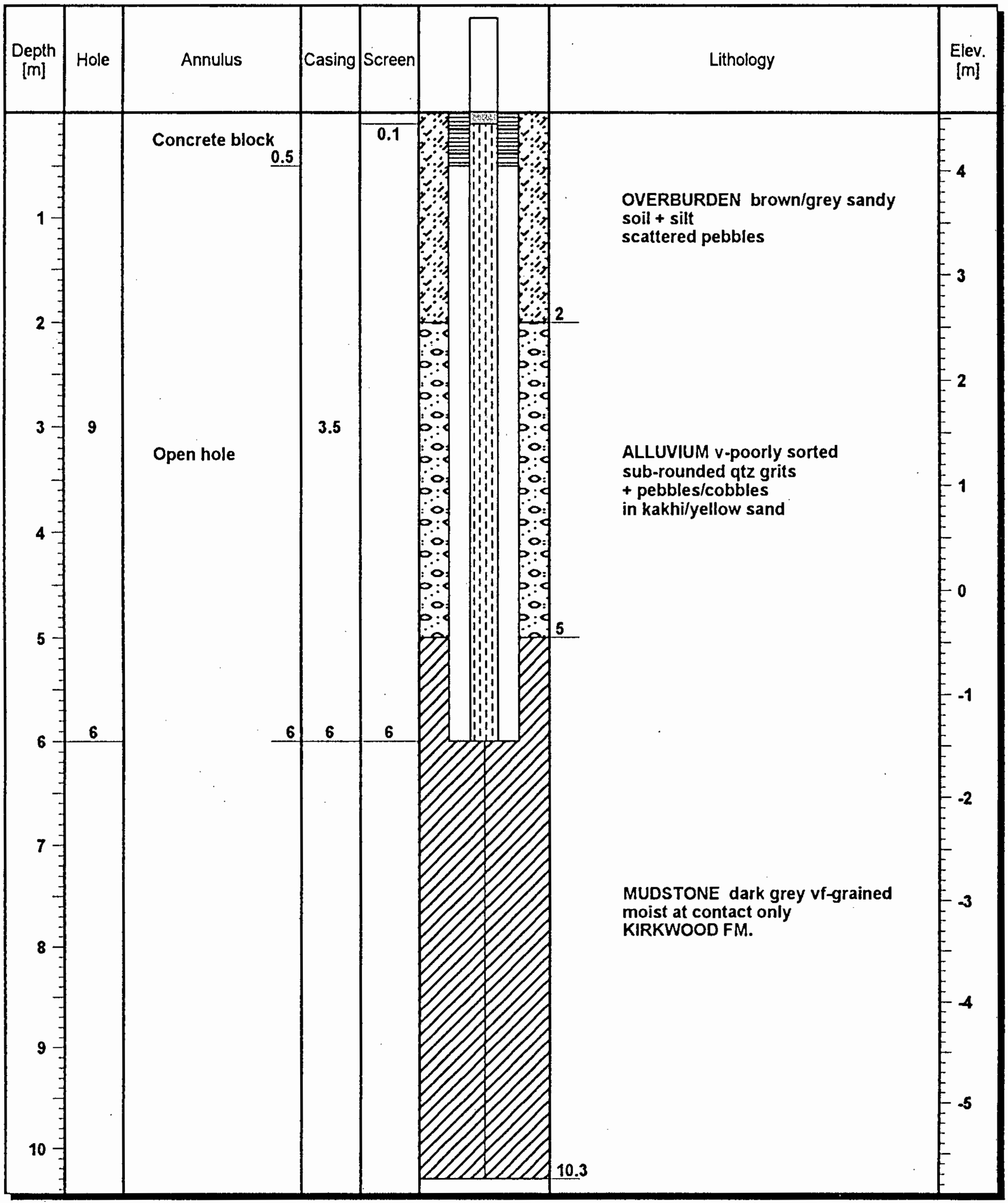
Drill. Method	Odex (air percussion)	Drill. Dates	12/06/94 - 12/06/94

X	363762.4	Y	6257853.2	Z	4.55	Meas. Pt. Elev.	5.45

All measurements are in meters. Hole and casing diameters in inches.

Scales (1: xxx)

Water Level (m AMSL)		Vertical 60.0	Horizontal



OVERBURDEN brown/grey sandy soil + silt scattered pebbles

ALLUVIUM v-poorly sorted sub-rounded qtz grits + pebbles/cobbles in kakhi/yellow sand

MUDSTONE dark grey vf-grained moist at contact only KIRKWOOD FM.

Well Log: Lithology & Construction

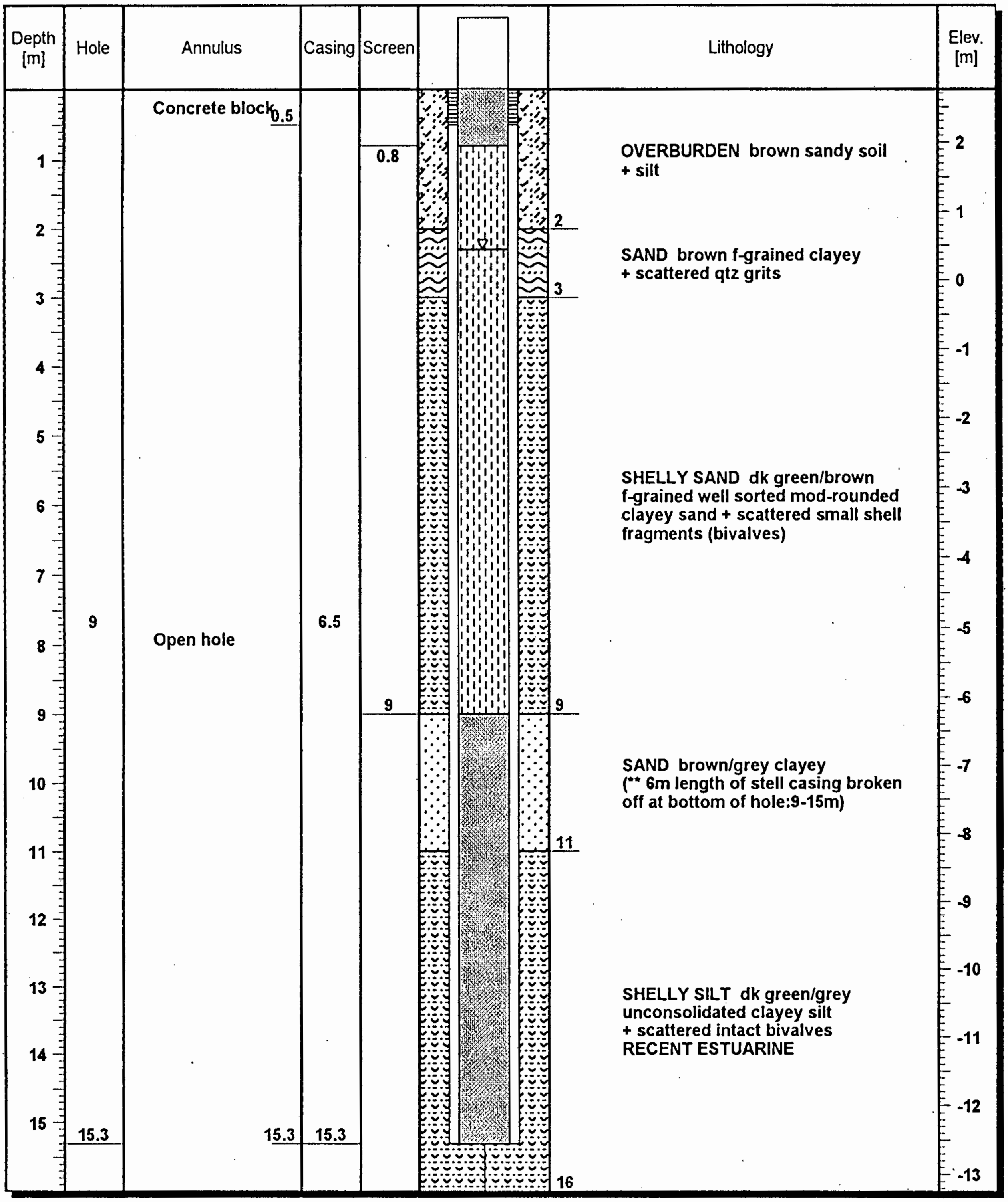
Well Ident	G40040
Name	REDHOUSE
Drill. Method	Odex (air percussion)
Drill. Dates	12/07/94 - 12/08/94

