THE GEOHYDROLOGY OF THE DOLOMITE AQUIFERS OF THE MALMANI SUBGROUP IN THE SOUTH-WESTERN TRANSVAAL REPUBLIC OF SOUTH AFRICA

by

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ABSTRACT

The studied area includes the Malmani Subgroup dolomite outcrops and sub-outcrops extending between the Klip River in the east and the town of Ventersdorp in the west.

The composition, structures and nature of the aquifers are investigated. The area is divided into geohydrologic units (compartments) defined by hydrologic boundaries, and several selected units have been studied in detail.

In part of the area the entire hydrologic set-up had been changed as a result of gold mining activities which often involve dewatering, artificial recharge and the run-off of effluents from the mines. In other parts semi-natural conditions prevail and groundwater discharges still take place through the natural outlet of springs.

An analysis of springs and rainfall-discharge relationships enables the understanding of the natural recharge in these aquifers. The mechanism of the replenishment may be schematically viewed as consisting of two phases namely, an early nearly immediate intake, and a later delayed phase with a time lag of approximately 4 to 6 months.

Annual outflows at springs observed over a succession of many years reveal the discharge to behave as a very strongly autoregressive process. The aquifer may be conceived as a reservoir which periodically, on the occasions of exceptionally high rainfall seasons, becomes over-filled, and henceforward for several years discharge is controlled more by this event of recharge than by the following moderate annual recharge increments. The application of a statistical model for prediction purposes simulated the discharge rather closely.

The rate of natural replenishment as a percentage of annual rainfall was found to be between 13 and 27 per cent. The effective porosity derived from book-keeping water balances and a chemical mass balance is of the order of 1 to 3 per cent. Pumping tests indicate that the storage coefficient varies considerably and could locally be of the order of 10^{-4}.

Sulphatic mine effluents of different concentrations and treated sewage waters are disposed of into the river courses resulting in the contamination of groundwater reservoirs and springs by artificial recharge. The interaction of this combined system of surface water and groundwater has also been studied. Under undisturbed natural conditions the concentration of the sulphate ion in groundwaters of the investigated area is negligibly small, but on the other hand, groundwaters encountered in this study are unsaturated with regard to sulphate. This parameter is therefore used to identify contamination, as well as for quantitative storage calculations by means of chemical mass balance models.

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1. GENERAL INTRODUCTION AND BACKGROUND

1.1 Objectives of the study

The objectives of this study are to enbale feasible predictions of the response of the aquifers to various changes of operational measures applied, and to supply the data necessary for general planning purposes.

Investigation of the dolomites, a real regional aquifer for either water supply or storage reservoir, attains some additional significance in the studied area due to:

(a) Location in proximity to centres of water consumption demands,

(b) possible extrapolation of results to similar terrains,

(c) the specific problems connected with prolonged extensive mining.

1.2 Requirements

A better understanding of many aspects is required, which include: The nature, composition and structure of the aquifers involved, delineation of geohydrologic boundaries, groundwater flow pattern, groundwater-surface water interrelations, the mechanism of natural replenishment, coefficients of storage and transmissivity, estimations of total storage, evaluation of the prospects of artificial recharge. Deterioration of water quality causes a growing concern. Background salinity as presented by semi-natural groundwater systems has to be studied in comparison to contaminated systems. An evaluation of the applicability of geophysical methods for borehole siting and mapping is also required.

1.3 Available data

An Interdepartmental Committee on Dolomitic Mine Waters in the Far West Rand which included representatives from the Departments of Mines, Water Affairs and Agricultural Economics, had been operating during the period of 1956-1960. Within the scope of its investigation were all aspects connected with disposal of groundwater pumped by gold mines to irrigation boards in the Far West Rand. Due to the lack of basic data at that time, much of the Committee's effort was directed towards collection, co-ordination and analysis of relevant geohydrological data, alongside with the evaluation of various schemes for water replacement. Reports submitted by this Committee constitute valuable sources of information.

Another, currently operating Interdepartmental Committee on Sinkholes and Subsidences has replaced the afore-mentioned Committee with an emphasis on engineering geology aspects, and valuable information has been accumulated through its activities.

The available data consists of: Lithologic descriptions of borehole logs, also descriptions of recently drilled new boreholes executed under geologist's supervision, groundwater level observations, either manual (monthly) or automatically recorded (continuous), surface flow measurements in matural drainage courses and in man-constructed canals, mine water abstraction amounts, part of which is estimated and part gauged. In some cases special surveys were conducted which included plotting, levelling and sampling of boreholes. Gravity surveys, where available, were incorporated in the present study. Groundwater and surface water samples were collected and analysed. Use was made of chemical data which appeared in previous reports and had been collected by various bodies such as the Rand Water Board etc. Aquifer tests were performed at selected sites and interpreted.

1.4 Previous work

Geohydrological aspects of the dolomite aquifers in Southwestern Transvaal have been studied by several workers (Enslin and Kriel, 1959, 1967; Enslin, 1968, 1971; Schwartz and Midgley, 1975). A detailed gravity survey, conducted by the Geological Survey in selected parts of the area, which was accompanied by extensive drilling, has also contributed to a better understanding of the hydrology of the dolomite aquifers (Kleywegt and Enslin, 1973; Enslin et al, 1976).

1.5 Methods

Various parts included in the rather extensive investigation area differ considerably in terms of the type and availability of basic geohydrologic data. Due to some natural subdivision, it became feasible to deal with each geohydrologic unit or compartment separately. In some of the compartments, like Schoonspruit and Steenkoppie, with the exception of springflow amounts, virtually no other information concerning groundwater was available. In other compartments such as those located in the Far West Rand, due to problems arising as a result of dewatering of the aquifers by the gold mines, a large amount of recorded data was at hand. Even where apparently a lot of information was expected to have accumulated over the last fifteen years or so, it often proved disappointing. The gaps usually arise from unsatisfactory spatial distribution of observation holes, long breaks in measurements, lack of simultaneous observations and only sporadic surface flow gaugings.

It was mainly the availability of data which dictated the methods applied and ultimately the results obtained from the study of each individual geohydrological unit. In a few cases water balances could be worked out which yielded storage coefficient figures and recharge rates. In others, as a result of spring analyses, the mechanism of natural replenishment could be elucidated and interpreted. Contamination of aquifers by mine effluents as well as artificial recharge could be proved by employing geochemical methods. A simulation model of the contamination process also permits the calculation of some storage figures.

It became evident at an early stage of the study that additional data had to be obtained. In three units: Schoonspruit, Steenkoppie and Zuurbekom, surveys have been conducted which included plotting, levelling and sampling of existing boreholes. In Zuurbekom a series of 34 boreholes at 23 sites were drilled, so as to complete a net of observation points. Aquifer tests were also conducted at selected locations. This will enable a long-term detailed study of a model dolomitic compartment.

2. GEOGRAPHY

2.1 Areal scope

The studied area extends between longitude 26°30'-28°00' and latitude 26°00'-26°30' (see Fig. 2.1). The combined area of the Pre-Cambrian dolomitic outcrops and sub-outcrops, overlain by a blanket of weathered rock material or soil, is of the order of 4 000 km^2.

2.2 Physiography

Physiographically the area constitutes part of the Highveld of the Republic of South Africa, elevations being in the range of 1 500 - 1 700 m. A rather smooth, flat, surface relief is characteristic of the dolomitic terrain. The sedimentary sequence of the Pretoria Group, overlying the dolomite, tends to form a hilly elevated country bordering the dolomites.

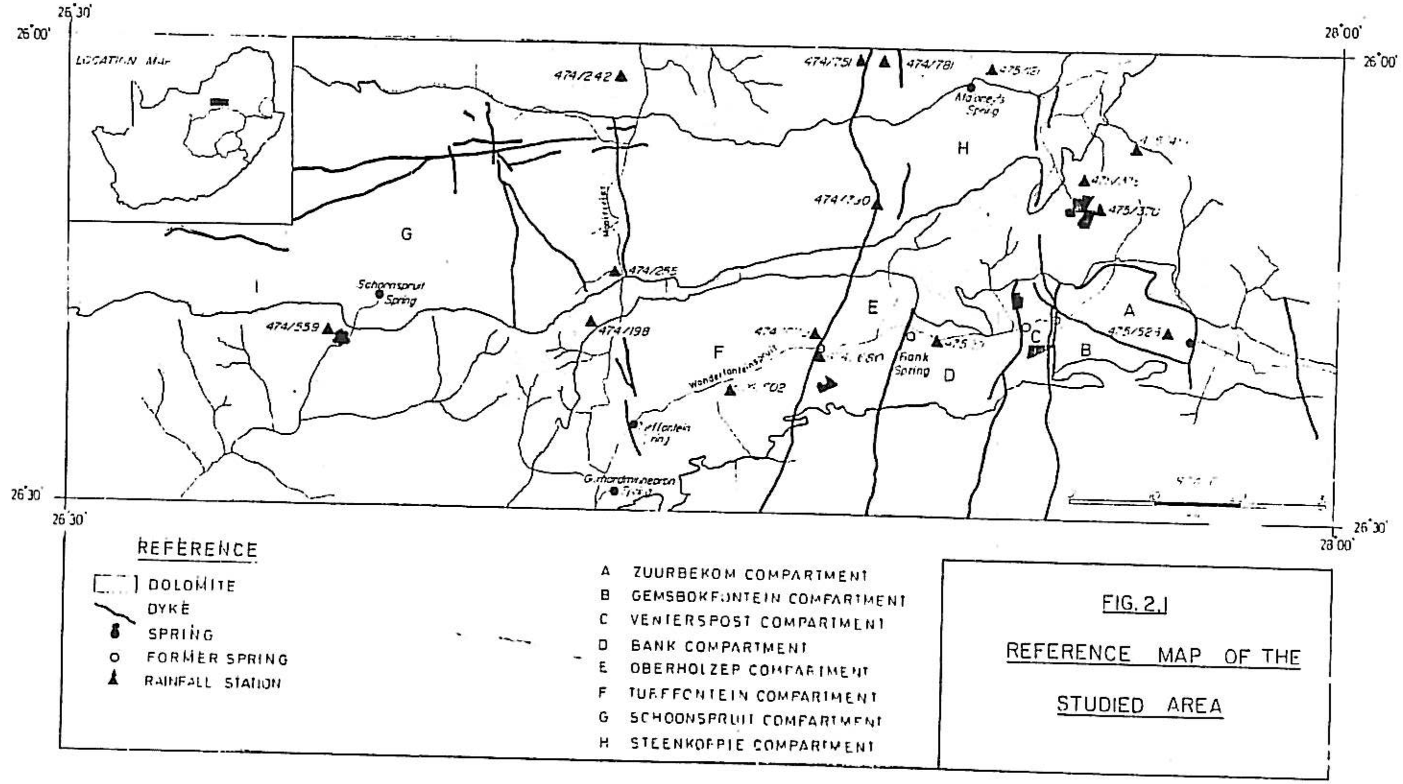


FIG. 2.1

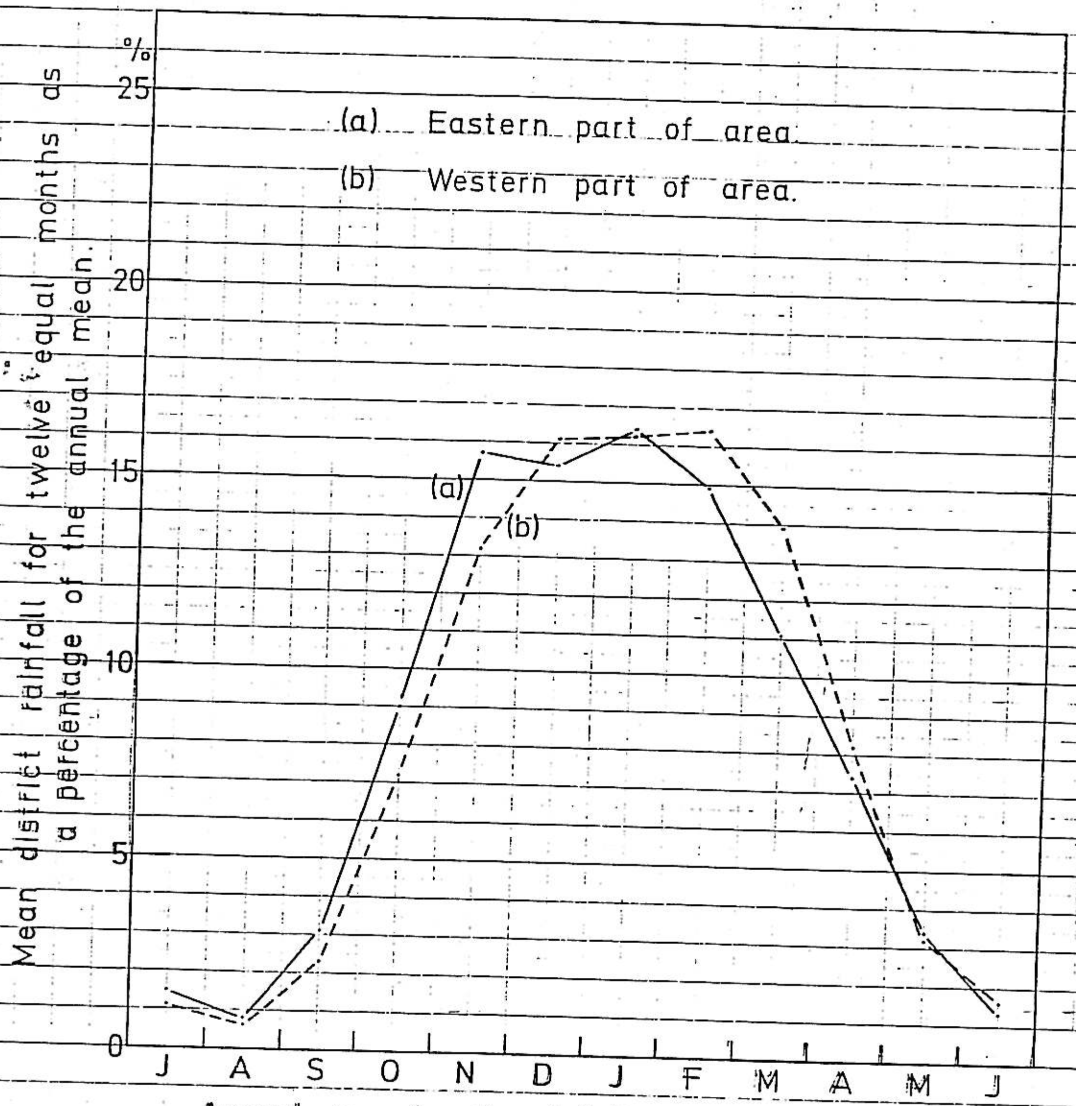
REFERENCE MAP OF THE STUDIED AREA

Most of the surface water on the outcrops of the dolomite drains to the Vaal River basin except for limited parts near Krugersdorp and northwest of Randfontein where water courses end in the Limpopo River basin.

2.3 Climate

The climate is sub-humid with typical summer rainfall and dry winters. Precipitation extends over a long period of the year compared to a short dry winter season. The annual march of rainfall, (Fig. 2.2), demonstrates the relative monthly amounts of precipitation. The highest monthly rainfall occurs from November to February. Folder 2.1 illustrates the daily rainfall pattern of a period of several consecutive years. The mean annual rainfall decreases from 700 mm in the east, to 590 mm in the west (Weather Bureau, 1972). Classification of climate and experimental work (Schulze, 1958) point to the high potential evapotranspiration prevailing in the area which also correspond in time to the rainfall season. Rainfall is often in the form of thunder storms and shows marked variations in daily amounts even between adjacent rainfall stations.

More than fifteen rainfall gauging stations were operating at one time or another in the area of which only seven to ten have been simultaneous.



Annual march of rainfall over South western Tvl
(data from: Climate of S.A., part 10, 1972)

FIG. 22

3. GEOLOGY

3.1 Statrigraphy

The aquifers involved in the present study consist of the near ground surface parts of the Malmani Subgroup and of accumulated weathered products of the Malmani Formations.

The rocks of the Malmani Subgroup were deposited in the so-called Transvaal Basin. Visser (1970) postulated two parallel depositional basins striking east-northeast, where the southern-most of the two is the Potchefstroom Basin. These basins were separated during the said period by a high that stretched from Ottosdal via Johannesburg to Bethal.

A recent revision of stratigraphic units, suggested by the Geological Survey (Provisional stratigraphic Subdivisions, 1980) replaces the former "Dolomite Series" by the Chuniespoort Group. The Malmani Subgroup includes four or five formations as presented in the following table (Fig. 3.1).

The total thickness of the Malmani Subgroup in the studied area as revealed by mine exploration boreholes does not amount to more than 900 to 1 100 m.

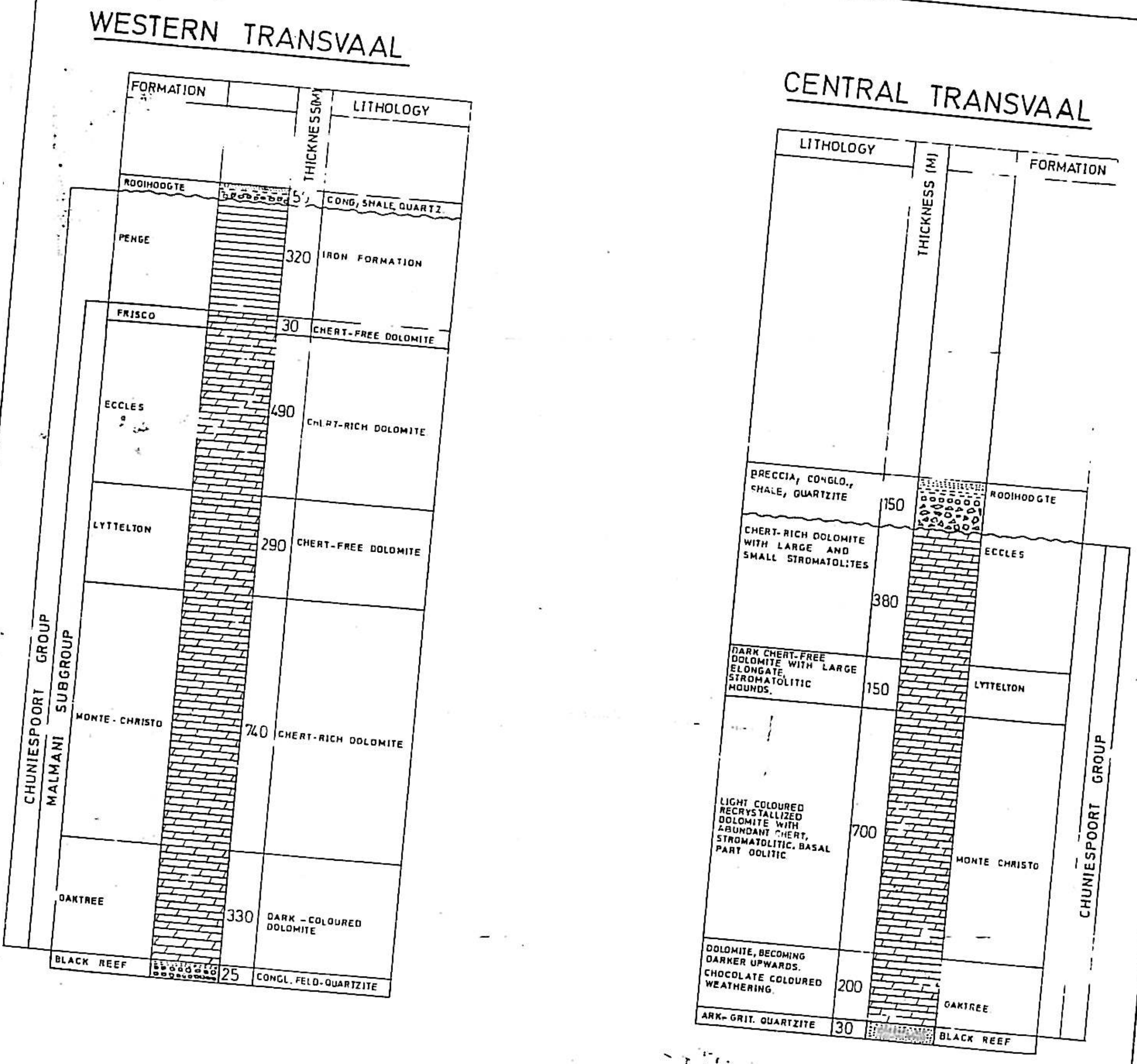


Fig. 3.1

Schematic stratigraphic subdivision of the Malmani Subgroup(After the Geological Survey, 1980)

The sequence of this subgroup is comprised predominantly of non-clastics, namely, dolomite, dolomitic limestone and cherty dolomite with intercalated chert beds and nodules. A rather high iron and manganese content is typical. these rock facies indicate quite shallow conditions where subsidence and deposition were in equilibrium for a long period. A stable shelf environment with a distal negative source area is suggested by Visser (1970).