X	Y	Z	Meas. Pt. Elev.
368255.3	6254681.6	2.75	3.75

All measurements are in meters. Hole and casing diameters in inches.

Scales (1: xxx)

Water Level (m AMSL)	Vertical	Horizontal
0.45	90.0	



OVERBURDEN brown sandy soil + silt

SAND brown f-grained clayey + scattered qtz grits

SHELLY SAND dk green/brown f-grained well sorted mod-rounded clayey sand + scattered small shell fragments (bivalves)

SAND brown/grey clayey (** 6m length of stell casing broken off at bottom of hole:9-15m)

SHELLY SILT dk green/grey unconsolidated clayey silt + scattered intact bivalves RECENT ESTUARINE

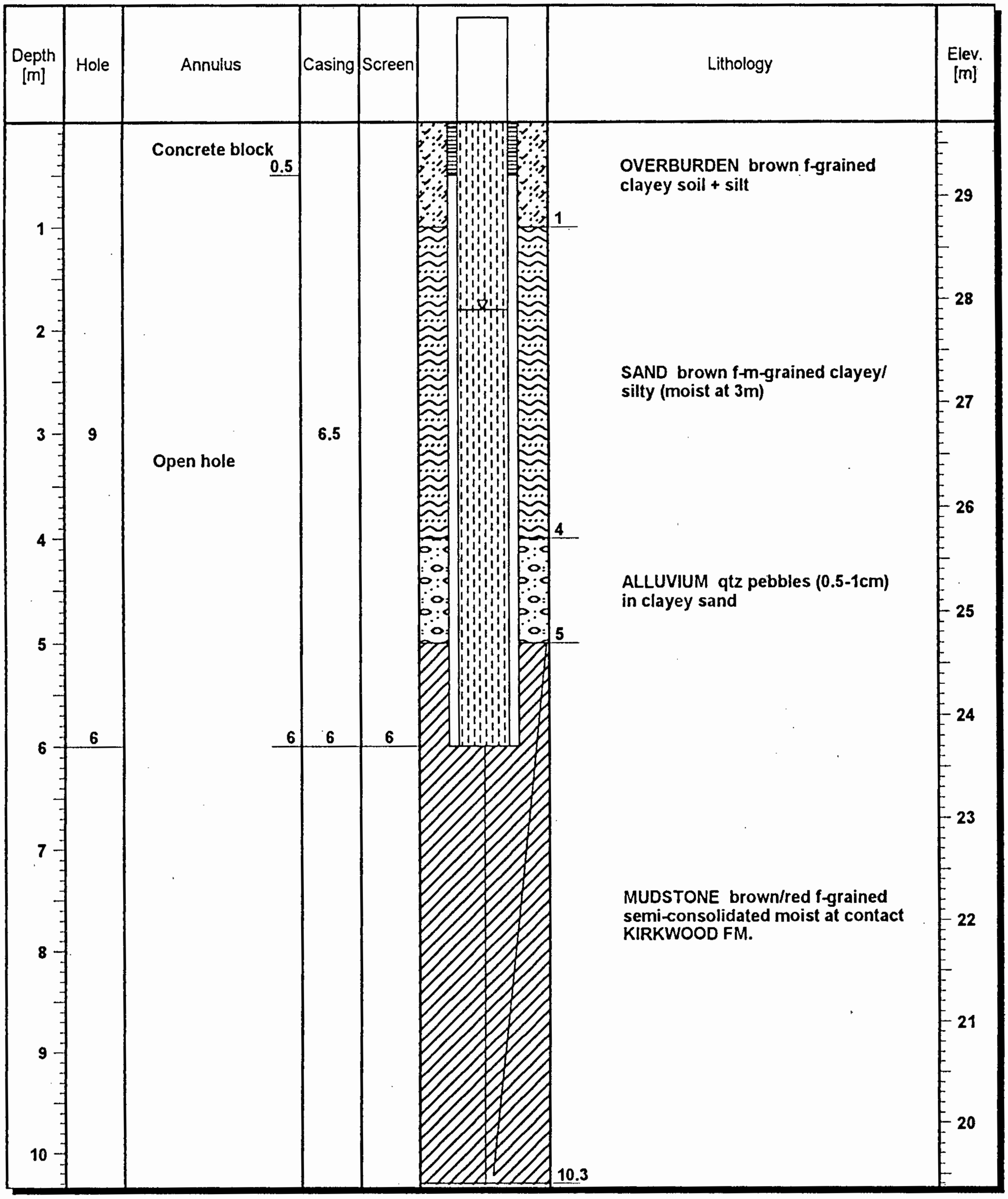
Well Log: Lithology & Construction

Well Ident	G40041	Name	UITENHAGE SEWAGE WORKS				
Drill. Method	Odex (air percussion)			Drill. Dates	12/09/94 - 12/09/94		
X	354255.0	Y	6260670.2	Z	29.70	Meas. Pt. Elev.	30.70

All measurements are in meters. Hole and casing diameters in inches.

Scales (1: xxx)

Water Level (m AMSL)	Vertical	Horizontal
27.90	60.0	



OVERBURDEN brown f-grained clayey soil + silt

SAND brown f-m-grained clayey/ silty (moist at 3m)

ALLUVIUM qtz pebbles (0.5-1cm) in clayey sand

MUDSTONE brown/red f-grained semi-consolidated moist at contact KIRKWOOD FM.

Well Log: Lithology & Construction

Well Ident G40041A	Name UITENHAGE SEWAGE WORKS

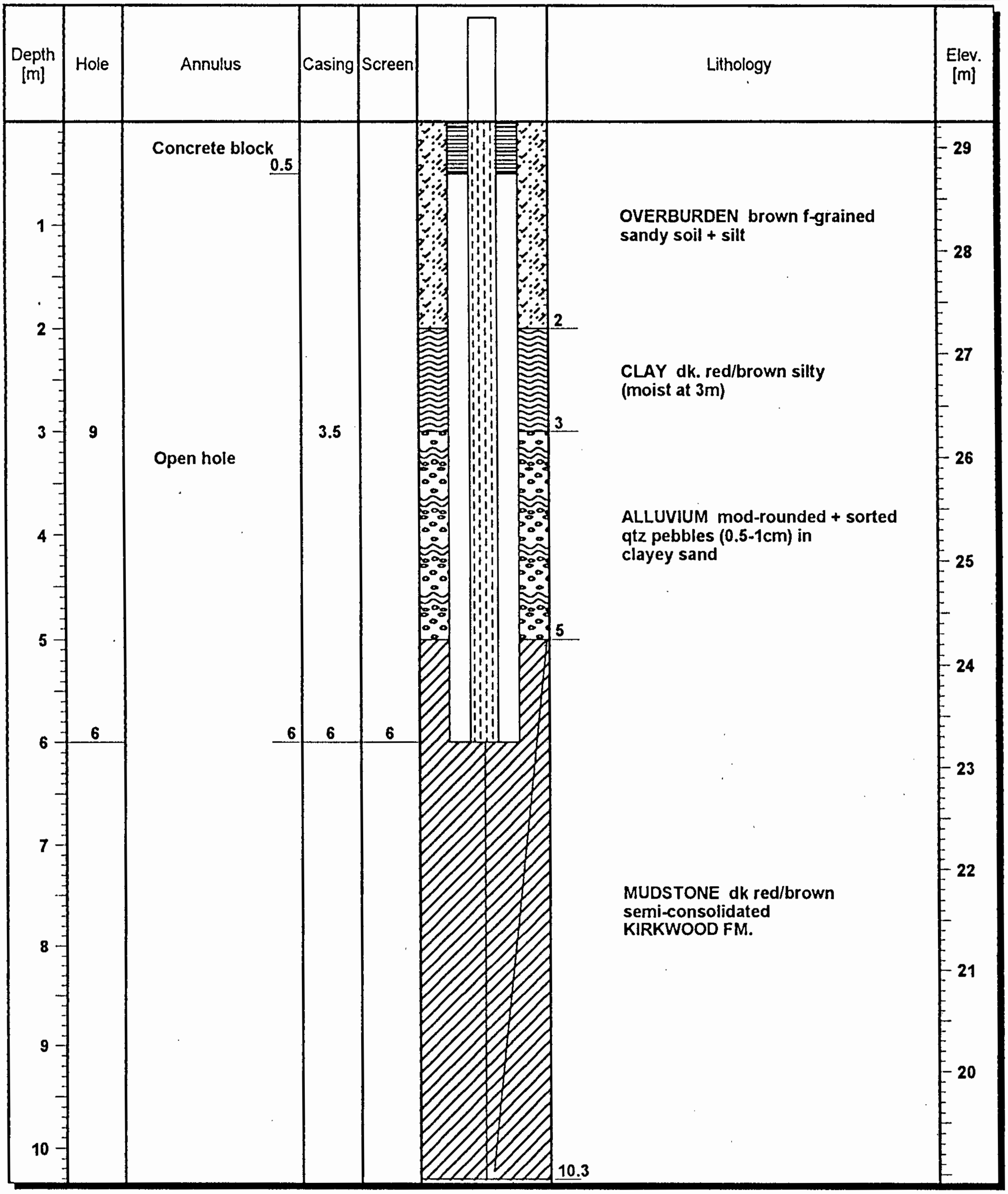
Drill. Method	Odex (air percussion)	Drill. Dates	12/09/94 - 12/09/94

X	354254.5	Y	6260701.0	Z	29.25	Meas. Pt. Elev.	30.25

All measurements are in meters. Hole and casing diameters in inches.

Scales (1: xxx)