The following cycle of deposition in the Transvaal Basin, the Pretoria Group, is composed mainly of argillaceous and arenaceous rocks with several lava flows. During this cycle, as compared to the dolomite, relatively unstable conditions prevailed, with mild basin subsidence and some uplift of the source area. The transition between the two cycles is rather sharp, simultaneous and recognisable over the entire basin. Lithologically the transition beds, Rooihoogte Fm., includes shale, quartzite, chert breccia and conglomerate.

The Malmani Subgroup rests on a well-defined thin zone of unconformity composed of clastics such as shales, conglomerates, quartzites, generally with a thickness of less than 30 m.

3.2 Structure and tectonics

The dolomites were subject to repeated phases of folding and faulting. The pre-Pretoria transition beds could indicate the first discordance due to limited folding. It is assumed (Van Eeden, 1972) that several tectonic cycles took place during the Transvaal sequence, characterised by some folding, tear and other faulting and gravity sliding. A major folding and faulting cycle accompanied the emplacement of the Bushveld Complex, ± 2 000 m.y ago. Another prominent folding and faulting is the Pilanesburg phase, dated 1 300 - 1 400 m.y. Later movements are related mainly to upwarping and on the whole, stable cratonic conditions prevailed in the studied area.

Two structural elements, the Vredefort Dome and the Ottosdal-Bethal Line, played a major role in shaping the folding. Between these two rising rigid nuclei of crystalline rocks, the compression of the Transvaal Sequence took place. An anticilinal structure along Ventersdorp-Krugersdorp thus divides the present dolomite outcrops into two units, one dipping northwards, the other, on the flank of Potchefstroom Syncline dipping southwards.

Intrusives, often diabase, as dykes and sills penetrate the dolomite. Some are probably connected with the Pretoria Group volcanic eruption -phases. Evidence for this magmatic activity is encountered in many mine exploration boreholes.

Other dykes of Pilanesburg age strike in a northerly direction. These dykes are major elements in the studied area. Tracing of the dykes had been accomplished with the help of electromagnetic and magnetic methods. Gelletich (1937) divided dykes systems in the central part of Southern Transvaal into three groups, according to different magnetic signature:

(a) Pre-Karoo Pilanesburg Dykes
(b) Post-Karoo Dykes of the East Rand
(c) Dykes which do not belong to either.

The major dykes in the studied area (Fig. 2.1) are syenitic dykes and belong to the first group. Radiodating of the dykes established an age of 1 310 ± 60 m.y. for the Pilanesburg Dykes (Van Niekerk, 1962) and 1 120 ± 45 m.y. for the East Rand Dykes (McDougal, 1963) namely also Pre-Karoo. A recent aeromagnetic survey interpretation by Day (1980) confirmed and in cases extended the previously mapped dykes. It also disclosed a group of E-W striking dykes.

A N-S schematic cross-section A-A' through Cooke-Section, Western Areas and Elsburg Gold Mines is shown in Folder 3.1. It is based on data from exploration boreholes plotted on the key map Fig. 3.2. The section illustrates a regional southward dip and the wedging out of the dolomite due to truncation. The thickness is minimal close to the Ventersdorp-Krugersdorp line. It also demonstrates a Pre-Pretoria major unconformity as a result of which the thickness of the dolomite had been reduced, in places, to 500 m as compared to the original thickness of 1 300 m.

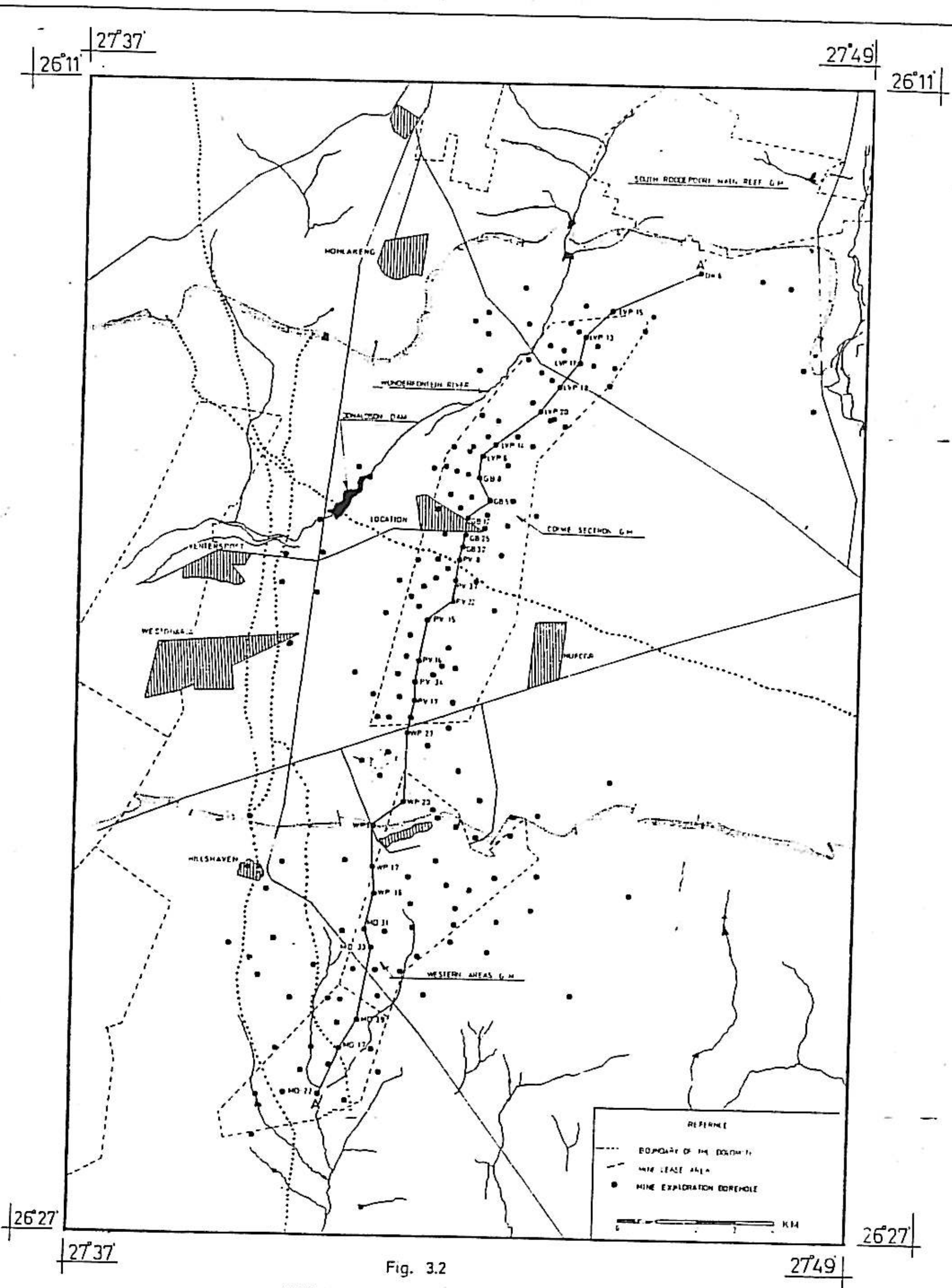


Fig. 3.2

KEY MAP FOR CROSS-SECTION A-A'

4. GEOHYDROLOGY

4.1 The bed rock

The Malmani Subgroup is composed of predominantly dark grey dolomite with chert and quartzite beds and nodules. A rather high iron and manganese content is typical. The dolomitic mass is practically devoid of any effective primary porosity. It is due to later processes such as dissolution, leaching and karstification that hydraulic conductivity has developed in these carbonates.

4.2 Morphology

It has already been noted by Brink and Partidge (1965) that morphologic features of the Transvaal karst differ in some aspects from classical karst as described for instance by Cvijic (1918). In most of the Transvaal dolomites there is no wide distribution of naturally occurring dolines and sinkholes. In the studied area however, true karst morphology such as disappearance of streams, disolution sinkholes and depressions, does occur although in limited parts of the area. The topography is rather flat, corresponding to the "African Erosion Surface" (King, 1962) as suggested by Marker and Moon (1969). the northern dolomite outcrops were described as "Plateau morphologic" type and the southern outcrops as "Vaal River" type by Martini and Kavalieris (1976).

4.3 Upper cover

The bedrock in these areas is generally concealed beneath a mantle of weathered materials, the thickness of which varies laterally considerably over relatively short distances.

This weathered zone cover consists of a variety of rock types, part of which developed in situ from the dolomite bedrock and part accumulated as transported alluvium. It includes residual soils, clays, shales, carbonaceous shales, marls, sands, rubble, gravels, brecciated chert, conglomerates and various combinations of these rock types.

4.4 The development of permeability

Karstification is a major process in the disintegration of carbonate rocks. Soluble carbonate rocks are susceptible to dissolution by meteoric waters which have become slightly acid, and therefore agressive, as a result of passing through the atmosphere and soil. The development of karst involves a combination of closely related surface and subsurface features. Chemical dissolution associated with the creation of cavities and voids systems is confined principally to the phreatic zone namely, the groundwater level surface. It is in this zone that subsurface erosion is most active, calcium, magnesium and bicarbonate ions being removed in solution by circulating groundwater. The insoluble residual products such as silica, quartz, clay minerals, oxides and hydroxides of iron and manganese (Wad) are left behind. The residual mass, when undisturbed, as in caves, is spongy, compressible, of low density and high void volume.

Lithologic and structural inhomogenities of the carbonate bedrock generally lead to differential dissolution. In the studied area numerous igneous intrusions, mostly in the form of dykes, penetrated the dolomite. Contact zones in the host rock, next to such intrusives, favour a more intensive leaching. Brink and Partridge (1965) postulated differential solution along a pattern of fracturing in three major sets, marked by the distribution of sinkholes and subsidences. According to these authors the fracturing had been caused by the emplacement of the Bushveld Complex which applied a stress field through folding along the margins of a structural basin.

Topographic relief, especially drainage base levels are among the main factors controlling karst development. The evolution of karst with time, under undisturbed conditions, may schematically be conceived as a cycle including several phases from youth through maturity and late maturity to old age, with typical manifestations at each phase. At maturity underground drainage is at maximum due to the completion of an extensive interconnected cavity system and the role of surface drainage is very limited. If, during the later phases of the cycle, no change of groundwater elevation takes place, ground surface will be planed down to the water table, terminating thus any further karstification, and surface drainage will again prevail.

Strictly stable conditions, where the water table would constantly remain at the same level, are seldom encountered in nature. The lowering of base levels through valley incision, accompanied by the drop of groundwater levels, is a more common process which initiates the rejuvination of karst formation at a lower altitude. The upper, earlier, karstified horizon remains above water level and within the vadose zone.

Cavernous systems in the vadose zone with an access to ground surface either through the original vertical crevices or due to later erosional opening tend to develop depositional features. Clay minerals in suspension and alluvial clastics are downwashed and settle in the empty space. Deposition of calcite or aragonite also contributes to the filling of space.

Another process active in this zone is caving or roofing-in i.e. disintegration and collapse of the rock cover above a cavity by descending waters. Extensive progressive upward caving may affect the entire rock section, up to the ground surface. Thus a rather loosely packed weathered zone is formed where instability is characteristic. Sinkholes of the compaction and collapse type (Jennings et al, 1965) and land subsidences are readjustment phenomena of the unstable residual cover.

The recent dewatering of a number of dolomitic compartments in the Far West Rand by gold mines has caused a substantial drop of groundwater levels. Parts of the weathered unconsolidated cover, which previously lay within the saturated zone, have been drained loosing thereby the interstitial hydrostatic liquid support. Artificially induced readjustment activity has thus been triggered with an acceleration of sinkhole formation.

4.5 The evolution of the aquifer

The development of permeability in the near-surface zone of the Malmani Dolomite in the study area, since its initial exposure to atmospheric conditions, is intimately related to karstification. Karstification is understood as a prolonged process whereby successive, laterally extensive, rock zones underwent dissolution and leaching in the upper part of the groundwater levels. Such a process, if viewed in step stages, would lead to the evolution of subsequent karstified horizons, each horizon having an integrated net of fissures, cavities and voids. The assumed lowering of groundwater level being a function of the erosional downcurving process constantly shaping land surface and base levels. Each new dissolution cycle would invoke a certain amount of disintegration (caving-in) in the rock material of the overlying vadose zone due to the action of meteoric water. This combination of fissured karstified bedrock and accumulated weathering products comprises the potential permeability in the studied complex.

As already mentioned, a number of intrusives, mainly syenite dykes cut through the dolomite, subdividing in this way the extensive dolomitic outcrops area into smaller geohydrologic units, or compartments (Fig. 2.1). The downward progress of karstification is dependent interalia on the rate of erosion of such dyke barriers which control base level elevations. It is noteworthy that permeability in the investigated aquifer generally does not extend beyond a depth of 100 - 150 m below surface. It may therefore be concluded that paleo valley incision never exceeded a depth of approximately 150 m.

Data collected from hundreds of boreholes in the Far West Rand drilled by the Geological Survey as well as some 30 new exploration boreholes recently drilled in the course of the current investigation in the Zuurbekom Compartment, have been examined. Occasionally some details of the geological succession penetrated by these boreholes were not clear enough and could not be accurately logged. This is because percussion and air drilling methods, without coring, were exclusively employed. For instance, it was sometimes impossible to distinguish between transported and residual weathered clastics. In a few instances water-bearing, fractured-jointed zones, which occurred in an otherwise solid rock succession, were difficult to identify. In spite of such minor problems a rather comprehensive picture of the sub-surface geology is disclosed.

The upper part in many boreholes consists of layered variegated clay-shales, red, brown, pink, yellow and white, often sandy and including chert gravels and fragments. Towards the bottom of this clay section, black carbonaceous shales may occur, resting on an irregular, brecciated, weathered chert and dolomite which often constitutes an aquiferous zone. These clastic outliers are remnants of Karoo sediments (Ecca Group), which once extensively covered the whole area. Karoo sediments also occasionally appear as outcrops overlying the dolomites. The total thickness of the clay section, when present, varies from several metres to a few tens of metres. It is inconsistent laterally, which is also true of the black shale member.

The brecciated leached and weathered aquiferous zone merges downwards into the solid rock formation.

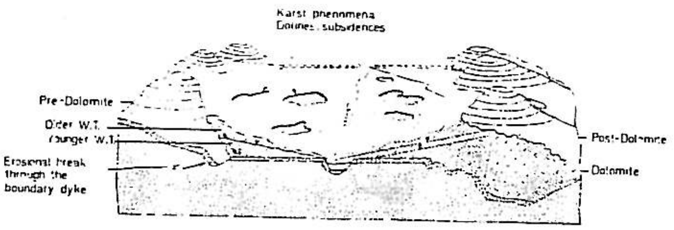
Groundwater levels in numerous boreholes in the study area, especially in well-defined compartments wuch as Zuurbekom, Gemsbokfontein, Venterspost and Bank, bear evidence to the extensiveness of a regional aquifer. Gradients are generally low within the boundaries of each geohydrologic unit. Discharge from dolomitic springs also confirms the existence of rather large groundwater systems with a well developed interconnection of voids. The aquifer is however by definition heterogenic and often anisotropic, as would be expected by the very origin of this karstic permeability. Transion from phreatic to confined conditions have been noticed.

It seems plausible to assume that the apparently weathered zone immediately overlying the solid rock consists of residual disintegrated collapsed rock material of an old vadose zone, formed as previously described due to karstic dissolution at a deeper level which had been activating the erosive consumption in the upper levels of this vadose zone. In such subsidence structures as dolines and polje conditions favoured the deposition of the black shale. The aquifer on the whole consists of a combination of karst debris and fluvio-glacial deposits, the relics of an ancient Pre-Karoo or Dwyka surface drainage system which possibly included also tillites and moraines. At a later stage, with the deposition of shaly Ecca beds, karstification had stopped. The coating of the dolomite by clays exerted an impregnating effect and sealed off the underlying pervious zone. As long as the aquifer was extensively covered by thick Ecca strata, no further karst formation was possible. Later geological developments gradually stripped off and uncovered parts of the buried aquifer (Fig. 4.1). With the exposure of renewed areas of intake and outlet for meteoric water, rejuvination of the aquifer started, the fossil aquifer being reactivated. In places a new karstification cycle began. Recent groundwater flow pattern often follows ancient underground channels such as burried relics of Pre-Ecca surface water courses or moraines.

Following the removal of the overburden above the dolomite and due to the irregularity of Pre-Karoo morphology, with areas of subsidences and sinkholes, patches of Karoo outliers were characteristically left behind. Present day topography is featured by renewed mild down-cutting of the land surface. In that way, reverse topography is sometimes encountered - a phenomenon already observed by Du Toit (1951) in the Lichtenburg area.

Geophysical methods such as gravity surveys proved an efficient exploration tool. In the Zuurbekom area the drilling programme was planned so as to locate most of the borehole sites on residual gravity lows (Folder 5.1) with the aim of penetrating a maximum thickness of the weathered zone, and assuming a potential aquifer. It was also expected that in such lows, more or less homogenous aquifer material and structure might be encountered, which in turn would enable the performance of aquifer tests. It was found that residual gravity maps convey the presence and extensiveness of Ecca outliers as well as of weathered rock material, chert breccias, glacial deposits etc. which form the aquifer. No distinction is possible on the residual gravity map between the different lithological units.

a

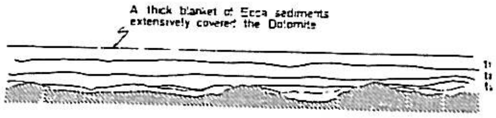


Block diagram showing an early phase of karstification. The products of karstification form the basal part of the present aquifer. Depth of karstification was regulated by erosion of the boundary dykes

b

Schematic section not to scale, showing the various lithostratigraphic components in connection with the aquifer

c



Schematic cross-section, not to scale, showing successive phases of erosion t₁ t₂ t₃ during which Ecca beds were stripped off. Eventually parts of the aquifer and solid rock became exposed to meteoric water

d

Schematic cross-section not to scale showing the zone of the aquifer resting on an irregular relief, outliers of Ecca shales occassionaly cover the aquifer. Intake areas for natural replenishment are rather restricted to the outcrops of the aquifer.

REFENCE FOR Fig
C AND d

Ecca shales
Aquifer zone
Solid rock

FIG.-4.1

THE EVOLUTION OF THE AQUIFER

The interpretation of geological findings whereby the formation of the aquifer is dated to at least Pre-Ecca times, would account also for the limited depth of the aquifer. Most of the dyke systems are assumed to be of Pre-Karoo ages and incision and erosion of these hydrologic boundaries took place during Dwyka times. Since then, and due to the protecting cover of later sediments, no further down-cutting of the relief occurred. On the other hand one could expect that such dyke boundaries had been down-planed in restricted places by glaciers and rivers forming gaps which allow groundwater flow between adjacent geohydrologic units.

4.6 The dating of karst

The dating of the karst formation in the Transvaal Highveld is rather complicated in the absence of stratified young deposits. Several workers applied geomorphological methods relating ancient water table zones to major erosion surfaces (King, 1962). Brink and Partridge (1965) considered an upper (+5 110') and a lower (+4 800') karst level in West Driefontein Cave, to have originated during Post-Gondwana and African times respectively - Similarly these authors maintain an African age of formation for the upper section at Sterkfontein Cave (+4 800'), and a later Post-African for the lower section (4 700'). According to Marker and Moon (1969) the Highveld caves fall into a group formed during the African Cycle (Late Cretaceous - Mid Cainozoic). Four periods of karst formation have been described by Martini and Kavalieris (1976), which correspond stratigraphically to major Post-Dolomite breaks in deposition. The latest, Tertiary to Recent, has according to these authors, contributed most to present day permeability of the dolomite.

Based on the present study it is suggested that a Pre-Ecca period of karst formation may be identified. This had been followed by and was partly contemporaneous with a fluvio-glacial period. Not much can be concluded concerning the new cycle which started after most of the Karoo sediments had been removed.

Evidence supporting climatic fluctuations between wet and more dry periods during the Quaternary, based on surface and cave depositional sequences in Northeastern Transvaal, have been postulated by Marker (1972). Such successions were not found in the studied area, probably because later geologic events are more of a denudational character.

5. INVESTIGATION OF ZUURBEKOM COMPARTMENT

5.1 Introduction

The dolomite aquifer in the Far West Rand, Southwestern Transvaal, is subdivided into smaller geohydrologic units or compartments by the presence of hydrologic boundaries such as impervious dykes (Enslin and Kriel, 1967). Zuurbekom Compartment constitutes such a unit, covering an area of some 130 km^2. It is bounded on its western, southern and eastern flanks by three major dykes. The northern boundary is formed by the wedging out of the Malmani Subgroup on top of the Pre-Dolomite formations namely, the Black Reef, Ventersdorp Lava and the Witwatersrand Super Group. A detailed investigation undertaken by Randfontein Estate Mine revealed a further complicated dyke pattern, within the said compartment (Fig. 5.1).

The Wonderfontein River crosses the compartment in a northeastern to southwestern direction and the Klip River runs parallel to the eastern boundary (Fig. 5.1). A moderately enlongated topographic divide separates the two water courses. In most of the area, ground surface slopes to the southeast.

The first step in the investigation included the compilation of data and a survey of some 70 boreholes (Table 5.1), information was summarized and recommendations outlined in a preliminary report (Gh3020). This was followed by an interim report which included partial results of water analyses. Later the drilling of observation holes and aquifer tests were undertaken.

Cooke Section of Randfontein Estates G.M. has lease areas within the compartment area, along the Wonderfontein River. Two shafts are presently operating. The reduction and recovery plant is situated in the northwestern corner of the compartment. Another mine, South Roodepoort Main Reef, borders the compartment to the north. A Rand Water Board pumping station, which includes several boreholes, is located at the southeastern part.

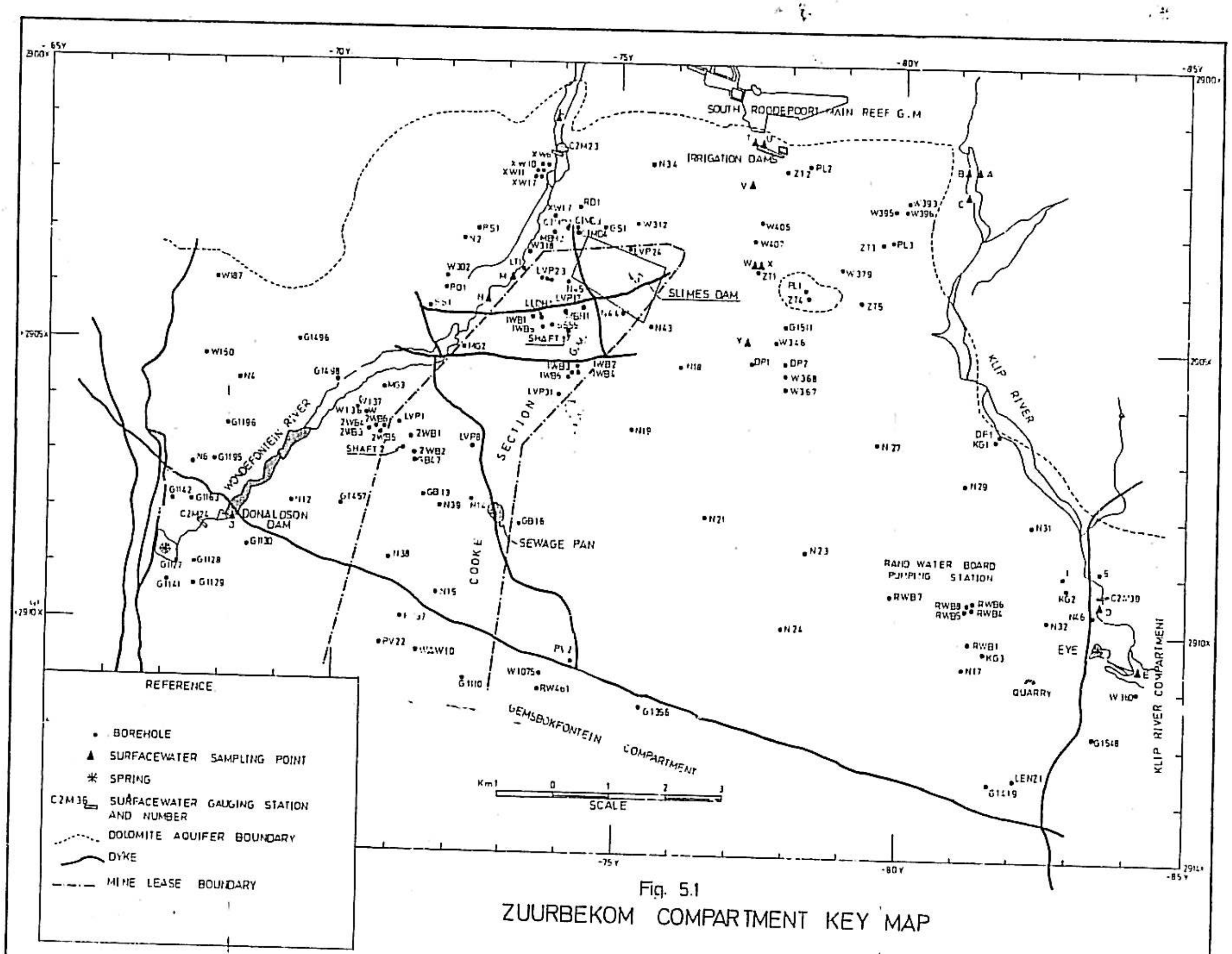


Fig. 5.1
ZUURBEKOM COMPARTMENT KEY MAP

TABLE 5.1: Borehole survey in Zuurbekom Compartment, November 1977

Use : D - Domestic water supply; C - Stock watering; I - Intensive pumping

Equipment: W - Wind-pump; O - Open hole; T - Turbine pump; P - Pump not defined

Observation: R - Automatic recorder; + - Manual observation; X - Observation possible

Borehole number	Elevation m a.m.s.l.	Use	Equipment	Observation
G1142	1566,40	-	O	+
G1163	1570,16	-	O	+
G1195	1574,69	-	O	+
W150	1585,98	D	W	+
G1196	1576,08	-	O	+
G1496	1594,40	-	O	+
G1457	1579,28	-	O	+
2WB1	1590,39	I	T	-
2WB3	1587,60	I	T	X
2WB4	1588,44	I	T	X
2WB5	1588,48	I	T	-
2WB6	1589,27	I	T	X
W137	1585,02	D	T	+
W136	1586,38	D	T	X
Mg3	1589,16	D	T	X
G1498	1590,40	-	O	+
WAW10	1605,44	-	O	+
PV22	1603,54	D	P	+
GB13	1585,57	-	O	R
GB47	-	-	P	X
LVP1	1591,40	-	O	X
W302	1605,21	D	P	X
LVP8	1594,28	-	-	X
GB16	1580,38	-	O	R
LVP31	1604,41	-	O	X
IWB1	1607,47	-	O	X
IWB5	-	I	T	-
SS55	1608,17	-	O	+
W318	1602,85	-	P	X
XW6	1613,05	-	O	X
XW7	1613,87	-	O	-

Borehole number	Elevation m a.m.s.l.	Use	Equipment	Observation
XW8	1614,01	–	O	–
XW9	1613,77	–	O	–
XW10	1613,15	–	T	X
XW11	1612,44	–	–	R
XW15	1612,18	–	T	X
XW16	1609,99	–	T	X
XW14	1612,63	–	T	X
1WB2	–	–	T	–
1WB3	–	–	T	–
1WB4	–	–	T	–
1WB4A	1608,14	–	O	X
1WB4B	1608,34	–	T	–
1WB4C	1608,36	–	T	–
LVP17	1613,30	–	O	R
G1356	1605,38	–	O	+
W312	1629,93	D	W	X
W367	1613,97	D; C	T	X
W368	1617,10	–	O	–
G1511	1623,90	–	P	X
W347	1627,07	–	P	X
W405	1628,94	D; C	W	X
PL1	1627,78	–	W	X
PL2	1648,91	–	P	X
RWB7	–	I	T	–
PL3	1616,27	–	W	X
G1419	1586,07	–	O	X
RWB1	1571,10	–	–	X
RWB4	1564,94	–	–	X
RWB5	–	I	T	–
RWB6	–	I	T	–
RWB8	–	I	T	X
DF1	1579,10	–	W	–
Lenz 1	1582,83	–	O	X
1	1575,56	D; C; I	T	X
G1548	1568,14		O	X
5(W364)	1567,07	D	W	X
W360	1563,06		W	X

This compartment has been selected for a long-term detailed study as it involves a combination of various aspects such as: Contamination of groundwater, surface and groundwater interaction, possible future dewatering and practical management and co-ordination problems.

5.2 Groundwater abstraction

For many years exploitation of groundwater in this compartment had been confined to fairly constant amounts of $10 \times 10^6 m^3$ per annum, abstracted by the Rand Water Board at its Zuurbekom pumping station, as can be seen in Fig. 5.2, based on Rand Water Board annual reports. Pumping from this site dates to the beginning of the century.

Pumping affected the natural discharge from this compartment, which used to issue at Klip River Eye. The eye dried up, although occasionally, following high rainfall seasons, it would temporarily resume its flow. No records are however available concerning these flow volumes. A vague estimation puts the pre-pumping flow amount at $5 \times 10^6 m^3$/year (Enslin, 1967). It is noteworthy that no substantial decrease in water level has been noticed. Flow measurements carried out recently at the Klip River Eye, between May and August 1980, reveal considerable amounts of discharge, between 314 m^3/h and 510 m^3/h.

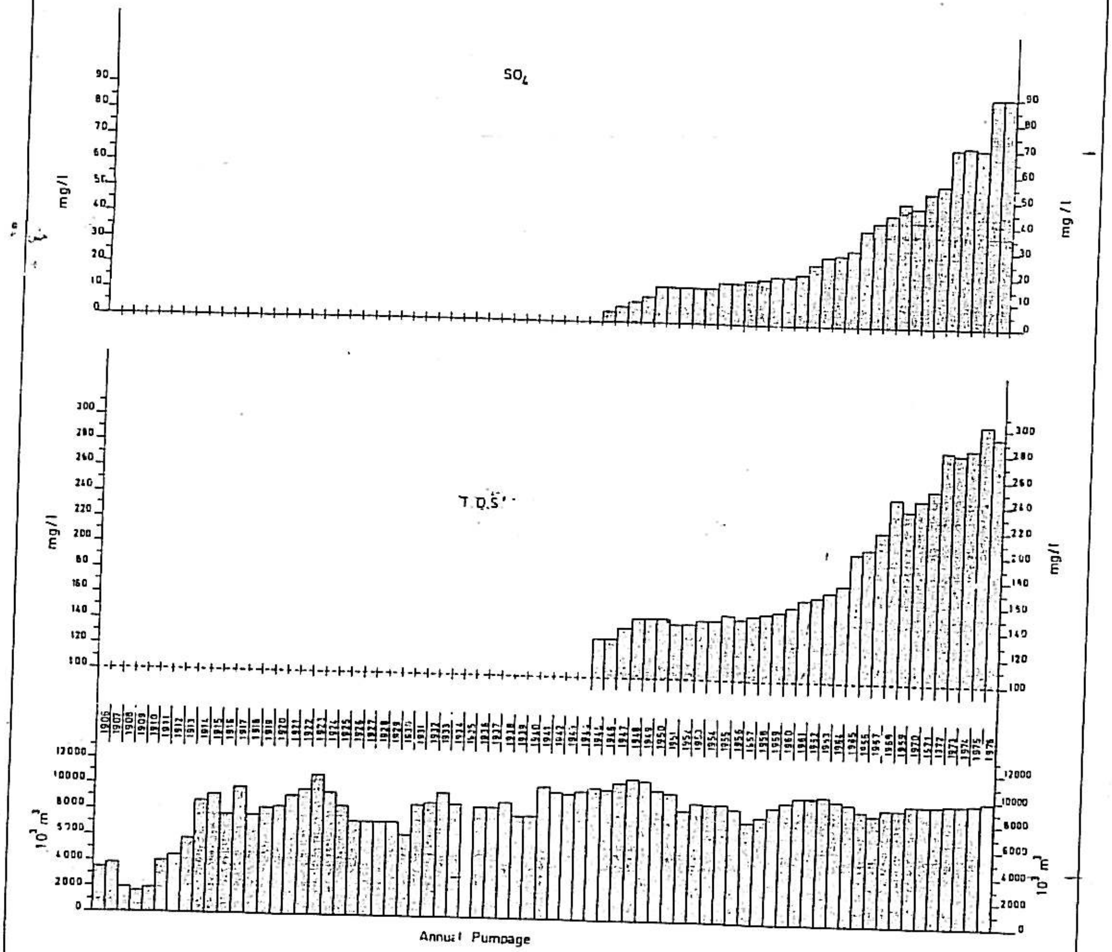


Fig. 5.2

SALINITY DEVELOPMENT AT THE RAND WATER BOARD PUMPING STATION, ZUURBEKOM

Conditions have, during the last years, changed with the introduction of mining to this area. The following table furnishes some figures concerning the sources of water supply and disposal at Cooke Section G.M., valid for 1978.

TABLE 5.2: Water balance at Cooke Section, in $10^6 m^3$

Source		Disposal	
Pumpage from Sahfts 1 and 2	6,2	Dolomitic water to Wonder=fontein R.	1,8
Pumpage from boreholes	3,4	Dolomitic water to under=ground	3,7
Purified sewage	1,3	Purified sewage to Wonder=fontein	1,3
Imported from R.E.G.M.	1,3	To farmer	0,6
		To quarry	0,2

The net abstraction therefore from the dolomitic aquifer:

$$6,2 + 3,4 - 3,7 = 5,9 \times 10^6 m^3/\text{year}.$$

Figures obtained recently (1980) indicate an increase of the net abstraction, namely: Total pumpage = 10,3, Total returns = 2,7

$$10,3 - 2,7 = 7,6 \times 10^6 m^3.$$

Abstraction of water by the mine includes water infiltrating into the underground workings, which is collected and brought to surface at the shafts, plus water pumped by boreholes from shallow depths. Areas where the shafts and pumping boreholes are located are indicated in Fig. 5.4.

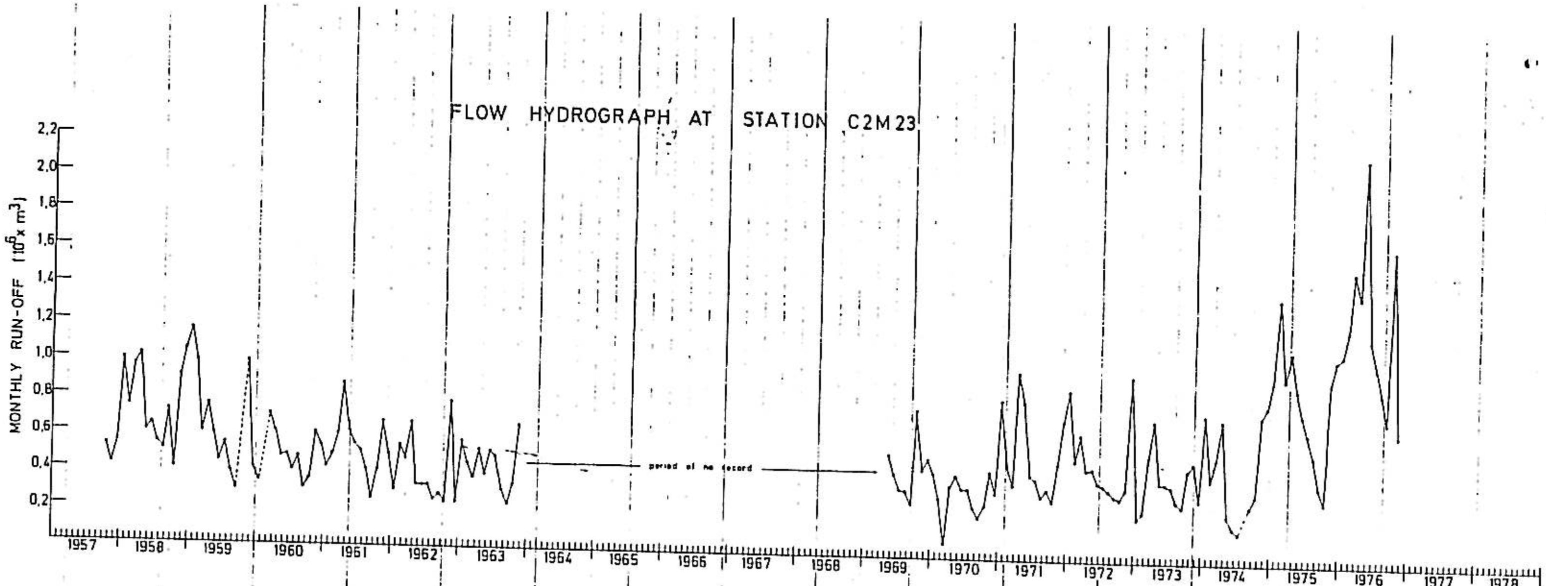

FLOW HYDROGRAPH AT STATION C2M23

FIGURE 5.3

5.3 Surface water and mine effluents

Flow in the surface water courses no longer accurately represents undisturbed conditions. It consists to a large extent of various effluents.

The annual flow in Wonderfontein River, gauged at Station C2M23, was previously in the range of 4-6 x $10^6 m^3$ (Hydrological Information, 1978). This flow has doubled since 1975/76, Fig. 5.3. This runoff is only partly due to high rainfall and most of the excess annual runoff comes from the following sources:

Mine effluents upstream (highly mineralised)	4-5 x $10^6 m^3$
Dolomitic groundwater from Cooke Section G.M.	1,7 x $10^6 m^3$
Reclaimed sewage from Cooke Section G.M.	1,0 x $10^6 m^3$
Reclaimed sewage from Krugersdorp Plant	2,5 x $10^6 m^3$

The combined runoff enters the Donaldson Dam reservoir and fills it to the maximum capacity, the rest spills downstream.

The nature of the flow in Klip River is similar. Mineralised mine effluents, treated and untreated sewage water are the major sources.

Another source of surface water has its origin at South Roodepoort Main Reef Gold Mine. In this case, the mine diverts pumped water into earth dams, see Fig. 5.1, and furrows which lead the water southwards. Water is practically being spread over the surface and eventually is absorbed in an excavation at point Y. Part of this water is being used for irrigation. The estimated quantity disposed of in that way amounts to 0,66 x $10^6 m^3$ per year.