Water Level (m AMSL)	Vertical 60.0	Horizontal



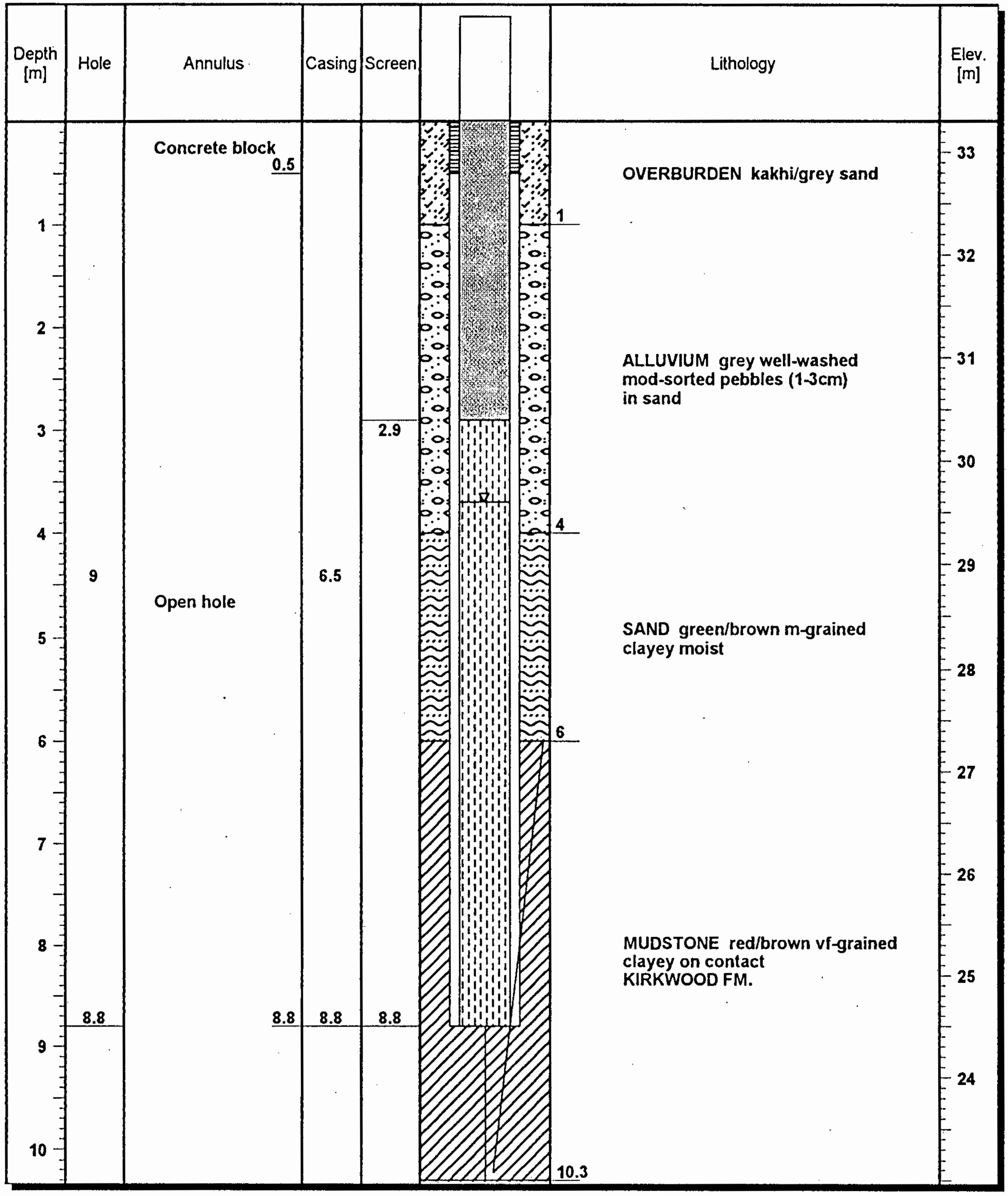
Well Log: Lithology & Construction

Well Ident	G40042	Name	CAPE OF GOOD HOPE				
Drill. Method	Odex (air pecussion)			Drill. Dates	12/12/94 - 12/12/94		
X	353265.6	Y	6259761.6	Z	33.30	Meas. Pt. Elev.	34.30

All measurements are in meters. Hole and casing diameters in inches.

Scales (1: xxx)

Water Level (m AMSL)	29.60	Vertical	60.0
		Horizontal	



Well Log: Lithology & Construction

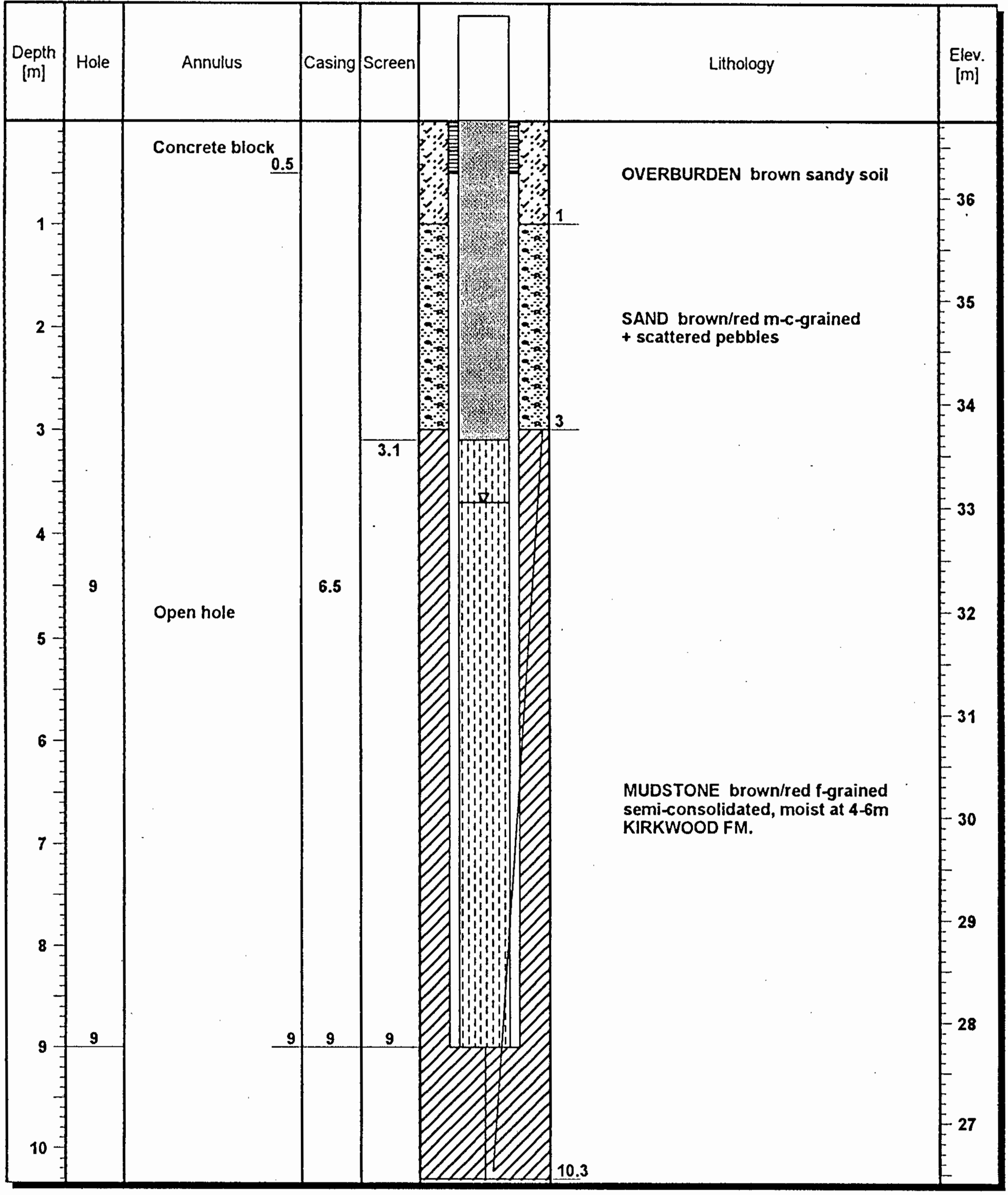
Well Ident G40043	Name EAST CAPE TANNING
Drill. Method **Odex (air percussion)**	Drill. Dates **12/13/94 - 12/13/94**

X 351918.2	Y 6260387.7	Z 36.75	Meas. Pt. Elev. 37.75

All measurements are in meters. Hole and casing diameters in inches.

Scales (1: xxx)

Water Level (m AMSL) 33.05		Vertical 60.0	Horizontal



OVERBURDEN brown sandy soil

SAND brown/red m-c-grained
+ scattered pebbles

MUDSTONE brown/red f-grained
semi-consolidated, moist at 4-6m
KIRKWOOD FM.