5.4 Groundwater flow pattern

Two simultaneous water level maps are shown in Figs. 5.4 and 5.5, the one of December 1977 and the other of September 1980, on which information derived from new observation holes has been incorporated.

A number of dykes further divide the compartment into smaller units in the area of Cooke Section Mine. These dykes were detected as a result of detailed mining exploration.

It is also inferred from groundwater levels, Fig. 5.5, that the west-trending dyke to the south of Cooke 1 shaft, extends further west and east than previously surmised. The apparently uncomplicated sub-surface structure in the eastern part of the compartment could well be due to insufficient information.

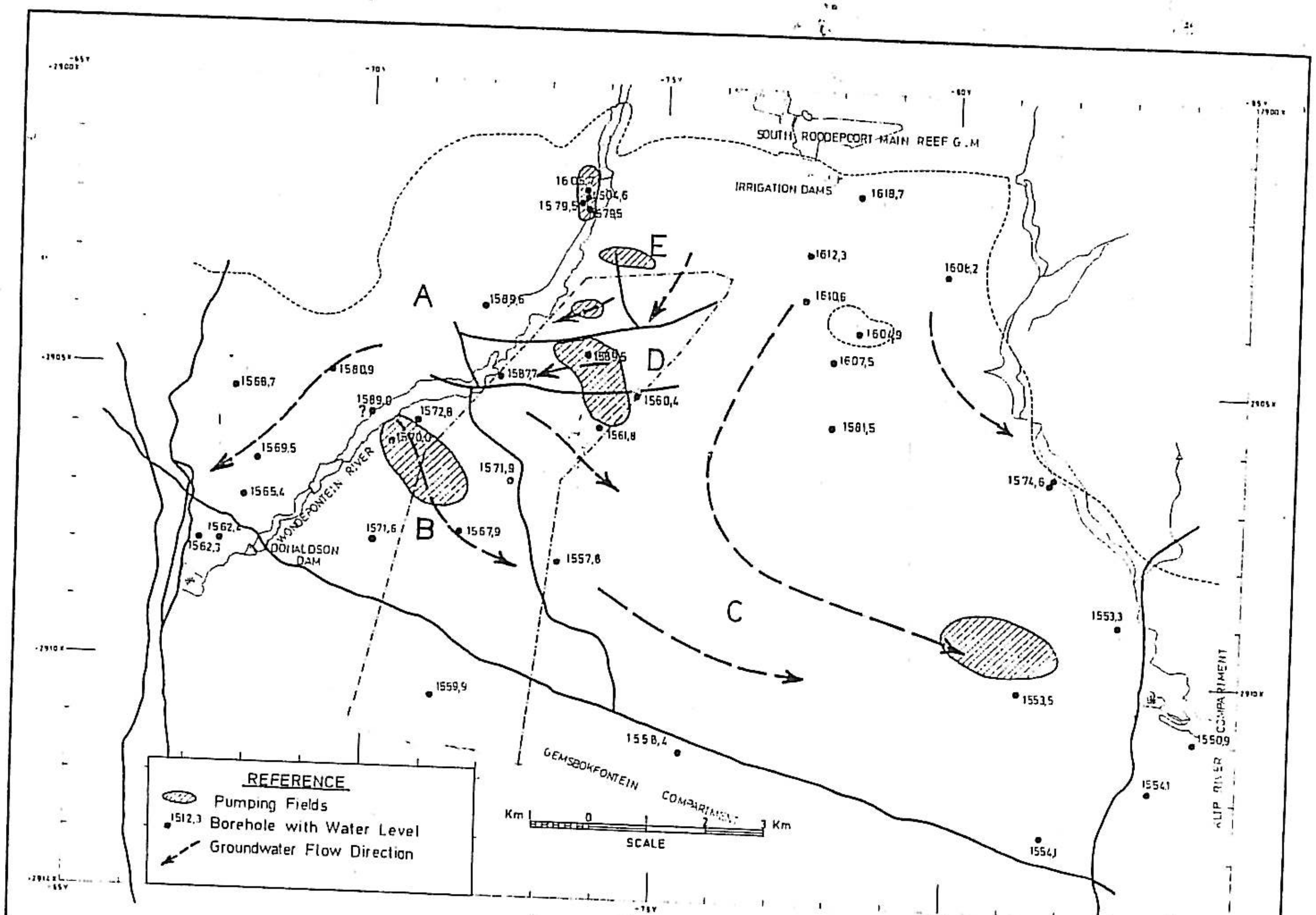


Fig. 5.4

GROUNDWATER FLOW PATTERN MAP, WATER LEVELS AS OF DECEMBER 1977.

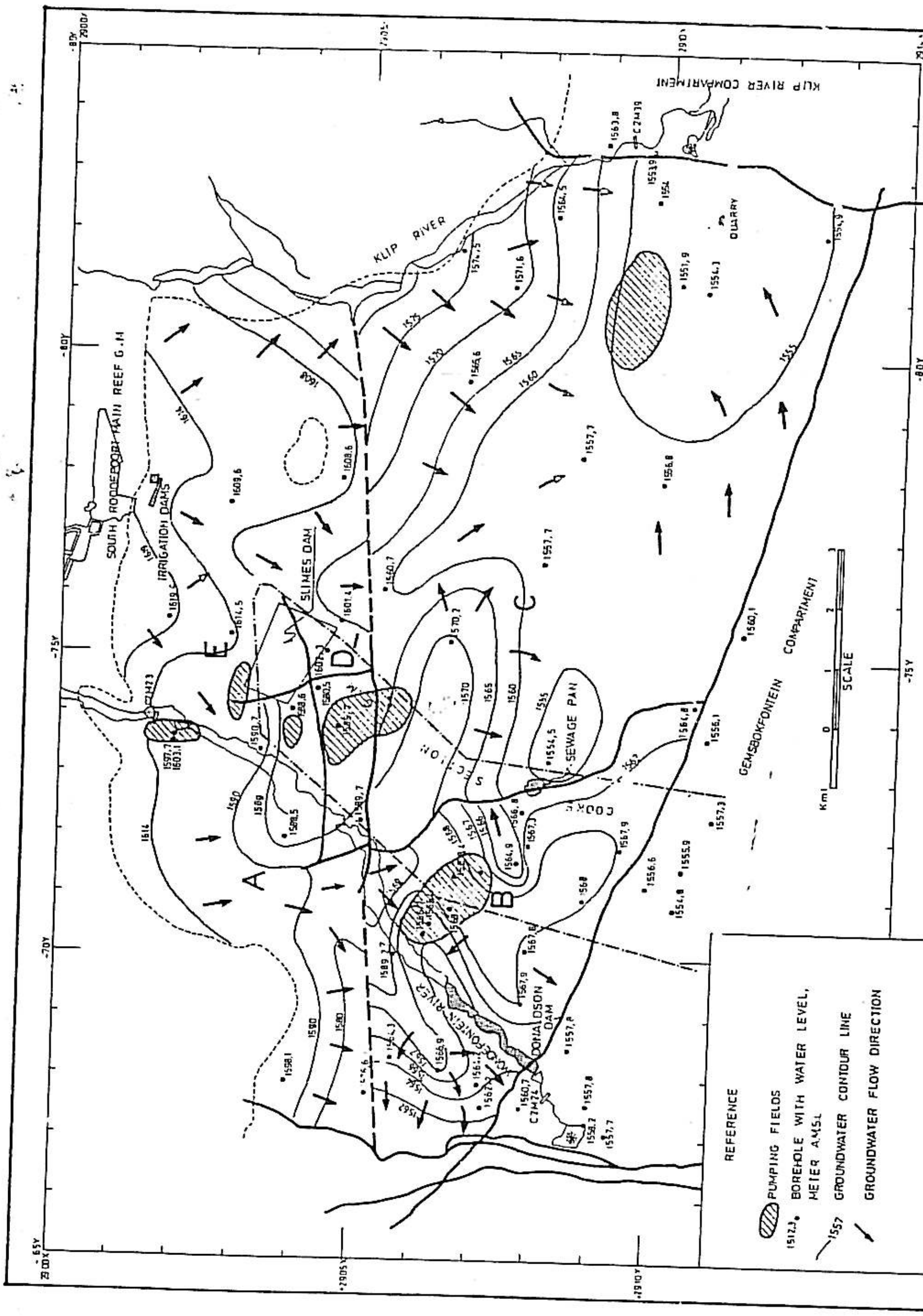


Fig. 5.5
GROUNDWATER FLOW PATTERN MAP. WATER LEVELS
AS OF SEPTEMBER 1980

The indicated flow directions suggest that under natural conditions, groundwater from sectors A, D and part of B, with a surface area of 37,75 km^2, drains westwards, eventually overflowing into the adjacent Venterspost Compartment. Groundwater from sectors C, E and part of B, with a surface area of 92,25 km^2 discharges at the Klip River Eye and the Zuurbekom Pumping Station.

It appears from Fig. 5.5 that a certain amount of groundwater from sector A also recharges sector B. This flow picks up contaminated river water which is thus introduced into sector B.

Influent conditions apparently exist in part of the eastern boundary. Here too, water flowing in the Klip River, presently mostly contaminated effluents, infiltrates into the aquifer.

It is obvious that the heavy pumpage undertaken lately by Cooke Section mine has already affected and distorted the natural flow regime. This may be noticed in the area of Shaft No. 1, where flow direction has reversed. It also manifests itself in the development of a local trough around GB16.

5.5 Qualitative study

A few boreholes in the area, where automatic recorders have been installed, for instance LVP24, GB16, GB13, reveal a pronounced cyclic tidal effect. Fig. 5.6 illustrates one such borehole. Two diurnal maxima and two minima can be noted. A sinesoidal

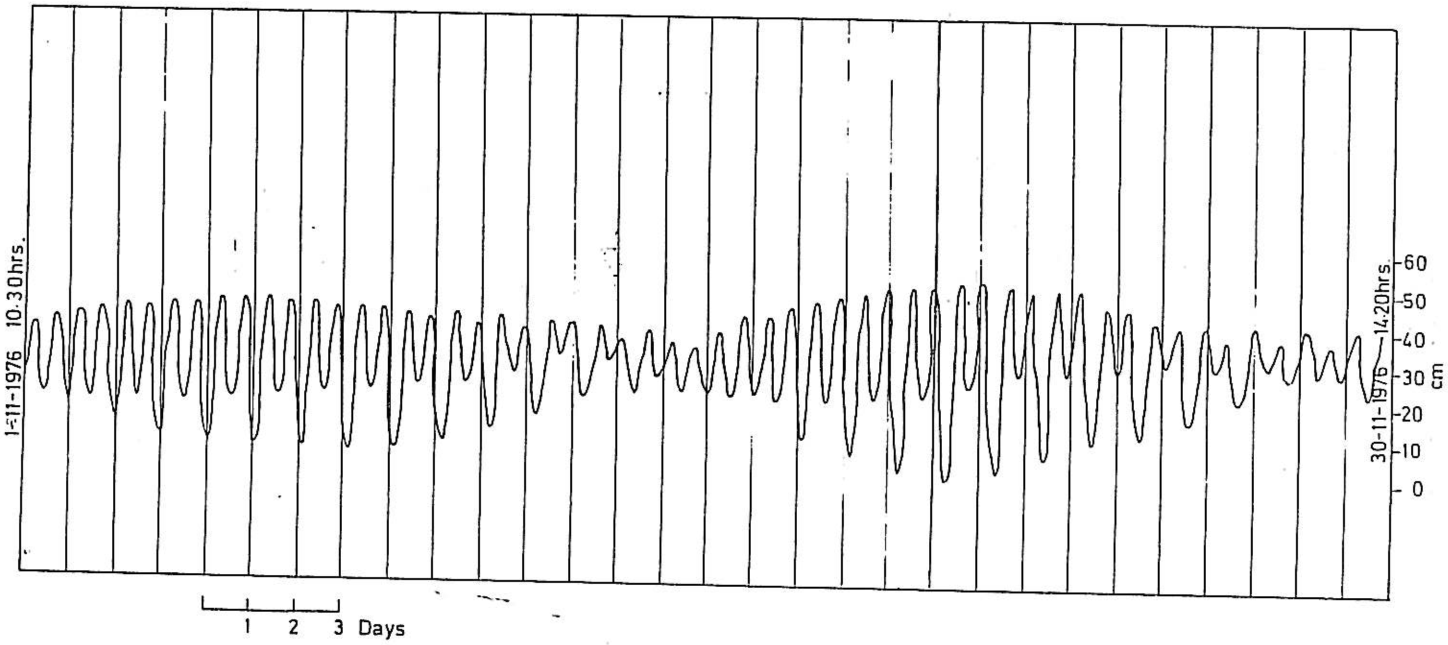


Fig. 5.6
AUTOMATIC WATER LEVEL RECORDING IN BOREHOLE GB 16 ILLUSTRATING TIDAL EFFECTS IN PARTS OF THE AQUIFER

change of the amplitude during each month showing two maxima and two minima can also be observed. This feature is characteristic to confined to semi-confined aquifers.

Behaviour of water levels in the dolomite aquifer does not reveal a simple relation between precipitation and rise of water levels. It will be suggested, later in this study (Part 10) that the mechanism of natural recharge involves a two phase system, an immediate one as shown in Fig. 5.7, and a delayed one with a lag period of four to six months. Records of groundwater levels for long-term observation periods are shown in Figs. 5.8, 5.9, 5.10 and 5.11. It is noticed that often the highest and lowest seasonal water levels are shifted forward in time by about six months relative to the rainfall distribution.

A substantial rise of the water levels corresponding to high rainfall seasons, such as 1970/71, 1975/76 and 1977/78 can also be seen.

In some boreholes the vertical magnitude of water level fluctuations is considerably bigger than in others, for instance borehole GB13 Fig. 5.11. This could suggest a relatively limited storage.

A marked drop of water levels which started in March 1978 can be observed in boreholes LVP17, GB13, GB16 and PV2, and this could result from a combined effect of natural discharge and

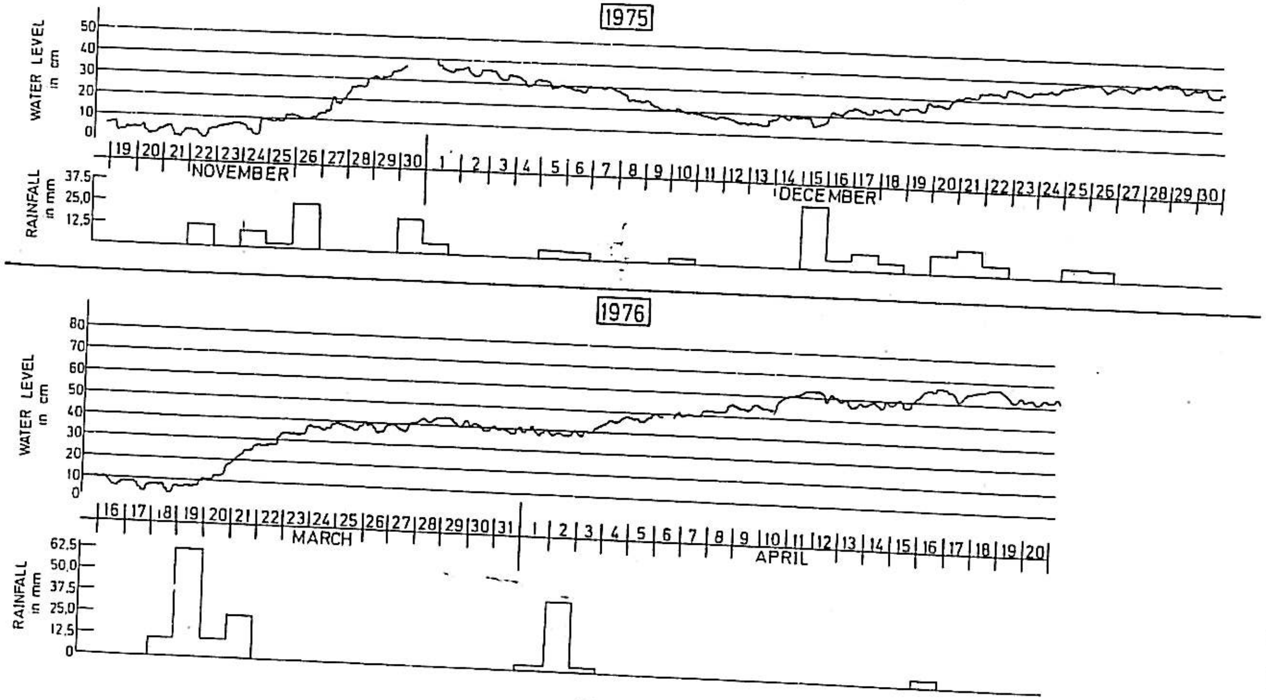


Fig. 5.7

AUTOMATIC WATER LEVEL RECORDING IN BOREHOLE SS55 vs DAILY RAINFALL

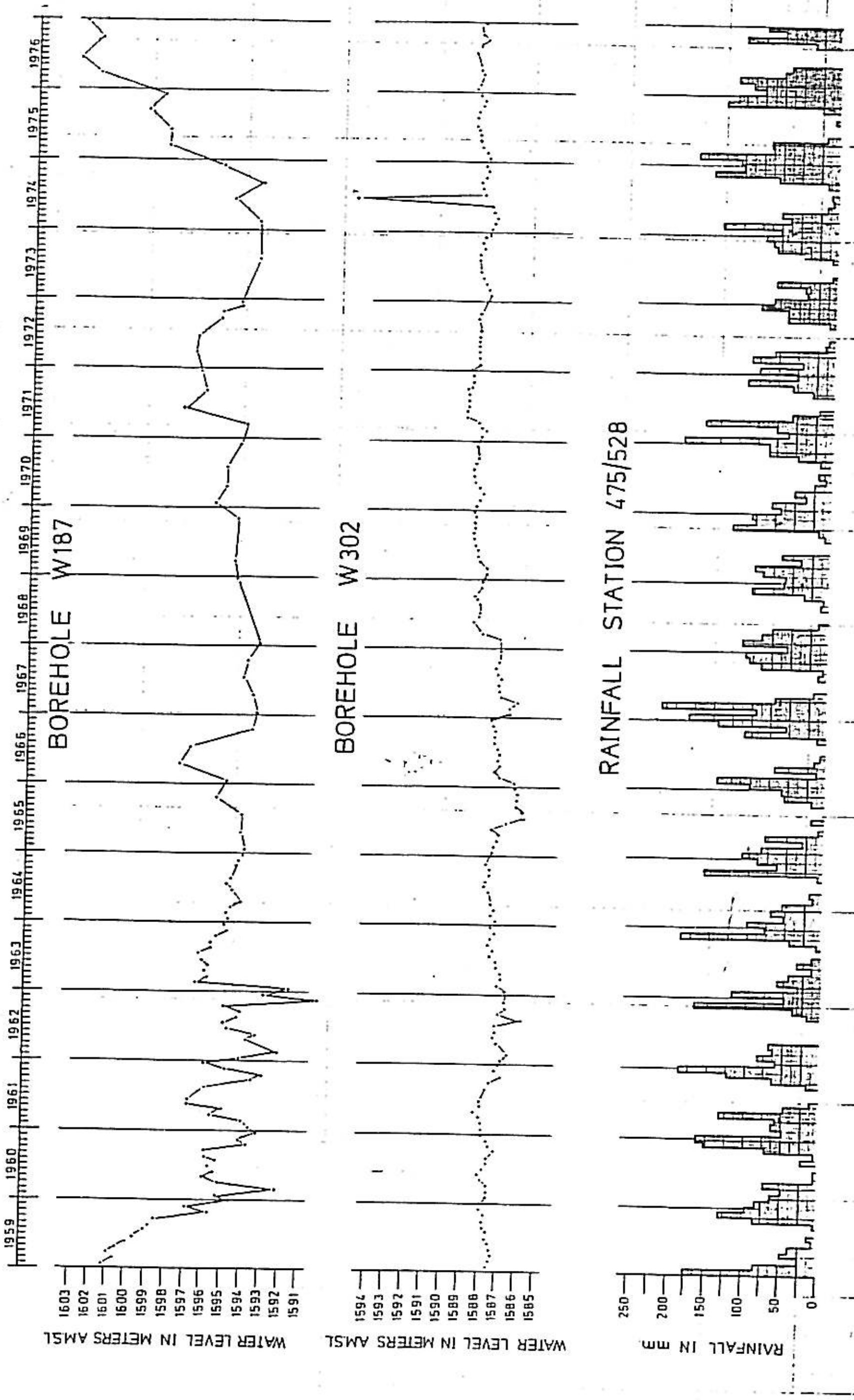
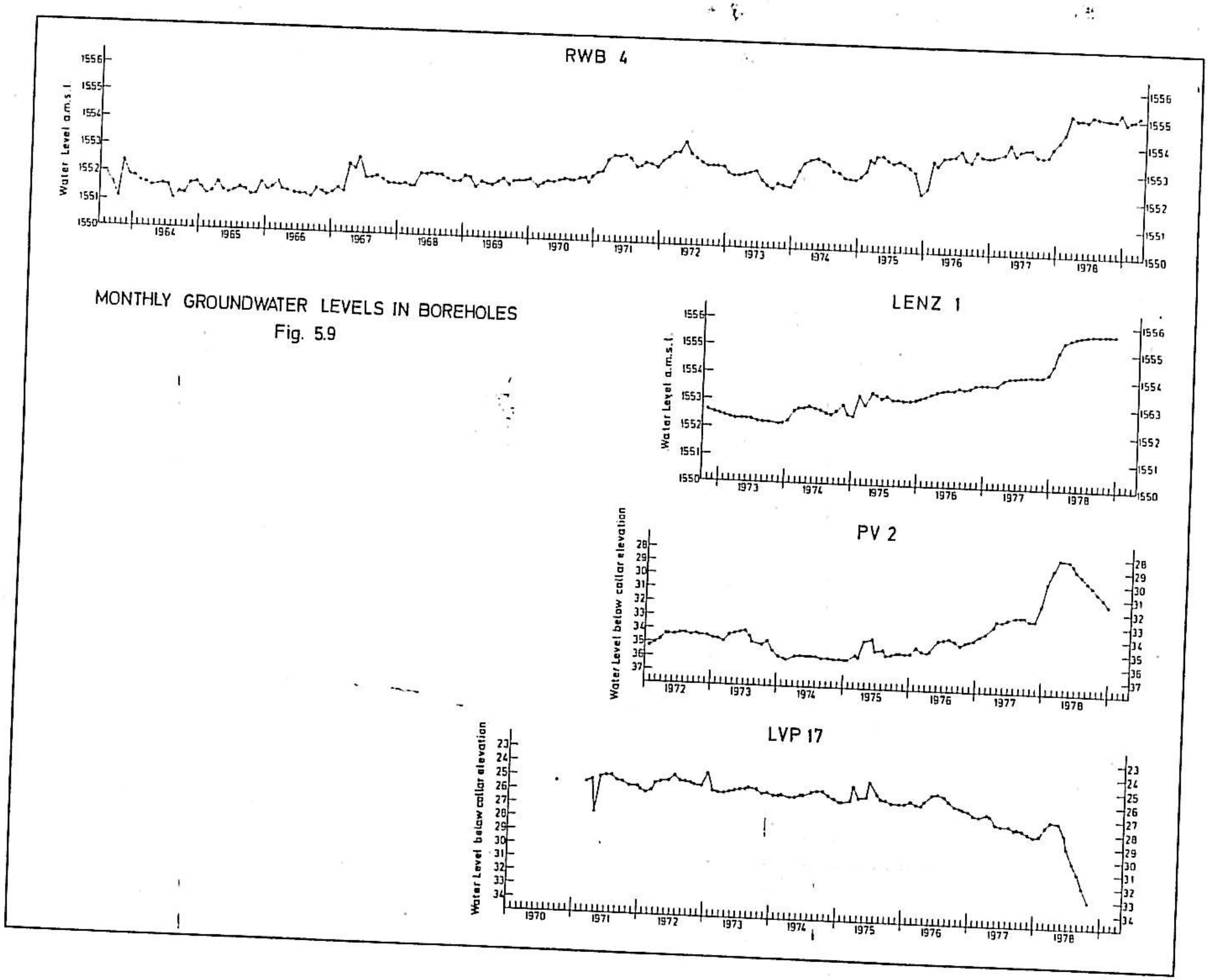


Fig. 5.8
MONTHLY GROUNDWATER LEVELS IN BOREHOLES AND MONTHLY RAINFALLS



MONTHLY GROUNDWATER LEVELS IN BOREHOLES
Fig. 5.9

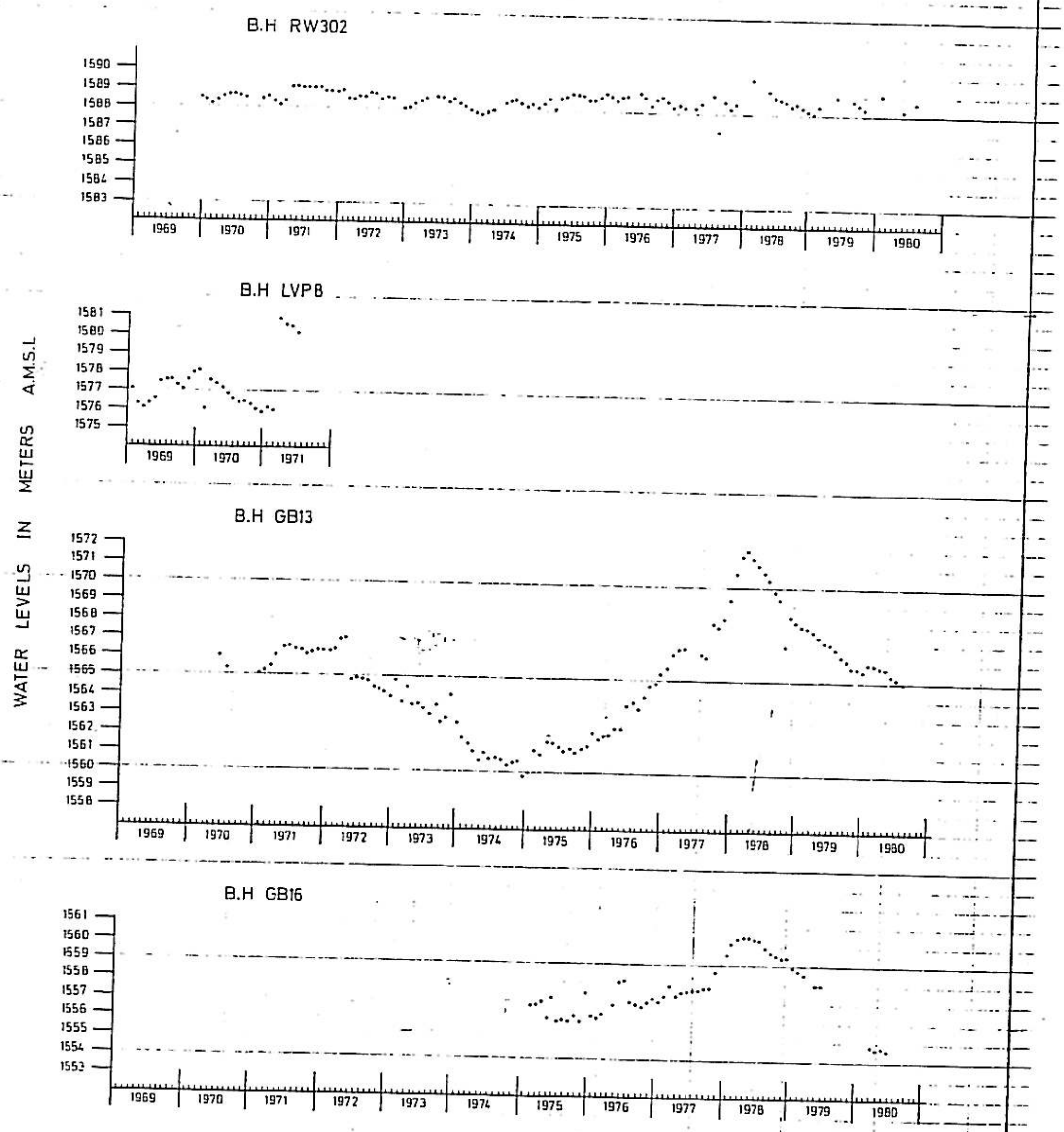


Fig. 5.10
MONTHLY GROUNDWATER LEVELS IN BOREHOLES

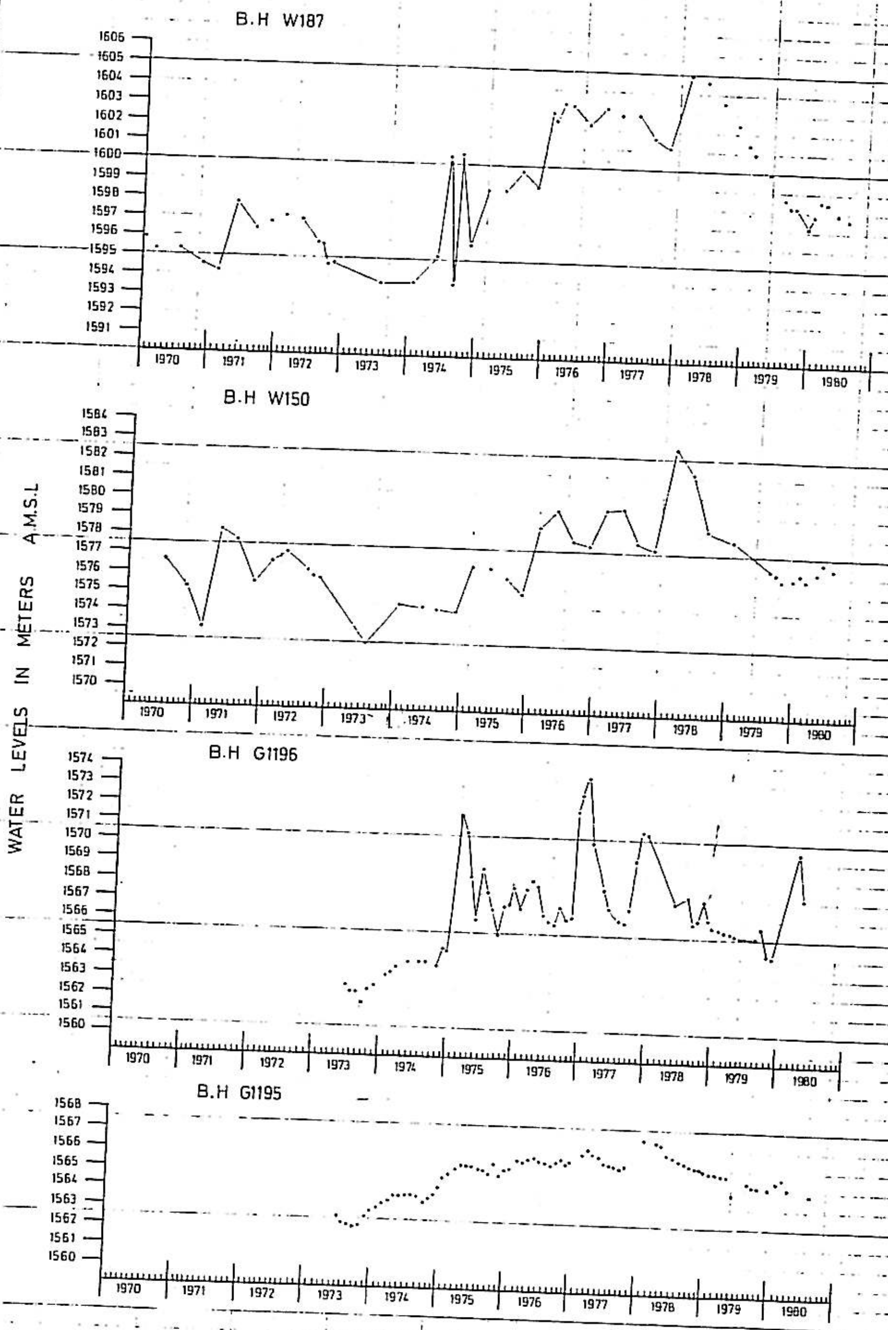


Fig. 5.11
MONTHLY GROUNDWATER LEVELS IN BOREHOLES

over-pumpage. A similar behaviour of the water levels has been recorded in the adjacent Gemsbokfontein Compartment, where only 40 - 60% of abstracted groundwater has been recirculated into the aquifer.

Gravity surveys conducted by the Geological Survey completely covered the studied compartment, as well as the bordering compartments to the west. Station spacing was generally 100 m. Readings were corrected for latitude, Bouguer Free Air, drift and tidal effects. Values were plotted and contoured to produce a Bouguer Anomaly map. The residual gravity map, presented in Folder 5.1 by courtesy of the Geological Survey, was derived by subtracting the regional gravity values from the bouguer Anomaly values. The regional gravity map presents a reference gravity surface at the water table elevation. Its construction was fascilitated by the drilling of a network of boreholes down to the solid dolomite. The observed gravity at each of these boreholes was corrected in such a way as to yield a value corresponding to a completely dolomitic section up to the water table reference plane.

The advantage of the resultant residual gravity map lies in the elimination or reduction of gravity effects of deep seated features. Negative areas or lows on the residual gravity map may be interpreted as areas including a comparatively thicker overburden of weathered rock material as opposed to positive highs where the solid dolomite bedrock is close to surface. The density of the weathered rock materials, on the average, is of the order of 2,35 g/cm^3 while that of the solid rock is around 2,85 g/cm^3. The density of the rock units comprising the overburden naturally varies considerably, 1,2 - 2,6 g/cm^3 (Kleywegt and Enslin, 1973).

Results of drillings are shown in Folder 5.1 for comparison with the residual gravity. The presented thickness of the weathered rock has been calculated to include all rock material down to the solid dolomite. Only part of such a section is a potential aquifer. It has often been noticed, that the top part of the dolomite, below the more clayey overburden is extensively leached, jointed and water-bearing. This zone, assumingly representing the latest karstification phase, has also been included in the weathered rock overburden. The thickness of this interface is inconsistent, but not exceeding 15 m.

Most of the observation-exploration boreholes drilled recently as part of this project were sited on gravity lows. All of them struck water and the correlation with light density rock material extending below the groundwater table is well established. Yet this property does not necessarily guarantee a high yielding borehole. In Fig. 5.12 condensed columnar sections of these boreholes are shown. It is noticed that in most cases the aquifer is semi-confined to confined and water was struck in irregular parts of the potential aquifer mass. Fig. 5.12 also explains the tidal effect observed in the hydrographs of many boreholes.

Lows on the residual gravity map would generally indicate a much more clayey sub-surface section as compared with highs where a relatively thin cover overlies the shallow bedrock. In trying to envisage the actual way in which natural replenishment into the aquifer takes place, Fig. 4.1, it is presumed that gravity

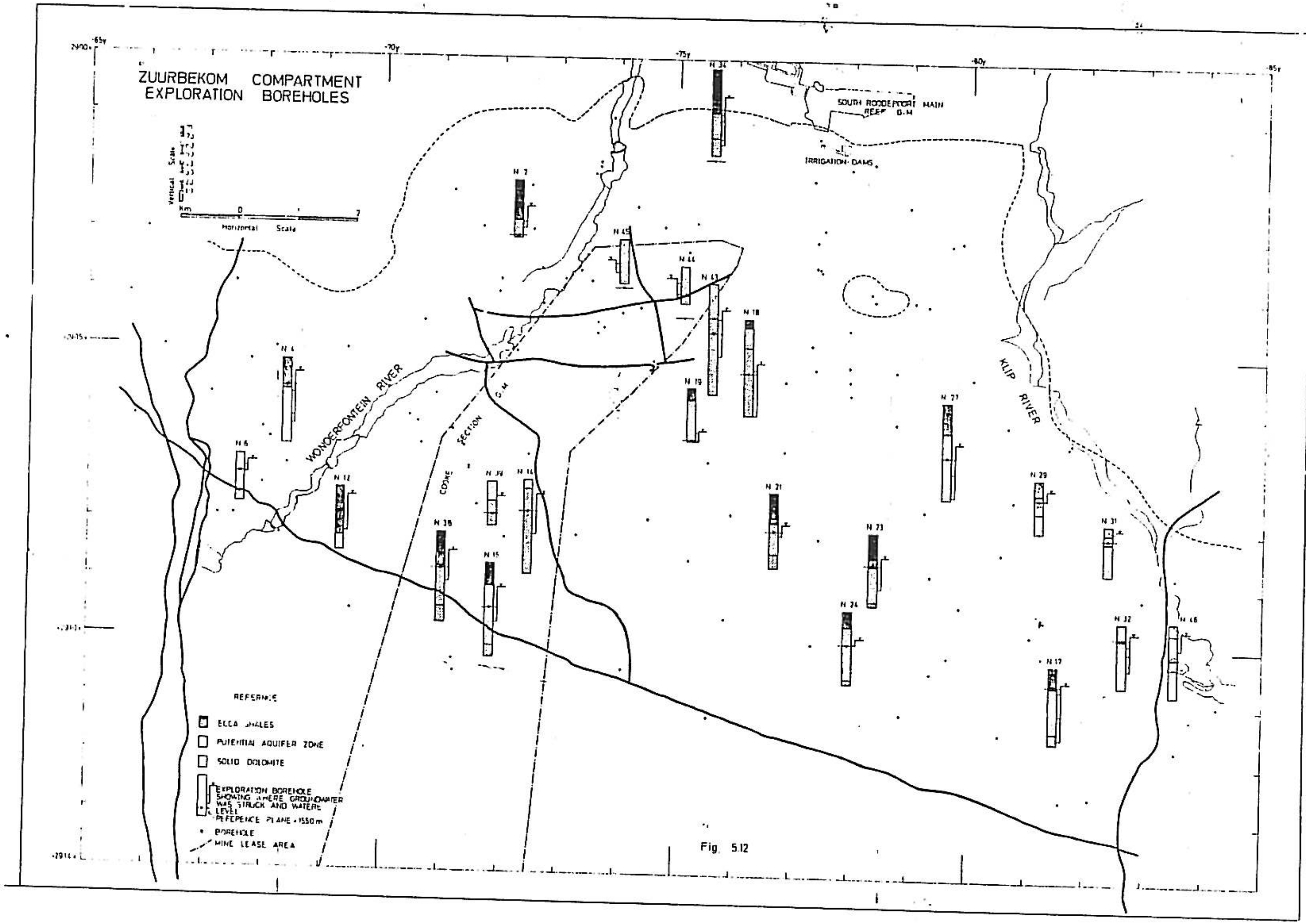

ZUURBEKOM COMPARTMENT
EXPLORATION BOREHOLES
Vertical Scale
Km
0
2
Horizontal Scale
SOUTH ROODEPOORT MAIN REEF G.M
IRRIGATION DAMS
KLIP RIVER
WONDERFONTEIN RIVER
COOKE SECTION
G.M
N 2
N 4
N 6
N 12
N 15
N 16
N 17
N 18
N 19
N 21
N 23
N 24
N 27
N 29
N 31
N 32
N 34
N 38
N 39
N 43
N 44
N 45
N 48
-65y
-70y
-75y
-80y
-85y
2900x
-2905x
-2910x
-2914x
REFERENCE
ECCA SHALES
POTENTIAL AQUIFER ZONE
SOLID DOLOMITE
EXPLORATION BOREHOLE SHOWING WHERE GROUNDWATER WAS STRUCK AND WATER LEVEL
REFERENCE PLANE +1550 m
BOREHOLE
MINE LEASE AREA

Fig. 5.12

highs possibly provide preferential intake areas, wherefrom the percolating rainwater starts its tedeous route along the fractured zone down to the water table. A smaller contribution to the recharge is expected over the areas of gravity lows, with the exception of the areas in proximity to the Wonderfontein River. Along the river, due to the erosion of clays, gravity lows often indicate recently weathered dolomite.