Well Log: Lithology & Construction

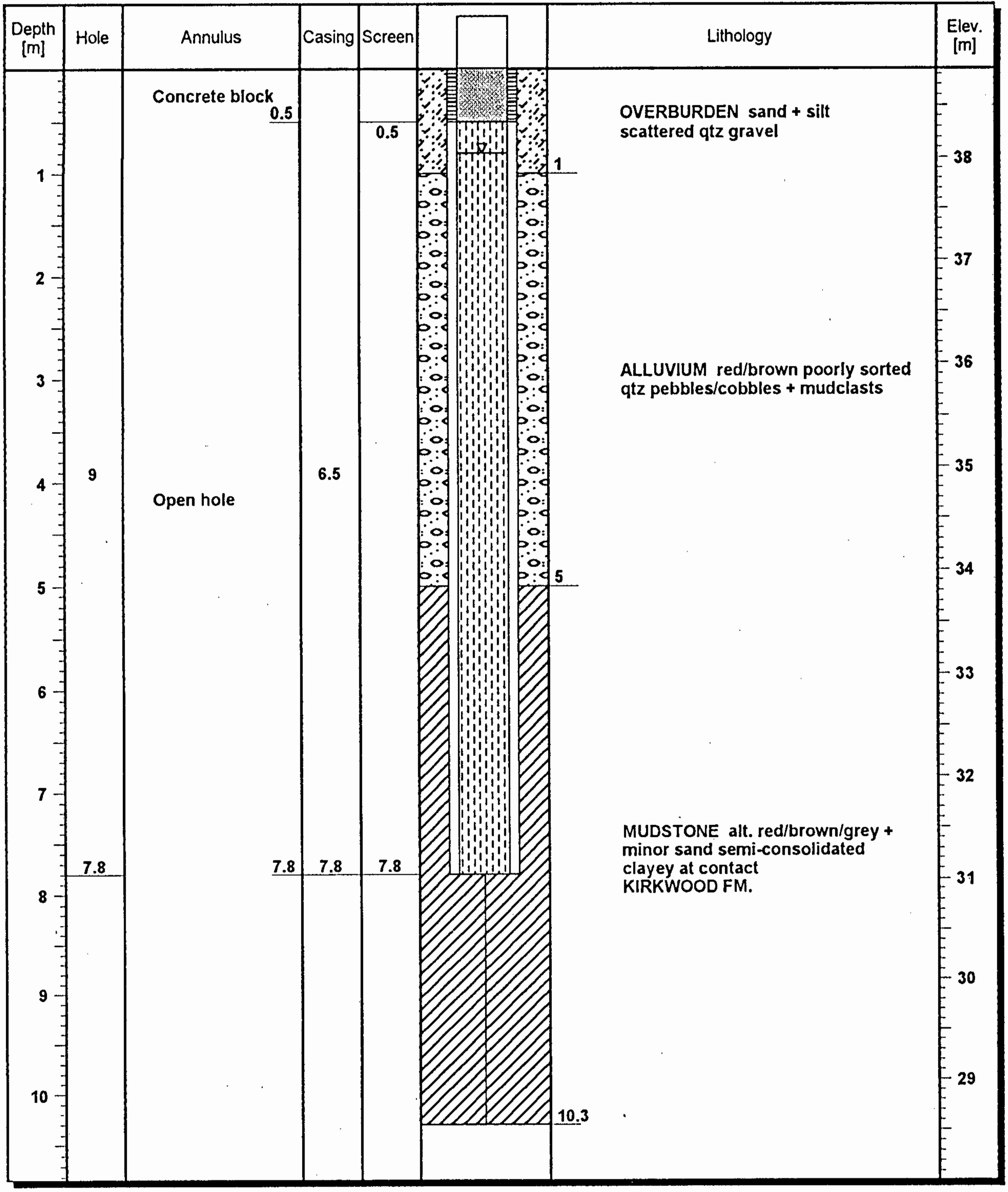
Well Ident	**G40044**
Name	NIVANS DRIFT
Drill. Method	Odex (air percussion)
Drill. Dates	12/14/94 - 12/14/94

X	350604.7	Y	6262123.4	Z	38.85	Meas. Pt. Elev.	39.35

All measurements are in meters. Hole and casing diameters in inches.

Scales (1: xxx)

Water Level (m AMSL)	38.05	Vertical	60.0
		Horizontal	



APPENDIX G:

AQUIFER TEST DRAWDOWN + RECOVERY CURVES

Boreholes G40035, G40039 + G40041

(from Maclear, 1995)

LEGEND

- Distance to observation well input as 0.17m (6.5" Ø) i.e. drawdown measured in pumping borehole.
- CR = constant rate test   Step = step test.

AQUIFER TESTING - Discussion of results

Introduction

Due to financial constraints it was not possible to conduct aquifer tests on every borehole drilled during the project reported on in Maclear (1995). Three sites were therefore chosen, approximately equi-distant apart (every 5km downstream), in order to attempt to obtain a representative testing of the alluvial aquifer. These test sites were, from west to east, boreholes G40035 (Inggsville), G40041 (Uitenhage Sewage Works) and G40039 (Perseverance Wool Pullery).

The aquifer test data, *viz.* the constant rate (CR) and step test (ST) data, were plotted on curves using the software package *Groundwater for Windows (GWW) Ver 1.1*, and were interpreted using the Theis drawdown methods. The drawdown curves are presented in this Appendix, (pages G9-G14), and the aquifer test results are summarised in Tables G1, G2 and G3 in this Appendix (page G7).

Curve fitting method

The Theis drawdown curve-fitting method was selected for the following reasons:

a) it is the most commonly used method to analyse aquifer test data, especially for confined aquifers, and it has diverse application,
b) the assumptions of this method - i.e. that the aquifer is homogeneous, isotropic, and of uniform thickness - are valid for the SRAA,
c) flow to the borehole is assumed to be in an unsteady state, and
d) the borehole must be fully penetrating and have a small diameter, therefore well storage can be neglected (Kruseman and De Ridder, 1991).

Features of software used - *Groundwater for Windows*

The software package *GWW* was used for solving the aquifer tests carried out in order to determine the aquifer transmissivity. Notable features of *GWW* - are outlined below. For full details of the data interpretation techniques, the reader is referred to Braticevic and Karanjac (1995)[1].

- The aquifer test solutions presented in *GWW* appear for the first time in the theory of aquifer tests,
- specialised new technology is provided for the computer processing of variable pumping rates,
- the program has 4 curve fitting routines (Theis, Jacob, Hantush and Recovery); the data for the Theis method are fitted using a 2-parameter (transmissivity and storage coefficient) iterative algorithm,
- the fitting is carried out automatically by the program, and if the fitting is successful the results are displayed together with an estimation error (standard deviation),
- the option is provided to skip any test data which are considered to be erroneous, and
- although boreholes are expected to be fully-penetrating (such as those tested in this study, see Appendix F, pages F4, F10 and F13), corrections for partially-penetrating boreholes are available.

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[1] Braticevic, D. and Karanjac, J. (1995). Groundwater for Windows. Ground Water Information System Software User's Manual. United Nations.

G40035 - Inggsville

During the aquifer tests on this borehole, the author noted the following:

- original steady-state conditions existed during the step-test with almost no water-table response to pumping in either the pumped or observation borehole for the first 4 steps (Table G3),
- there was minimal drawdown over the 24 hour CR test (3.0m at a pump rate of 4.6ℓ/s),
- after the pump was shut-down, there was almost immediate recovery (2.9m recovery in 1 minute), and
- the groundwater quality remained constant for the duration of the CR test at 25mS/m.

From these observations the conclusion was reached that the Swartkops River, 60m to the north of the borehole, was acting as a recharge boundary, i.e. the Swartkops River was in direct hydraulic contact with the pumped aquifer. Induced infiltration of river water to the alluvial aquifer therefore occurred with extended pumping when the water-table was locally lowered below the surface of the river.

Nortz et al. (1994)[2], in a study in similar geohydrological conditions, found that pumping a borehole in hydraulic contact with a river causes a steeper hydraulic gradient on the river side of the borehole than on the land side, thus flow towards the borehole is greatest on the river side.

The conclusion that the Swartkops River acted as a recharge boundary during the aquifer test is confirmed from Figure G1, where the borehole water chemistry (G40035) is more similar to the river water chemistry (Bullmers drift) than that of the alluvial aquifer water (G40033). This indicates that the alluvial aquifer was being recharged by the river during pumping.

The CR drawdown curve (page G9) shows that the CR test failed between 200 and 300 minutes after commencement of the test, after maintaining a relatively constant gradual drawdown at the pump rate of 4.6ℓ/s. The failure is noticeable at the inflection in the drawdown curve at about 0.7m drawdown. The reasons for this failure are uncertain but could be a function of the following:

- the source of recharge to the pumping borehole may have been an elongated pool of standing water (which existed during the test) 20m north of the borehole, rather than the flowing Swartkops River. This body of water was probably a temporarily truncated tributary of the main stream, and the storage of water in this pool was exhausted after 200 minutes of pumping when a groundwater volume of about 55m^3 had been abstracted via the pumped borehole,
- the result of dewatering of a zone in the aquifer of higher transmissivity by a progressive lowering of the water-table below this zone with pumping, after which time (>200 minutes) the transmissivity of the next contributing aquifer layer was too low to maintain the flow of groundwater to the borehole, equivalent to the pumping rate,
- the interbedded sand and clayey-sand layers logged in observation boreholes G40035A + B (Appendix F) were not observed while logging borehole G40035; they may, however, have been present in the near vicinity resulting in localised impedance of groundwater leakage from the aquifer, and/or
- the screen may have become blocked by clay and silt below a certain depth.

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[2] Nortz, P.E., Scott Bair, E., Ward, A. and White, D. (1994). Interactions Between an Alluvial-aquifer Wellfield and the Scioto River, Ohio, USA. *Applied Hydrogeology*, 4, 23-34.

Since no early part of the Theis curve is available for curve fitting and as a result of the failure of the CR test after 200 minutes, the interpretation of the aquifer tests for borehole G40035 becomes very difficult. Consequently, the exceedingly high values obtained for T (450-660m²/day for the Theis Method, from Table G1) should be treated with circumspection. Even by isolating the first 200 minutes of the CR test (before the inflection point) a high T (1 400m²/day) was still obtained using the Theis method.

It should be noted, however, that the extraordinarily rapid water-level recovery in G40035 (Table G2), after pump shut-down, gives some credibility to the high values of T obtained for this part of the SRAA. It is therefore suggested that these figures for T should not be discounted altogether, but should rather form the basis for future studies to determine aquifer hydraulics, and thereafter confirmed or rejected.

In retrospect, a lower pumping rate over a longer test period (72hrs), would have been more suitable for borehole G40035, since more workable data would have been obtained for interpretation purposes, especially in the early part of the Theis drawdown curve.

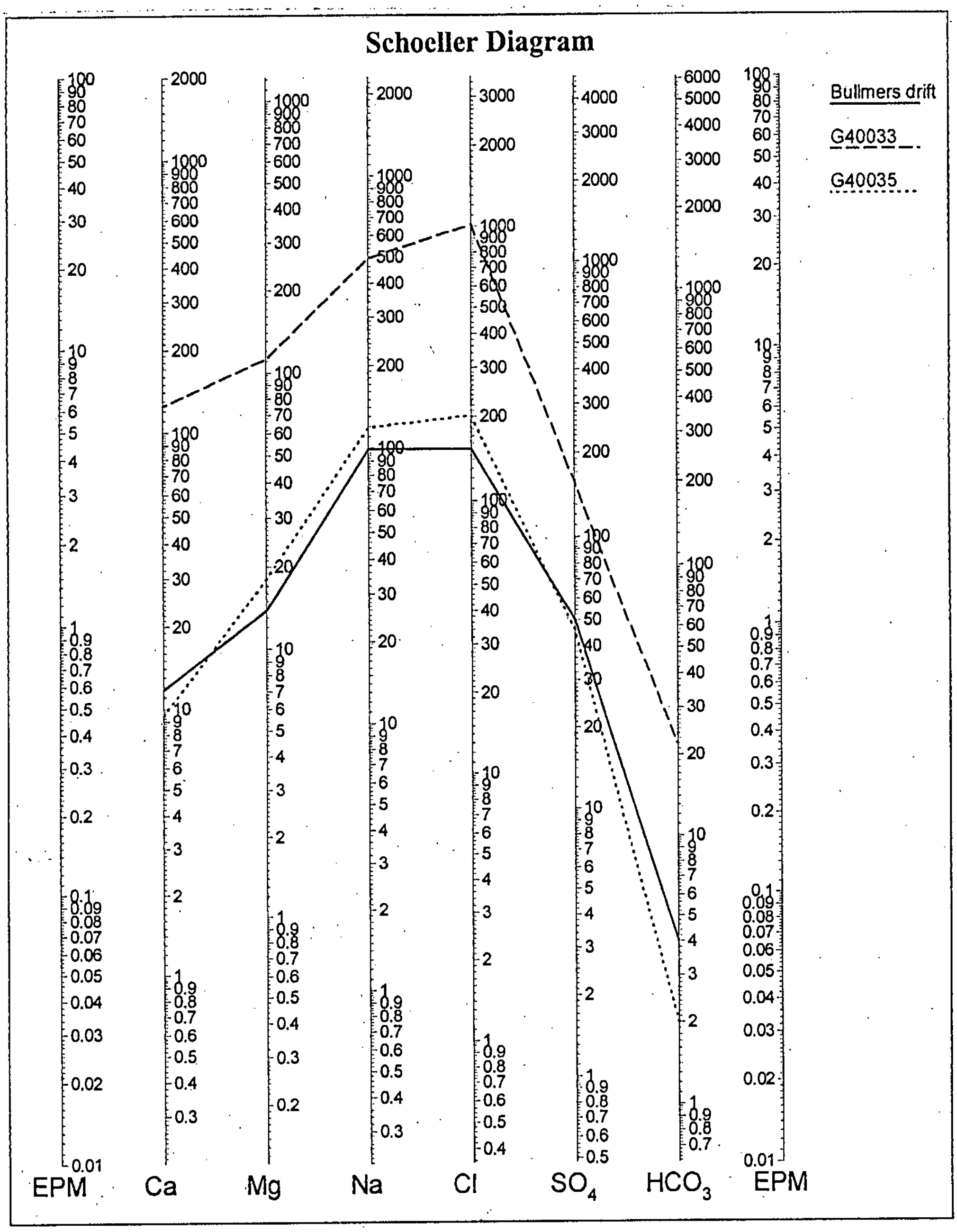


Figure G1: Comparison between river and groundwater hydrochemistry.