5.6 Geochemistry of the waters

Some 60 water samples have been analysed, the bulk of which are listed in Table 5.3. Sampling points and sulphate content are shown in Fig. 5.13. The samples come from boreholes as well as from surface waters.

The sampled waters may be divided into five groups from A to E:

Group A

Contains uncontaminated aquifer water. Natural groundwater in the area is characteristically bicarbonate water with calcium and magnesium as major cations. A rather low TDS content is also noticed. Included in this group are samples from boreholes KG1, DP2, DP1, ZT2, ZT3, ZT4, ZT5, PL3, W312 and GS1 (No. 10, 14, 15, 19, 20, 21, 22, 23, 32 and 33).

Group B

Sulphate waters, designated H to O, sampled in the Wonderfontein River which carries a mixture of fresh surface water and various effluents. Samples H, I and J which include mine effluents and

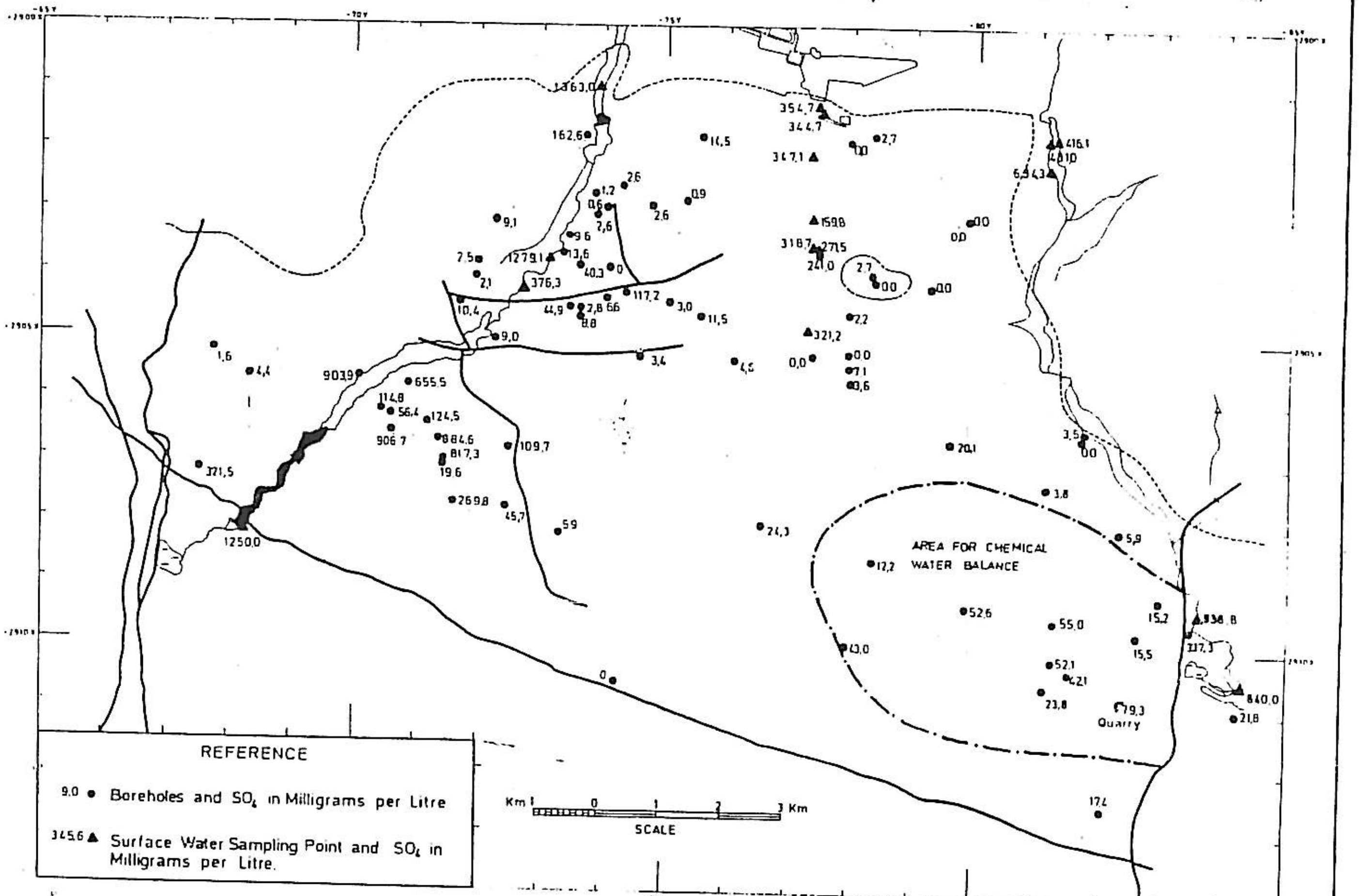


FIG. 5.13

WATER ANALYSES SAMPLING POINTS, AND SULPHATE CONTENTS

TABLE 5.3: Chemical analyses of waters from Zuurbekom Compartment, in milligrams per litre

BOREHOLES

No.	Source	TDS	pH	Ca	Mg	Na	K	Si	Cl	SO_4	HCO_3	NO_3
1	Lenz 1	348	7,62	40,5	29,7	6,8	1,8	1,9	4,4	17,4	245,9	0,5
2	RWB4	314	7,52	33,0	32,3	4,9	0,0	15,6	2,9	55,0	178,8	5,9
3	RWB4	279	7,71	33,9	27,5	4,1	0,7	10,5	3,1	77,7	125,7	6,2
4	RWB1	247	7,30	35,5	17,5	5,3	0,9	11,6	3,6	52,1	129,5	2,9
5	RWB7	245	7,72	30,9	20,5	4,0	1,0	9,0	2,9	52,6	127,4	5,1
6	Quarry	366	7,43	30,9	38,1	9,6	2,7	0,0	10,8	79,3	188,0	5,9
7	W360	267	8,20	32,9	20,6	3,4	0,6	8,6	4,1	21,8	168,2	15,2
8	KG2	299	7,65	39,1	21,2	4,4	0,9	10,6	3,8	15,2	198,4	15,4
9	KG3	362	7,65	42,3	29,0	10,8	1,1	9,4	17,8	42,1	183,0	35,3
10	KG1	220	7,48	27,7	18,7	2,5	0,8	10,1	2,7	0,0	157,2	9,8
11	DF1	218	8,25	27,5	15,3	3,0	1,1	10,0	2,7	3,5	156,0	8,3
12	PL1	26	6,4	1,7	0,0	0,0	0,4	4,2	2,4	2,7	14,4	3,9
13	G1511	174	7,22	15,4	12,1	3,3	7,0	2,0	2,7	2,2	48,9	81,4
14	DP2	85	7,19	19,7	6,4	1,6	1,0	7,4	0,8	0,0	62,8	1,5
15	DP1	84	7,02	10,6	6,4	1,6	1,0	6,5	0,8	0,0	61,4	1,9
16	W368	83	7,20	6,4	2,2	2,1	0,9	5,0	1,4	7,1	39,2	2,5
17	W367	96	7,75	10,4	4,6	2,5	1,3	7,0	0,7	3,6	68,3	4,4
18	ZT1	414	6,68	43,3	21,2	49,0	2,5	5,4	18,8	241,0	28,8	9,2
19	ZT2	85	6,93	10,2	6,1	2,4	0,9	7,6	0,4	0,0	63,4	1,5
20	ZT3	161	7,35	19,6	12,2	5,0	1,0	13,7	1,5	0,0	108,6	12,4
21	ZT4	19	5,54	0,9	1,2	2,0	0,8	4,2	2,5	0,0	6,9	4,3
22	ZT5	70	6,80	5,2	7,8	1,2	0,7	7,8	1,9	0,0	51,1	2,1
23	PL3	166	7,90	19,9	10,9	3,8	0,7	13,6	2,2	0,0	120,5	7,1
24	PL2	57	7,35	5,8	2,4	0,5	0,9	5,5	1,3	2,7	41,0	2,6
25	W407	341	7,12	31,2	16,4	49,8	0,5	6,6	17,2	159,8	50,0	15,8
26	XW6	360	7,40	49,3	31,6	9,5	0,4	6,8	6,9	162,6	90,7	8,4
27	W302	69	6,80	7,1	1,6	7,1	0,5	5,4	11,2	2,5	30,3	8,2
28	P01	51	6,38	4,5	3,3	1,9	0,2	5,5	1,3	2,1	31,0	1,7
29	SS1	432	10,22	0,0	0,3	121,3	0,0	17,8	20,9	10,4	261,4	0,4
30	MBH1	150	7,14	16,8	13,9	1,9	0,6	3,0	0,7	6,6	106,1	0,8
31	MBH2	198	7,41	23,3	15,5	4,3	0,9	4,8	6,2	2,6	131,7	8,7
32	W312	76	7,60	8,3	5,1	1,6	0,3	4,8	1,9	0,9	51,6	1,8
33	GS1	104	7,18	11,8	7,8	1,9	0,3	5,4	1,3	2,6	69,3	3,9
34	RD1	84	6,56	8,6	6,2	1,9	0,0	4,9	1,6	2,6	50,6	7,9
35	W318	122	7,05	13,9	7,1	3,3	0,9	5,8	4,5	9,6	75,0	2,5
36	Mg2	100	6,90	5,9	3,9	13,8	0,6	6,4	15,0	9,0	15,6	36,4
37	SS55	38	4,04	3,4	1,7	3,8	1,8	5,2	2,0	8,8	0,0	16,1
38	1WB1	192	7,64	15,5	10,2	17,4	3,9	1,2	19,8	2,8	59,0	63,0
39	LT1	113	7,19	14,5	10,0	2,9	0,6	5,1	1,2	13,6	66,3	3,4
40	LVP17	737	8,84	4,8	0,2	105,0	163,0	20,2	83,6	117,2	251,5	10,6
41	1WB4C	126	8,09	15,0	7,9	1,7	0,6	6,4	0,7	3,4	93,2	1,9
42	GB16	213	8,20	17,7	5,6	28,8	1,7	2,8	2,7	5,9	149,7	0,1
43	LVP8	192	6,90	37,6	2,9	8,5	6,3	0,7	2,7	109,7	14,8	9,2
44	GB13	564	11,32	126,8	0,2	28,4	5,4	1,5	15,0	269,8	115,2	1,4
45	GB47	148	7,89	16,2	10,1	6,4	0,9	1,1	2,7	19,6	89,8	2,4
46	2WB2	1 298	7,75	194,7	94,0	39,6	1,4	8,9	26,4	817,3	89,5	34,0
47	2WB1	1 373	7,60	216,7	96,7	45,4	1,7	8,5	20,3	884,6	74,7	32,4
48	LVP1	226	6,40	49,5	5,3	6,7	5,2	0,3	4,1	124,5	19,6	11,4
49	W136	121	6,67	15,5	9,3	3,3	0,5	5,6	3,3	56,4	25,0	7,7
50	Mg3	1 022	7,98	136,9	86,0	30,3	1,6	6,4	22,6	655,6	64,9	24,0
51	G1498	1 317	6,91	251,5	52,4	54,2	5,2	4,8	18,8	903,9	30,3	0,4
52	W137	236	6,38	24,9	21,6	11,4	0,5	4,8	15,4	114,8	25,0	22,0
53	W150	99	7,50	12,1	5,3	1,4	0,7	5,7	2,7	1,6	69,0	5,8

WONDERFONTEIN RIVER

No.	Source	TDS	pH	Ca	Mg	Na	K	Si	Cl	SO_4	HCO_3	NO_3	NH_4
H	W.R.C.G.M. effluents	1 270	7,16	568,4	50,0	63,2	31,3	0,9	28,6	214,2	43,3	48,8	221,8
I	Effluents in river	2 787	6,89	612,5	100,0	61,8	6,3	0,9	106,7	1 812,0	45,4	33,7	7,7
J	Reclaimed sewage	518	6,88	50,0	13,5	60,8	13,5	3,9	50,0	178,6	138,2	3,8	5,7
K	Tributary R.E.G.M. effluents	2 482	6,95	484,2	111,1	73,7	4,7	3,7	142,9	1 625,0	34,0	1,4	0,8
L	River water	1 967	4,32	379,0	87,5	57,9	0,4	4,5	28,5	1 363,0	0,0	46,0	0,5
M	River water	1 890	5,8	410,9	51,2	75,0	2,9	1,5	34,6	1 279,1	0,0	33,2	1,5
N	River water	1 032	7,01	97,7	5,7	119,9	7,8	10,4	16,4	376,3	15,8	340,2	41,8
O	Donaldson Dam	1 758	6,32	323,0	70,0	56,0	4,3	1,9	23,0	1 250,0	0,0	29,4	0,0

KLIP RIVER

No.	Source	TDS	pH	Ca	Mg	Na	K	Si	Cl	SO_4	HCO_3	NO_3
A	Irrigation furrow in Peat	806	7,75	99,1	63,0	32,7	1,8	10,9	23,4	416,1	162,9	6,8
B	Stagnant water, excavation in Peat	853	6,63	102,9	70,9	41,0	1,1	6,3	30,5	431,0	165,9	9,3
C	River water, brown	948	4,39	192,4	35,0	29,3	4,7	3,0	26,2	634,3	1,1	24,7
D	River water	1 420	6,77	266,4	61,0	53,8	6,0	2,1	32,9	938,8	51,6	9,2
E	Average river water			285,0	59,0	50,0	2,0		22,5	840,0		

SOUTH ROODEPOORT MINE EFFLUENTS

No.	Source	TDS	pH	Ca	Mg	Na	K	Si	Cl	SO_4	HCO_3	NO_3
T	South Roodepoort G.M. Effluents	605	7,06	72,3	31,3	60,8	2,3	9,1	18,9	354,7	50,3	5,0
U	Irrigation dam	545	6,97	68,5	29,5	55,2	2,4	3,4	16,7	344,7	21,5	3,1
V	Irrigation furrow	585	6,94	71,6	31,2	60,8	2,8	8,0	18,7	347,1	39,3	5,1
W	Small irrigation dam	516	6,74	66,0	30,0	55,5	4,0	3,3	17,6	318,7	20,6	0,0
X	Farm dam	452	7,23	57,2	25,2	50,8	5,4	3,4	18,6	271,5	18,7	0,7
Y	Recharge excavation	532	7,09	66,8	30,3	59,8	3,1	6,8	18,5	321,2	22,6	3,2

reclaimed sewage were collected higher upstream and are not shown on the map, Fig. 5.13. This group includes also another set of similar waters, designated A to E from the Klip River.

Group C

Sulphate effluents originating from South Roodepoort Main Reef G.M., designated T to Y. These waters are partly consumed by irrigation.

Group D

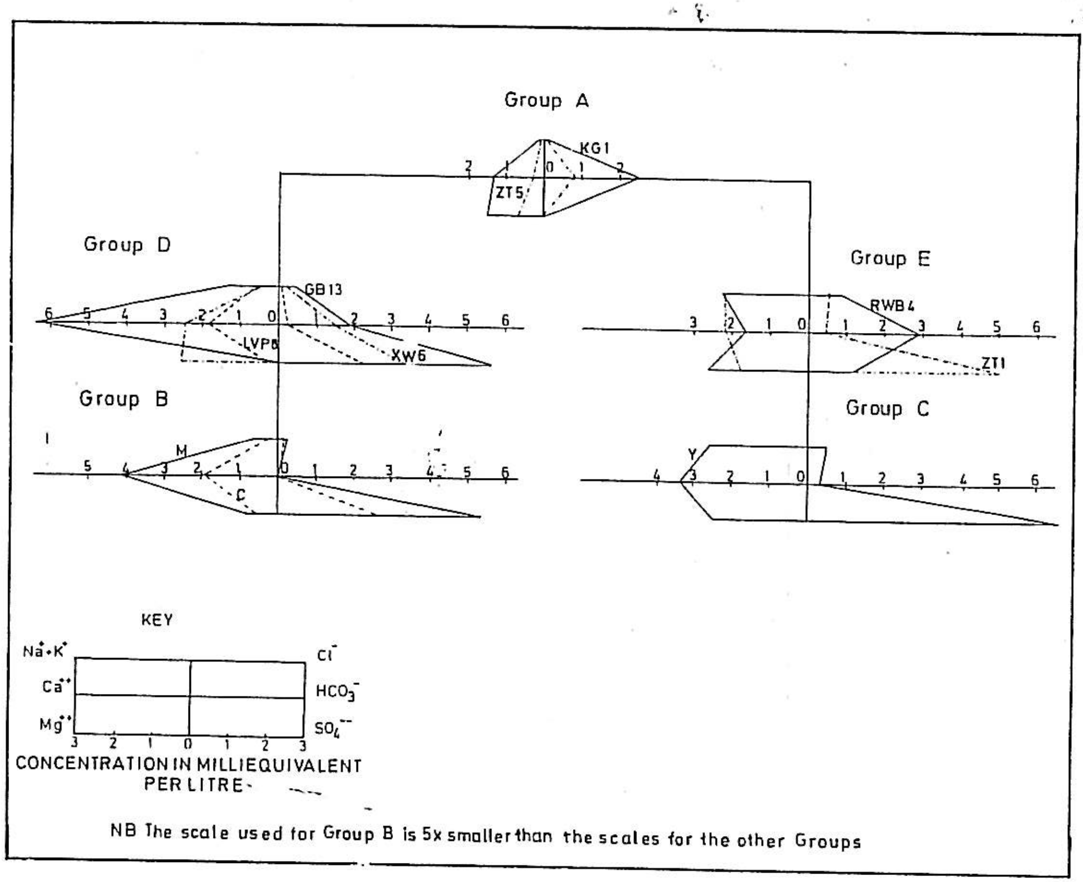
Borehole waters sampled near the Wonderfontein river and assumed to be a mixture of aquifer and effluent water. Samples from boreholes XW6, LVP8, GB13, 2WB2, 2WB1, LVP1, W136, Mg3, G1498 and W137 (No. 43, 44, 46, 47, 48, 49, 50, 51 and 52) indicate the magnitude of mixing.

Group E

Groundwater abstracted by the Rand Water Board downstream and close to where natural drainage previously took place. Relevant samples are from boreholes RWB4, RWB1 and RWB7 (No. 3, 4 and 5).

Representative samples of the above groups are demonstrated on stiff diagrams Fig. 5.14.

A cumulative enrichment in bicarbonate and alkaline - earth cations proportional to the distance from the upstream boundary of the aquifer would be expected. This can be observed when



NB The scale used for Group B is 5x smaller than the scales for the other Groups

Fig. 5.14

CHEMICAL CHARACTERISTICS OF THE VARIOUS GROUPS OF WATER AND SUGGESTED MIXING PATTERNS.

STIFF DIAGRAMS OF WATER TYPES

Group E, water pumped at Zuurbekom, is a mixture of Groups A and C. Group D is likewise a mixture of A and B.

comparing the first ten analyses in Table 5.3 with the remainder. In a simple, completely confined aquifer, this enrichment would be exclusively due to leaching of the aquifer material and would be dependant on the intensity of interaction of groundwater with the aquifer rock. Intensive interaction is a function of time. A longer reaction period is achieved either due to distance covered, or to flow restrictions encountered. In the case under study, because of the intake of recharge in patches all over the area, additional contributions of bicarbonate salinity may be expected from soil water along the groundwater flow route.

When mixing of groundwater with infiltrating effluents is considered, another chemical process is significant: By the entry of $CaSO_4$-rich solution, a common ion, Ca^{++} is introduced which affects the solubility of calcite. All samples which appear in Table 5.3 have therefore been investigated as regards solubility of calcite and gypsum and were consequently found to be undersaturated with respect to sulphate, Fig. 5.15 (After Hem, 1970).