G40041 - Uitenhage Sewage Works

This borehole is situated within the eastern industrial area of Uitenhage near to factories and assembly plants and down-gradient of the Uitenhage sewage works (USW). Approximately 100m across the road from the test site, a well-field was developed in the SRAA by a groundwater consulting company to provide groundwater to Industex (Pty.) Ltd. - a textile processing plant - in times of drought. Reported blow-yields for this well-field were in the region of 10ℓ/s. G40041 was thus chosen for an aquifer test in order to determine the aquifer parameters for a region of the SRAA that was expected to be high-yielding.

On commencement of the step-tests, however, it was noted that the reputed high-yields could not be maintained for this site, and the test design was accordingly adjusted to lower pumping rates, culminating in a CR test yield of 0.7ℓ/s. The difference in aquifer conductivity between the two sites - *viz.* the private well-field and that of G40041 - is possibly sedimentologically controlled and a function of different aquifer thickness and clast grade or the occurrence of a palaeo river channel. The other possibility is that the reported blow-yield of 10ℓ/s for the private well-field will be found to be incorrect when the well-field is commissioned.

Only a 1m thick package of alluvial material in a clayey-sand matrix, overlain and confined by a 3m thick unit of clayey-sand (Appendix F), was intersected in this borehole which explains the relatively low yield of the borehole during the CR test as a result of low permeability. The moderate value for T obtained from the aquifer tests (50m²/day, Table G1), however, indicates that the thin basal alluvial package has a high *Kh* and/or that the *Kv* leakage component from the overlying clayey-sand is significant. Examination of the aquifer test (page G11) supports the former since the inflection on the CR drawdown curve at between 600 and 800 minutes (about 1.8m drawdown) indicates a progressive reduction in aquifer storage (in excess of leakage from the overlying clayey aquitard) with time.

Water quality remained relatively constant with time during the CR test at 520mS/m EC, which indicates that the groundwater quality of the storage component of the aquitard is similar to that of the aquifer, or that the abstracted groundwater is almost exclusively from the storage component of the basal coarse alluvial lag comprising the aquifer. The latter argument is supported for reasons presented in the preceding paragraph.

G40039 - Perseverance Wool Pullery

This borehole is situated 70m south of the Swartkops River and 3m of the screened section is located below river-level. No induced infiltration of river water to the aquifer with pumping occurred, as with borehole G40035, since the salinity of the aquifer water was approximately 1.5 times that of the river water. This salinity increased gradually during the CR test from 590mS/m at the beginning of the test to 620mS/m at the end of the test, compared with a river water salinity of 400mS/m. If induced infiltration was occurring, there would have been an expected progressive decrease in salinity of the pumped water with increasing duration of the CR test as more river water flows to the pumping borehole. The high salinity of the pumped water instead indicates the contributing effect of the seepage effluent from the PWP evaporation dams immediately up-gradient (15m southwest) of the monitoring borehole.

The clayey nature of the alluvium intersected by this borehole (Appendix F), results in the low aquifer transmissivity rates ($T = 6m^2/day$, Table G1) and hence the low pump rate for the CR test ($0.3\ell/s$). It is further proposed that the highly contaminated nature of the groundwater (high salinity) indicates that the assimilative capacity of the aquifer material below this test site has been exceeded, where a reduction in the grading of the alluvial material has occurred as intergranular pore spaces are clogged by precipitation of dissolved solids out of solution. This in turn negatively affects the fluid transmitting capability of the aquifer.

Due to the elevated position of the borehole above the river, the saturated thickness of the alluvial package below this test borehole site is a thin 2m, (Table G2) compared with the average saturated thickness for the monitoring network boreholes of 4m. Of this saturated thickness, only 1m is a coarse alluvial unit, the remaining thickness comprising clayey sand (Appendix F) which results in an aquifer of low storage and conductivity potential below this site.

The fact that there was no observed water level response to pumping at the observation borehole G40039A is explained by the low pumping rate and the proximity of the observation borehole to the river (50m). The water-level in the observation borehole is thus a function of river stage rather than an effect of the aquifer test. In addition, the low aquifer conductivity (described above) would typically result in a steep and narrow cone of depression around the pumping borehole during the CR test. This would produce only a small radius of influence around the pumping borehole, which further explains the lack of any detectable water-level response in the observation piezometer during the aquifer test.

Table G1: Constant rate and step tests using the Theis drawdown interpretation method.

Borehole No. + *site name*	Test type*	Calculated transmissivity (T in m^2/day)
G40035 *Inggsville*	CR	661
	ST	451
		G40035: selected T = 450m^2/day*** estimated *Kh* = 130m/day**
G40039 *Perseverance wool pullery*	CR	5.8
	ST	6.8
		G40039: selected T = 6m^2/day estimated *Kh* = 6m/day**
G40041 *Uitenhage sewage works*	CR	51.9
	ST	53.6
		G40041: selected T = 50m^2/day estimated *Kh* = 51m/day**

* CR = constant rate test, ST = step test.

** Estimated values for aquifer *Kh* assuming negligible leakage from the confining aquitard.

*** Aquifer test results for G40035 are considered inaccurate due to interpretation difficulty.

Table G2: Constant rate test details.

Borehole No.	Pumping duration (minutes)	Av. pumping rate (ℓ/s)	Rest water level (mbs)	Saturated thickness (m) *	Available drawdown (m) **	Final drawdown (m)
G40035	1440	4.6	5.6	3.4	3.1	3.0
G40039	1440	0.3	4.0	2.0	4.1	3.9
G40041	1435	0.7	1.3	3.7	2.9	***2.2

* saturated thickness of sand and alluvium excluding Kirkwood Fm. bedrock.

** available drawdown in borehole to pump intake (includes well storage).

*** max. drawdown = 2.8m @ 1115 minutes resulted in pump cavitation therefore pump rate reduced to 0.6ℓ/s.

Times for water-levels to recover to <5% of total drawdown:-
G40035 = *1 minute* (1.5%)
G40039 = 150 minutes (3.5%)
G40041 = 40 minutes (4%)

Table G3: Step test details.

Borehole No.		Step 1	Step 2	Step 3	Step 4	Step 5	Step 6
G40035	Step duration (mins)	* 25	* 15	* 10	90	80	80
	Pump rate (ℓ/s)	0.3	1.3	3.3	4.5	6.4	6.9
	Drawdown (m)	0.1	0.1	0.1	0.3	1.2	2.2
G40039	Step duration (mins)	80	60	80	60	60	-
	Pump rate (ℓ/s)	0.18	0.19	0.21	0.22	0.24	-
	Drawdown (m)	1.7	** 1.6	1.8	2.0	2.5	-
G40041	Step duration (mins)	80	80	80	80	87	-
	Pump rate s(ℓ/s)	0.36	0.37	0.41	0.68	0.96	-
	Drawdown (m)	0.6	0.6	0.7	1.3	2.3	-

* G40035 Steps 1-3 treated as single extended step test (see text for explanation).