It is concluded that the sulphate provides a reliable parameter for the quantitative evaluation of contamination. It is further observed, Fig. 5.15, as expected, that enrichment in HCO_3 can be traced to increase from the upstream intake area of the aquifer towards the discharge boundary.

Results from chemical analyses of waters from newly-drilled boreholes and supplementary data from existing boreholes, Table 5.4 confirm by and large the partial contamination of the aquifer already at the upstream reaches.

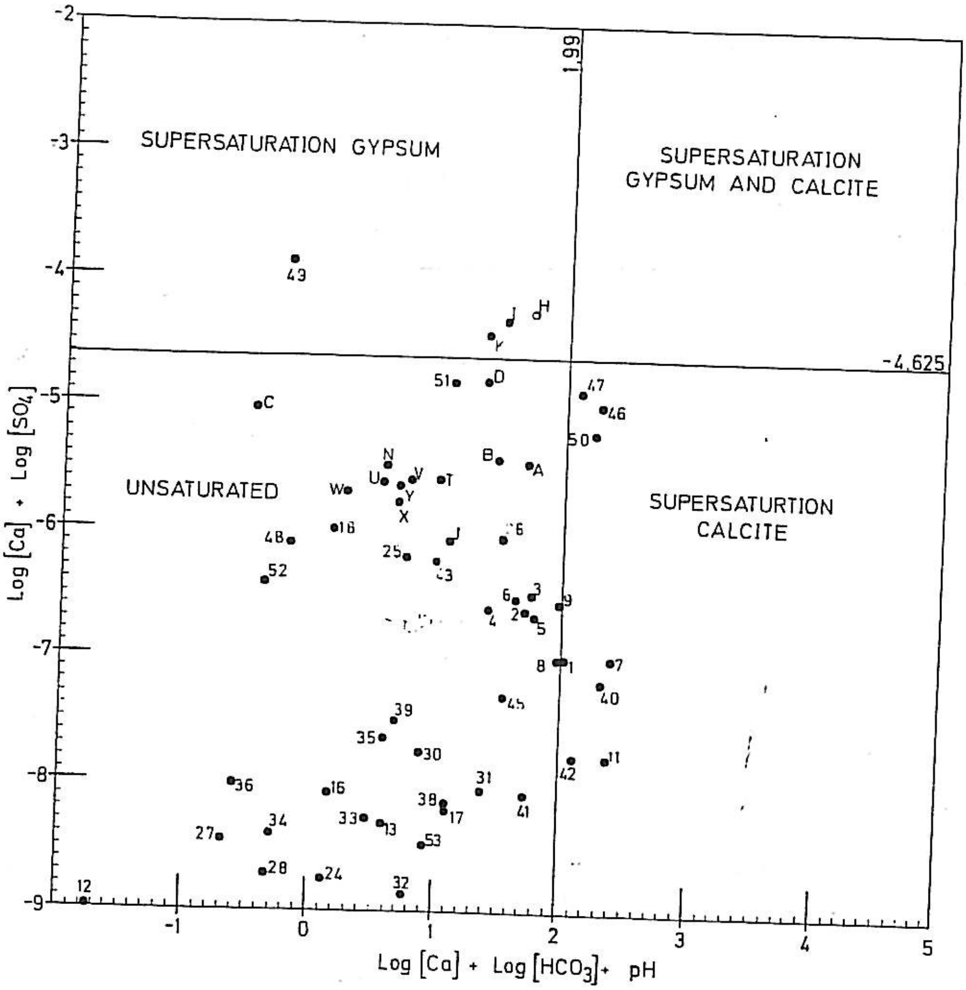


FIG. 5.15

CALCITE AND GYPSUM EQUILIBRIUM SOLUBILITY LIMITS, 25°C AND 1 ATMOSPHERE PRESSURE.

TABLE 5.4: Chemical analyses of groundwater from newly-drilled boreholes and from various other water sources in Zuurbekom Compartment collected during 1979-1980, in milligrams per litre

EXPLORATION BOREHOLES (*SAMPLE OBTAINED BY PUMPING OR AIR DRILLING)

Source	Date	TDS	pH	Ca	Mg	Na	K	Si	Cl	SO_4	HCO_3	NO_3
N46	1.8.79	582	7,35	72,6	46,8	22,3	1,2	8,9	25,1	337,3	68,1	0,0
N32*	7.8.79	174	7,58	23,6	14,1	1,6	0,8	8,1	2,1	15,5	103,8	4,4
N17A*	14.8.79	264	7,41	32,4	23,2	5,0	0,5	0,0	6,5	23,8	165,5	7,3
N31*	17.4.80	187	7,50	27,5	14,5	3,7	0,7	9,1	1,5	5,9	122,4	1,8
N29	14.1.81	175	7,10	25,2	15,0	2,4	1,1	12,0	1,5	3,8	112,5	1,2
N27*	10.3.80	510	9,40	2,0	66,9	47,2	16,3	1,5	49,0	20,1	307,3	0,0
N23	9.10.79	80	8,18	10,2	6,4	1,1	1,4	0,3	1,0	12,2	46,7	0,3
N24*	11.9.79	259	7,00	24,4	28,6	2,7	1,0	0,0	3,9	43,0	153,2	2,5
N21*	23.10.79	119	7,00	11,4	9,2	2,0	1,0	0,3	1,6	24,3	68,5	0,3
N18*	2.12.80	170	7,10	29,7	11,3	1,5	0,8	6,1	1,5	4,6	114,1	0,0
N43	29.11.79	207	7,90	19,8	21,2	7,3	1,5	2,3	7,5	11,5	135,9	0,0
N44	1.10.79	50	6,34	4,7	2,9	1,6	1,3	4,7	4,2	3,0	26,7	0,9
N45	12.9.79	14	7,83	0,7	1,1	1,6	0,5	0,0	1,3	0,0	8,2	0,8
N34	18.6.80	142	7,30	16,6	12,4	3,9	2,0	2,7	3,3	14,5	86,7	0,1
N2	9.5.80	67	5,60	5,5	4,1	2,4	1,3	4,6	2,9	9,1	30,6	6,6
N14	6.6.79	442	7,40	63,5	31,0	3,5	1,3	4,9	4,9	45,7	287,3	0,3
N39	6.6.79	294	7,99	36,9	23,6	2,9	0,7	4,2	4,0	1,1	218,9	1,2
N15	5.6.79	87	7,80	12,1	5,4	1,4	4,9	0,2	0,9	0,0	62,3	0,2
N38*	18.6.79	148	7,69	17,9	11,4	1,4	0,4	7,6	1,2	7,8	96,3	4,4
N12*	26.11.80	194	7,10	20,0	21,8	4,3	1,0	9,8	2,1	12,8	121,6	0,1
N6*	15.12.80	587	7,20	95,3	48,3	17,1	1,3	7,5	10,9	321,5	83,8	1,4
N4*	18.11.80	69	6,50	7,8	5,7	1,4	0,6	4,9	0,8	4,4	43,4	0,4

MINE WATERS ARTIFICIALLY RECHARGED THROUGH BOREHOLES

Source	Date	TDS	pH	Ca	Mg	Na	K	Si	Cl	SO_4	HCO_3	NO_3
Near 1WB1	14.11.79	977	7,44	90,3	7,7	164,6	7,9	10,1	18,5	465,5	51,1	160,8
Near sewage pan	8.5.80	1346	5,80	167,3	27,5	221,0	15,0	10,0	34,2	686,1	62,3	122,8

MINE EFFLUENTS

Source	Date	TDS	pH	Ca	Mg	Na	K	Si	Cl	SO_4	HCO_3	NO_3
To Wonderfontein R.	18.7.79	841	7,19	77,4	6,9	157,1	8,3	9,1	15,3	464,8	52,1	50,1
Irrigation supply	18.6.79	803	7,30	56,8	6,9	150,5	6,3	9,5	15,0	401,1	48,3	108,4

SEWAGE WATER

Source	Date	TDS	pH	Ca	Mg	Na	K	Si	Cl	SO_4^{--}	HCO_3	NO_3
Sewage pan	9.10.79	1606	6,21	260,4	47,5	201,7	16,9	11,9	24,6	855,6	7,9	179,3

SLIMES DAM WATER

Source	Date	TDS	pH	Ca	Mg	Na	K	Si	Cl	SO_4	HCO_3	NO_3
Pumped into dam	18.7.79	5129	3,65	473,0	159,4	127,3	13,5	131,4	165,8	4040,6	0,0	18,2
Standing in dam	18.7.79	5417	3,29	522,3	153,1	132,2	29,8	115,5	159,5	4280,4	0,0	24,5

SUPPLEMENTARY DATA FROM EXISTING BOREHOLES

Source	Date	TDS	pH	Ca	Mg	Na	K	Si	Cl	SO_4	HCO_3	NO_3
XW17	14.11.79	74	6,62	7,9	4,0	1,9	0,7	3,5	0,4	1,2	54,3	0,5
C1MD2*	14.11.79	141	7,20	17,1	8,9	1,9	0,5	6,2	1,1	0,6	98,0	6,6
1WB1*	14.11.79	189	6,85	20,6	10,1	12,0	1,4	6,4	2,6	44,9	71,4	20,0
LVP23*	27.6.79	175	7,16	21,8	12,2	4,7	0,4	6,6	3,8	40,3	80,2	5,3
2WB4*	11.12.79	1383	7,30	231,6	92,0	44,5	3,2	9,5	26,7	906,7	60,1	9,0
PV2	6.6.79	248	7,53	29,8	18,9	6,9	0,1	2,8	1,3	0,0	188,1	0,0

KLIP RIVER EYE

Source	Date	TDS	pH	Ca	Mg	Na	K	Si	Cl	SO_4	HCO_3	NO_3
Point of issue	10.7.79	392	7,44	51,1	32,4	7,9	1,9	6,5	6,7	85,9	196,9	2,2
Point of issue	7.8.79	391	7,49	58,2	29,1	6,0	0,5	5,8	4,9	77,3	208,2	0,9
Downstream	7.8.79	400	7,60	54,5	30,4	9,4	1,5	4,6	7,9	87,9	203,2	0,6
Point of issue	29.10.79	406	7,76	56,4	26,2	7,5	0,4	7,0	5,3	79,2	222,7	1,6
Point of issue	22.5.80	388	7,30	55,1	32,3	6,6	0,6	7,7	6,7	97,9	180,7	0,2

KLIP RIVER WATER

Source	Date	TDS	pH	Ca	Mg	Na	K	Si	Cl	SO_4	HCO_3	NO_3
Johannesburg Road	10.7.79	1649	7,86	317,2	73,7	57,5	11,3	2,3	50,5	1041,9	82,1	12,0
Johannesburg Road	22.5.80	1476	6,90	295,4	65,6	59,5	4,7	5,1	34,8	957,9	51,6	1,8
Downstream mixed	22.5.80	1436	7,00	284,0	64,9	59,5	5,1	3,9	34,2	925,7	56,7	1,5

Borehole N46 drilled east of Zuurbekom Compartment's boundary, indicates conatamination of the Klip River Compartment by river effluents, this is supported by water analyses of private boreholes in Lenasia along the Klip River (Report Gh3158, Fleisher, 1981).

It is noteworthy that water recharged artificially by Cooke Section Mine is also considerably mineralised as can be seen in Table 5.4, and the same applies to effluents diverted by this mine to the Wonderfontein River.

A sewage pan located in a topographic depression on the boundary between sectors B and C, Figs. 5.1, 5.4 and 5.5, occupied an area of approximately $10^5 m^2$. The composition of the water has also been presented in Table 5.4. Presently purified sewage is allowed to flow into the Wonderfontein River and this site has been abandoned as far as sewage water is concerned.

Slimes dams were constructed at the northern edge of Cooke Section lease area. These dams have been in operation since 1978. Analyses of water samples appear in Table 5.4 and give an idea of the order of salinity involved in slimes dams, to be discussed at a later stage.

5.7 Hydrologic assessments

In Fig. 5.2 a continuous increase in SO_4 and TDS at Zuurbekom Pumping Station since 1956 can be observed. Moreover the concentration of the contaminant seems to increase exponentially as can be noticed in Fig. 5.16. This phenomenon cannot be correlated in a simple way with exploitation through pumpage.

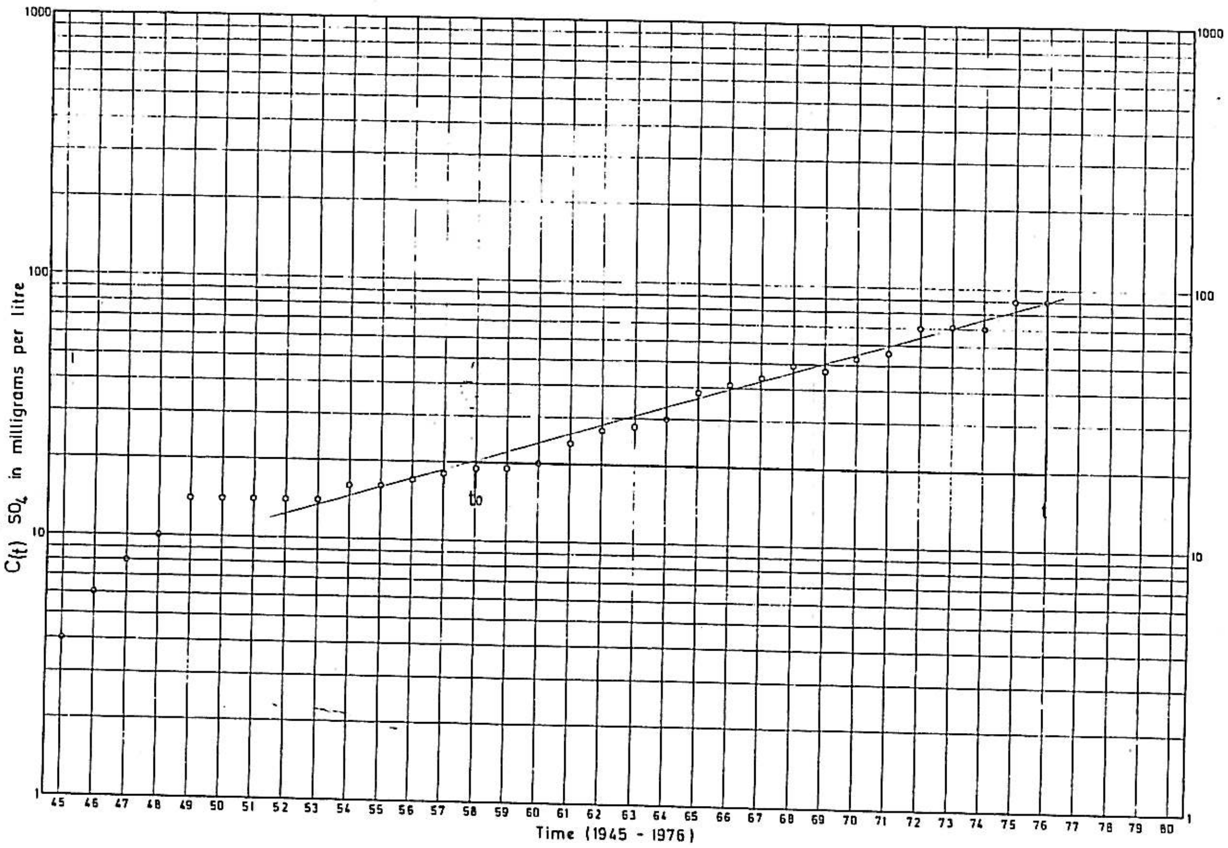


FIG. 5.16

Exponential increase with time of measured sulphate salinity plotted on semi-logarithmic paper provides a means of forecast and storage calculation

Two upstream sources of contamination have to be considered: The contamination of the aquifer in the eastern part of the studied compartment, namely in sector B (Figs. 5.13 and 5.14) has been identified and the mixed water designated as group D (see section 5.6). This contamination is due to effluents in the Wonderfontein River. It is restricted to a small area where groundwater is of the influent type. It is also maintained that this contamination is a rather recent development, caused by intensive localised pumpage by Cooke Section Mine, and could therefore not account for the observed long-term process. The second source consists of effluents from South Roodepoort G.M. which are being spread on the surface in the upstream area and utilised for irrigation. As stated before, the current estimated amount of effluents from this source is $0{,}66 \times 10^6 m^3$/year with a sulphate content of 320 mg/l.

It is further assumed that the latest pumping figures from this mine may also be considered the highest. The total annual sulphate salinity expected from this source is thus $0{,}66 \times 10^9 \times 320$ mg/l $= 211 \times 10^9$ mg as compared to the minimum annual discharge of sulphate at the outlet $10 \times 10^9 \times 80$ mg/l $= 800 \times 10^9$ mg. In other words, salinity derived from this source could only account for part of the salinity observed at the discharge point. An additional source of contamination is therefore sought further downstream.

Bearing in mind however that the previously discussed source of salinity injection has been operating constantly for many years, one could expect equilibrium conditions to have been reached by now in the aquifer. These conditions are reflected in Fig. 5.16

during the period 1949-1953 when sulphate salinity stabilised at 15 mg/l. Water pumped at Zuurbekom station, most probably presents the best available homogenous mixture of aquifer water with South Roodepoort contaminants, due to the position of the pumping field at the downstream end of the groundwater flow, and before a second contamination mixture takes place. The figure of 0,66 x $10^6 m^3$/year refers to rather recent pumping quantities at South Roodepoort Mine, it is reasonable to assume that previously somewhat smaller amounts of 0,5 x $10^6 m^3$/year had been abstracted at this mine. The above-mentioned stabilised salinity observed enables an approximate estimation of the annual natural recharge as follows:

$$320 \text{ mg/l} \times 0{,}5 \times 10^9 \text{ l} = 1{,}5 \text{ mg/l} \times X \times 10^9 \text{ l}$$

$$X = \frac{320 \text{ mg/l} \times 0{,}5}{15 \text{ mg/l}} = 10{,}7 \times 10^6 m^3\text{/year}$$

In considering a suitable model to explain the additional salinity observed at the discharge point it is noted firstly that no lowering of groundwater table has been noticed during a considerable period, and secondly that salinity development appears to follow an exponential trend. Annual sulphate values were plotted on semi-logarithmic paper, Fig. 5.16, and a straight line can be fitted.

Water flowing in the Klip River has consisted of various effluents since the early fifties. It is tentatively assumed that the salinities and quantities involved increased exponentially, although no details are available to support this assumption. It is suggested that most of the salinity at the discharge point, of the order of 600×10^9 mg sulphate per year, must come from the Klip River, and is caused as a result of concentrated pumping.

Two potential source zones where raw effluents infiltrated into the dolomites may be considered, one along the Klip River bed, upstream of station C2M39, still in the studied compartment, and the other the Klip River Dolomitic Compartment which extends to the east of the studied compartment. In both cases it would be expected that the raw surface effluents of 850 mg/l sulphate be diluted with aquifer water, the second alternative however, would mean inflow of groundwater via the diabase boundary dyke.

The water sample obtained from borehole N46 (Table 5.4), and a series of additional groundwater samples collected in Klip River Compartment and mentioned before, prove beyond doubt that this unit is already contaminated, at least in the vicinity of the river. Yet the overflow from Zuurbekom Compartment at the Eye seems to exclude the possibility of a contaminated groundwater flow from Klip River Compartment to the pumping station.

Although no unequivocal clue may be drawn from the few available groundwater analyses collected upstream of C2M39, it seems most likely that this is the source zone of salinity to the system.