** Apparent recovery due to very low pump rate + surging.

Aquifer Test Limitations

- The discrepancy between the values for T obtained from the constant rate and step tests for borehole G40035 (Table G1) is a function of the difficulties in line fitting by the software package influenced by an unusual data set.
- It was difficult for the test-operator to accurately maintain the low pumping rates required for the CR tests on boreholes G40039 (0.3ℓ/s) and G40041 (0.7ℓ/s). Small differences in pumping rates thus caused deviations from the theoretical drawdown curve, in turn causing inaccuracies in the curve-fitting procedure, even with the option of excluding some data points from the data set.
- Only a few blow yields were able to be conducted during borehole development due to general low permeabilities, and these yields differed by at least a factor of ten from the final pumping rate for the CR tests. In addition, no previous testing of the hydraulic parameters of the Swartkops River Alluvial Aquifer had been done prior to this study. As a result, the choice of step test pumping rates were trial and error. Consequently, the first step was started too high (G40041) or too low (G40035), resulting in shortening of individual steps or combining a number of shortened steps into an extended first step (Table G3).
- The relatively short duration of the aquifer tests (24hr CR) resulted in limitations to the long-term safe-yield interpretation and reliability of the determined T's, since steady-state flow conditions were not reached in all the tests and aquifer characteristics are more accurately revealed only with increasing duration of the aquifer test (Kruseman and De Ridder, 1991).
- In at least one of the aquifer test sites (G40039 - Perseverance Wool Pullery) the groundwater is contaminated to such an extent that it has been permanently discoloured, and the grading of the original aquifer material is considered to be changed as a result of attenuation of pollutants. This causes a significant reduction in hydraulic conductivity of the coarse alluvial material comprising the aquifer.
- The variable nature of the aquifer and aquitard material (thickness, grading, degree of saturation and pollutant attenuation etc.) result in inhomogeneous hydraulic characteristics of the Swartkops River Alluvial Aquifer on a regional river-basin scale. This, together with the limited number of aquifer tests carried out over a large area during the study, results in difficulties with respect to confident extrapolation of the hydraulic parameters obtained from the test sites to other areas of the aquifer.

It is, however, emphasised that the original intention of the Swartkops River Alluvial Aquifer drilling project was to design and construct a network of boreholes for monitoring groundwater quality and not for providing groundwater on a safe-yield basis for supply purposes. The direct and indirect measurement of aquifer parameters (T and K respectively) was, therefore, secondary to the primary study aim. The results obtained, nevertheless, are considered useful in terms of providing an initial data-set for future studies and management purposes. To this end, the project is considered to have been successfully completed.

Pumping Test

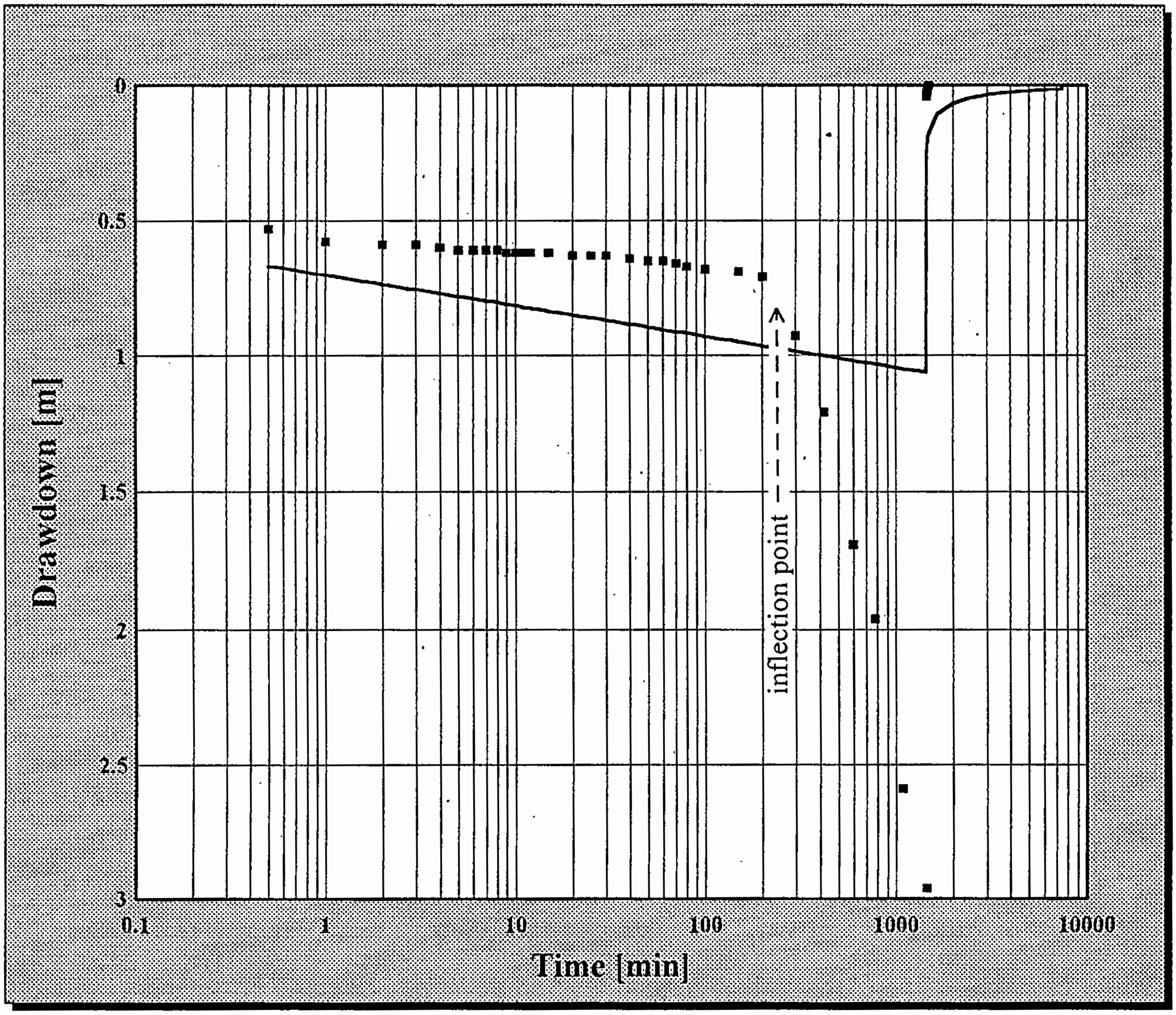
Well Ident **G40035-CR**	Name

Obs. Well Distance [m] **0.17**	Average Pump. Rate [l/s] **4.6**	Duration [min] **1480**	Initial Sat. Thickness [m]

Results

Transmissivity [m2/day] **661**	Storage Coefficient	Leakance [1/day]	Estimation Error [m] **0.44**

Fit Method **Theis Method**



Pumping Test

Well Ident **G40035-Step**	Name

Obs. Well Distance [m] **0.17**	Average Pump. Rate [l/s] **5.1**	Duration [min] **320**	Initial Sat. Thickness [m]

Results

Transmissivity [m2/day] **451**	Storage Coefficient	Leakance [1/day]	Estimation Error [m] **0.40**

Fit Method **Theis Method**