It should be kept in mind that the salinity of the effluent generated at South Roodepoort G.M. has not been observed regularly for a long period, as would be required to arrive at average figures. If, for instance, it is found that the sulphate salinity amounts to 400 mg/l, as encountered in various

effluents from different gold mines, then the calculation of the natural replenishment has to be adjusted accordingly:

$$400 \text{ mg/l} \times 0{,}5 \times 10^9 \text{ l} = 15 \text{ mg/l} \times X \times 10^9 \text{ l} \quad x = \frac{400 \times 0{,}5}{15} = 13{,}3 \times 10^6 \text{ m}^3\text{/year.}$$

The percentage of percolated annual natural recharge out of total annual rainfall may also be calculated as follows: The average annual rainfall for a period of 10 years, 1969/70 - 1978/79, at rainfall Station 475/528 amounts to 690 mm. The area involved extends over 92,25 km^2, and includes sectors C, E and part of B which under natural conditions would drain to the Klip River Eye. The natural underground flow regime has lately been affected locally through pumpage by Cooke SEction Mine. These changes were ignored because the balance reflects an average over many years. The total rain volume is thus $0{,}69 \text{ m} \times 92 \text{ km}^2 = 63{,}5 \times 10^6 \text{m}^3$. The annual recharge = $10{,}7 \times 10^6 \text{m}^3$ or $13{,}2 \times 10^6 \text{m}^3$. The percolation percentage will therefore be in the range of

$$\frac{10{,}7 \times 100}{63{,}5} = 16{,}8\% \text{ to } \frac{13{,}2 \times 100}{63{,}5} = 20{,}8\%.$$

These are somewhat high figures compared to 12,8% calculated for the nearby Gemsbokfontein Compartment. Taking into account that not all the annual recharge at Zuurbekom comes from rainfall, it is concluded that the difference 16,8% - 12,8% = 4% is due mostly to inflow from the Klip River. Quantitatively this contribution

will amount to $\frac{10{,}7 \times 10^6 \text{m}^3 \times 4}{16{,}8} = 2{,}5 \times 10^6 \text{m}^3\text{/year.}$

Based on the aforegoing it is further possible to calculate the order of magnitude of groundwater which flows out into the adjacent Venterspost Compartment. The area involved, sectors A, D and part of B, (Figs. 5.4 and 5.5), covers 37,75 km^2 and by applying a recharge coefficient of 13%, the outflow will be

$$\frac{37,75 \times 10^6 m^2 \times 0,69 \text{ m} \times 13}{100} = 3,39 \times 10^6 m^3/\text{year}.$$

For the purpose of storage calculation a model is suggested which is analogous to the one described for the Turffontein area, (Part 9), modified to account for the exponential salinity development observed in Zuurbekom.

Supposing that inflow to the aquifer equals outflow, then from equation (2) of the model, (section 9.9), one derives

$$\frac{VdC}{dt} = C_I Q - CQ$$

where V denotes the storage of the aquifer, C the concentration of contaminant in the aquifer as measured at the outflow, C_I the concentration of the contaminant in the inflow to the aquifer, Q the inflow and outflow and t time. This equation describes the conservation of mass of contaminant in the aquifer. Thus, if (from Fig. 5.16) the concentration of the contaminant increases exponentially, i.e.

$$C(t) = a \exp (bt)$$

For some parameters a and b one derives

$$C_I(t) = \frac{a(Q + Vb)}{Q} \exp (bt) = \frac{Q + Vb}{Q} C(t)$$

Thus if $C(t)$ is of exponential form then $C_I(t)$ is of exponential form with some constant b.

Plotting C_I versus t on semilog paper in the same manner as the outflow concentration should then also yield a straight line with the same slope. Furthermore, if the source contaminant C_I is known at some time t, since a and b are known from Fig. 5.16, one can then calculate the storage V by

$$V = \frac{Q}{b} \quad \frac{C_I(t)}{a} \quad \exp(-bt) - 1 \quad = \frac{Q}{b} \quad \frac{C_I(t)}{C(t)} - 1$$

Klip River infiltrated water, of the order of 2,5 x $10^6 m^3$/year, contributes most of the salinity into the system. In the earlier days when no contamination in the Klip River took place, most of this amount was taken annually into Zuurbekom aquifer as fresh water. This is based on the assumption that since then, and due to the discharge of effluents into this water course, sulphate salinity and the magnitude of the percolated water have increased. The intake salinity is thus regulated by a combination of fresh water and raw effluents.

To estimate the salinity C_I, data concerning average salinity in boreholes located close to the influent section of the river is required. Unfortunately no such data is available. Some idea about the expected concentrations in boreholes can be deduced from analogeous conditions in Sector B. Although this information is insufficient for reliable calculations, it may nevertheless serve to present the method.

$$V = \frac{Q}{b} \quad \frac{C_I(t)}{C(t)} - 1 \quad ; \text{ b is found from Fig. 5.16}$$

$$\log 90 - \log 20 = 0{,}6532; \quad b' = \frac{0{,}6532}{18} = 0{,}036$$

$$b = \frac{b'}{\log_{10} e} = \frac{0{,}036}{0{,}434} = 0{,}0829$$

Assume an average salinity in boreholes near the river = 400 mg/l and the corresponding C(t) = 86 mg/l

$$C_I(t) = \frac{10{,}7 x 10^9 l x 15 mg + 2{,}5 x 10^9 l x 400}{10{,}7 x 10^9 l} = \frac{160+1000}{10{,}7} = \frac{1160}{10{,}7} = 109 \text{ mg/l}$$

$$V = \frac{10{,}7}{0{,}0829} \quad \frac{109}{86} - 1 = 129 \; [1{,}26 - 1] = 129 x 0{,}26 = 33{,}6 x 10^6 m^3.$$

This storage refers to part of the aquifer only where complete chemical mixture is a prerequisite as delineated on Fig. 5.13. In the case under discussion the surface area of this portion is approximately 19 km^2. The saturated thickness of the aquifer is 60 m. The storage coefficient S, can thus also be calculated:

$$S = \frac{34 \text{ x } 10^6 m^3 \text{ x } 100}{19 \text{ x } 10^6 m^3 \text{ x } 60 \text{ m}} = \frac{34 \text{ x } 100}{1140} = 3\%$$

5.8 Results from pumping tests

Table 5.5 sums up the results of the various pumping tests in Zuurbekom Compartment. Six sites were selected for the performance of interference tests, N4, N6, N12, N38, N21 and N32 (Figs. 5.1 and 5.12) and for this purpose the drilling of observation boreholes at these sites was undertaken. The observation boreholes were located at distances of 20 - 60 m from the pumping borehole and within the residual gravity anomaly.

TABLE 5.5: Aquifer constants obtained from pumping tests T in m^2/day and S dimensionless

Method	Theis	Jacob	Res. recovery	Recovery	Remarks
N4B	T 378	407	416	-	Pumping borehole
	S -	-	-	-	Q max=92 Q test=89
N4A	T 425	450	365	-	Observation
	S $5,7x10^{-4}$	$5x10^{-4}$		-	r = 62,35 m
N4	T 315	391	365	-	Observation
	S $4,9x10^{-3}$	$3,4x10^{-3}$	-	-	r = 29,87 m
N12B	T 20,6	21,9	20,3	-	Pumping borehole
	S -	-	-	-	Q max=59 Q test=54
N12A	T 515	608	465	-	Observation
	S $1,7x10^{-3}$	$1,3x10^{-3}$	-	-	r = 65,81 m
N12	T 313	465	377	-	Observation
	S $8,5x10^{-3}$	$6,5x10^{-3}$	-	-	r = 50,56 m
N6B	T -	-	29 166	27 898	Pumping borehole
					Q max=193 Q test=146
N6	T -	-	-	20 051	Observation
					r = 21,20 m
N6C	T -	-	-	29 166	Observation
					r = 43,74 m

Method		Theis	Jacob	Res. recovery	Recovery	Remarks
N32	T	-	328	444	-	Pumping borehole
	S	-	-	-	-	Q max=108,1 Q test=97
N32A	T	-	5 015	4 634	5 329	Observation
	S	-	$7,5\text{x}10^{-3}$		$1,8\text{x}10^{-2}$	r = 29,78 m
N32B	T	-	4 263	4 394	5 603	Observation
	S	-	$1,2\text{x}10^{-2}$		$1\text{x}10^{-2}$	r = 56,88 m
N29	T	-	261	267	256	Pumping borehole Q max=92,1 Q test=74,7
N31	T	-	-	773	810	Pumping borehole Q max=81,1 Q test=49,2

Q max = The highest yield during step drawdown test.

Q test = Constant yield during interference test.

Q in m^3/hour.

At two sites, N6 and N21, phreatic conditions prevail. In the case of N6 no confining strata were encountered while at N21 the impervious layers are above the groundwater level. At site N32 phreatic conditions develop as a result of pumpage when the dynamic water level falls below a shallow upper argillaceous layer. At all other sites the aquifer is confined.

The transmissivities obtained at the sites where the aquifer is confined are rather low, several hundred m^2/day, this could however be expected since only certain parts along a vertical section of the saturated aquifer are in fact water conducting.

It is worth mentioning that in tests from sites N4 and N12 after a long enough period of time, a near steady state has been reached which can as well indicate characteristic semi-confined conditions of a leaky aquifer. Knowing the local geologic set-up, it is very difficult to assume vertical leakage at these sites and one is inclined to explain the observed phenomena as due to transition of the aquifer into the phreatic type within a comparatively short distance from the pumping site.

The transmissivities observed at sites N6 and N32 are definitely much higher as can be seen in Table 5.5. An exception is noticed in the case of N32 where the apparently low transmissivity may be linked with partial penetration of this borehole into the aquifer.

The storage coefficient varies considerably, at the more confined sites it is of the order of $10^{-3} - 10^{-4}$ while when the aquifer becomes phreatic it is of the order of 10^{-2}.

Measurements obtained from boreholes at the same site could not be combined for interpretation purposes, and results from each borehole had to be dealt with separately. This variation observed at each site also points to the anisotropic character of the investigated aquifer.

The main problem encountered with the performance of the present set of pumping tests was a technical one i.e the discharge at the pumping boreholes was too small and insufficient to cause big enough drawdowns. This is the reason that no results are available from site N21. Another example: At borehole 6B, while developing, air lift pumping at a rate of 193 m^3/h affected the water table in a nearby observation hole by only 26 cm.

At a number of sites step drawdown pumping tests have also been done and it appears from a few tests that borehole construction is unsatisfactory, a subject which will be discussed elsewhere.

5.9 Conclusions

The Zuurbekom Compartment displays a rather intricate set-up due to the internal subdivision into smaller units on the one hand, and the percolation of recharge water through the river bed on the other. This is further complicated by human activities such as pumpage and contamination.

It appears from this study that a serious management problem is to be dealt with. The present groundwater abstraction exceeds the estimates of natural replenishment. The Rand Water Board is pumping 10,5 x $10^6 m^3$ per annum while Cooke Section of Randfontein Estates G.M. is pumping an additional annual amount of 7,6 x $10^6 m^3$, hence a total of around 18 x $10^6 m^3$/year.

The interference with natural conditions however enables an in-depth study and the utilisation of contamination processes for hydrologic assessments. The amount of natural recharge found is 10,7 x $10^6 m^3$/year.

A wide range of variations in transmissivity has been observed which points to the heterogenic and anisotropic character of the studied aquifer. Low lateral transmissivity could also account for the unique discharge mechanism of the aquifer as observed in the study of springs (Part 10). As will be described later, the annual discharge in cases of exceptionally high rainfall seasons from a closed system of the aquifer as monitored at a spring, consists of only a part of the annual replenishment, the balance affects the annual discharge for several years after the intake.

Storativity coefficients obtained from the pumping tests also show a wide range, even of the order of magnitude, reflecting local conditions. Storativity coefficient of 3% arrived at through the chemical mass balance is somewhat less reliable because of the many assumptions which had to be made, yet the areal sector where this balance was made is highly developed due to the natural groundwater flow regime, and is therefore most probably highly porous.

As for prospection methods it has been proved that residual gravity could indicate favourable drilling sites in the sense of striking groundwater below the regional water level, but falls short of predicting successful production boreholes. The electrical resistivity method compared with the drilling results reveals a fairly accurate prediction as far as the weathered zone is concerned, but it is not applicable in discriminating between a fissured, jointed zone on top of the solid dolomite and the dense rock below. This zone often contributes considerably to the intake and forms an integral part of the aquifer.

A monitoring system has been established which enables a long-term study of Zuurbekom Compartment as a geohydrologic model. When more data is available, results concerning aquifer constants may be revised and refined and natural recharge rates calculated by means of volumetric book-keeping methods.

The application of the suggested mass balance model requires continuous and simultaneous data regarding $C(t)$ and C_I. It is hoped that additional boreholes near the Klip River bed could supply the necessary data despite the heterogenic properties of the aquifer. The boundaries of the area involved in the storage balance should also be more accurately outlined. This too may be achieved by drilling more boreholes.

6. INVESTIGATION OF GEMSBOKFONTEIN COMPARTMENT

6.1 General setting

The main dolomite outcrops cover an area of 84 km^2. Farther south some additional 16 km^2 of dolomite inliers occur as faulted outcrops surrounded by relatively impervious Pretoria Group beds. At least part of these inliers are geohydrologically connected with the main aquifer body. The total surface area of proven aquifer is 90 km^2. The compartment is delineated by rather impermeable boundary dykes (Folder 6.1). To the south confining strata of Pretoria Group overlie the dolomite. The aquifer rests on a highly irregular upper surface of the dolomite bedrock. Relics of Ecca sediments, in depressions, escaped later erosion and occur as detached remnant outliers. All rock formations are concealed under soil cover of varying thickness.

Ground surface slopes gently northwestwards, to the Wonderfontein River and northeasterly to the Klip River, separated by a surface water divide. The Wonderfontein River runs through the northern corner of the compartment. Donaldson Dam, on the same river, is located on both sides of the dyke boundary. In the southern part of the compartment, Western Areas and Elsburg Gold Mines have areas under lease.

Before large scale artificial groundwater abstraction commenced, a water table contour map, derived from a few measuring points, showed a low gradient towards Gemsbokfontein Eye (Folder 6.1). The annual discharge at the Eye used to be 3 x $10^6 m^3$. This figure is however based on rather limited records. The Eye dried up in 1972 due to the lowering of the groundwater level. In mid-1975 it started flowing again. Groundwater conditions in the compartment have changed significantly during the last eight years or so, due mainly to intensive mining activity there. Geohydrological observations have been made over the last years but no evaluations have been undertaken. Priority was given to engineering geology, i.e. problems related to sinkhole formation and land subsidence.

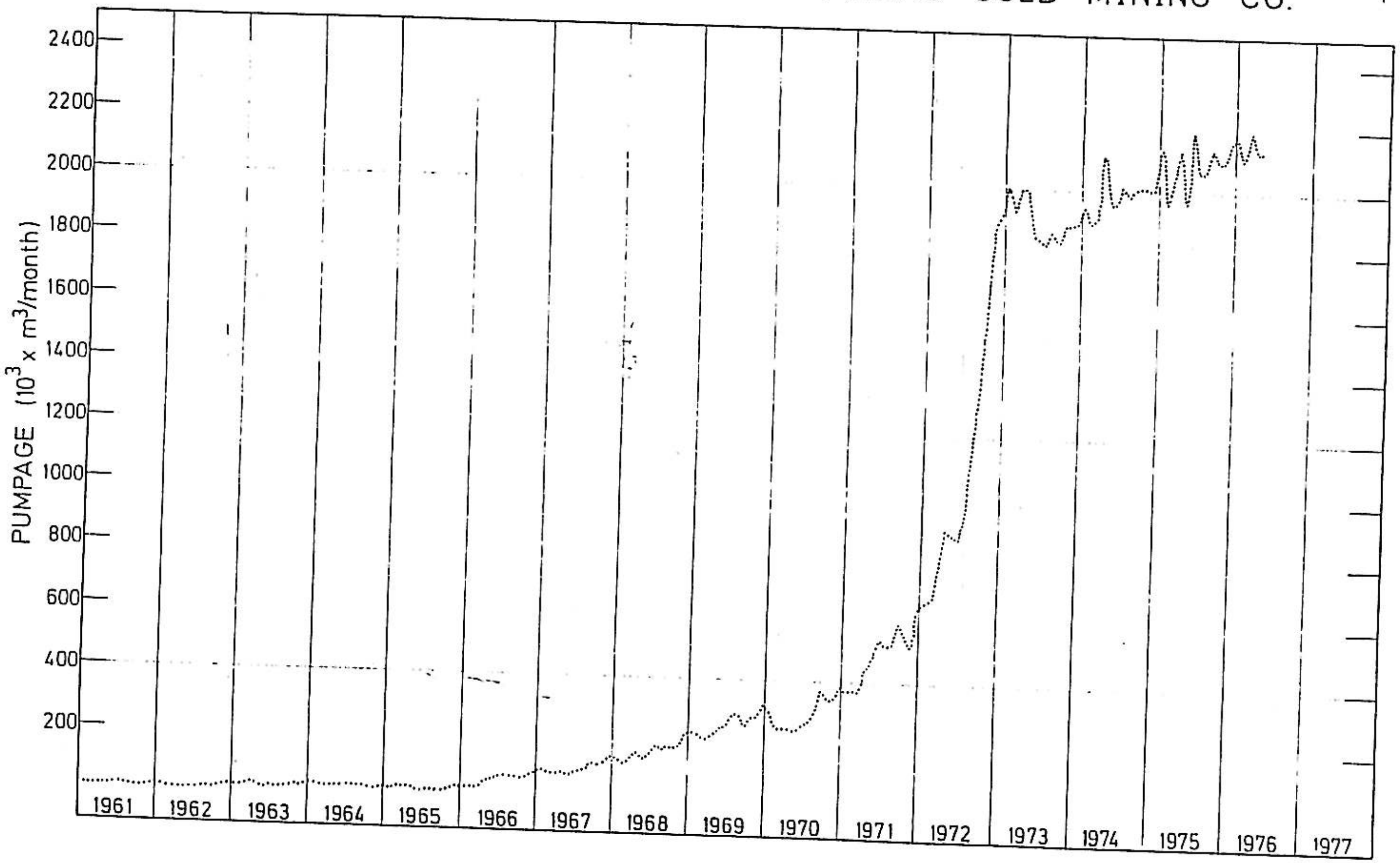
6.2 Previous work

Geohydrological aspects of the combined Gemsbokfontein and Zuurbekom Compartments were described by Enslin and Kriel (1959). A figure of 7,9% of the average annual rainfall was found to percolate into the underground water. This assessment was derived from a water balance based on gauged and estimated surface water flows, compared with discharges at the eyes and pumped amounts of Zuurbekom Pumping Station.

6.3 Recent geohydrologic conditions

Up to 1966 groundwater abstraction by the mines was around 40 x $10^3 m^3$ per month and increased to 200 x $10^3 m^3$ at the end of 1968. During 1969-1970 the pumped amounts fluctuated between 200 and 380 x $10^3 m^3$/month. At the beginning of 1971 the amount increased drastically as a result of an inflow to Western Areas underground mine works, as can be seen in Fig. 6.1. Within a period of 26 months, 1/1971 to 2/1973, an accumulated amount of 24,320 x $10^6 m^3$, was pumped from the compartment, and a negative balance developed. The results of this deficiency were two-fold: A considerable lowering of the water table over the whole compartment, in some places by up to 7 m (Figs. 6.2 - 6.26) and the development of sinkholes and subsidences in areas which previously had a shallow water table.

The danger of collapse of the highway and railway line from Johannesburg to Potchefstroom, crossing the compartment called for urgent measures. The policy adopted was to recirculate the pumped water back into the aquifer through recharging boreholes. At first water was also pumped from Venterspost Compartment and from Donaldson Dam to Gemsbokfontein Compartment, to overcome the deficit. The surroundings of the Eye were used as spreading grounds for artificial recharge. Later, recirculation coupled with natural recharge succeeded in raising the water table to "normal" levels.



MONTHLY PUMPAGE AT WESTERN AREAS GOLD MINING CO.

Reproduced from Ground Stability report by Western Areas G. M. Co.

FIGURE- 6.1

MONTHLY HYDROGRAPHS OF GROUNDWATER LEVELS IN BOREHOLES, GEMSBOKFONTEIN COMPARTMENT. CONTINUED TO PAGE 84

FIGURE 6.2

G 1163

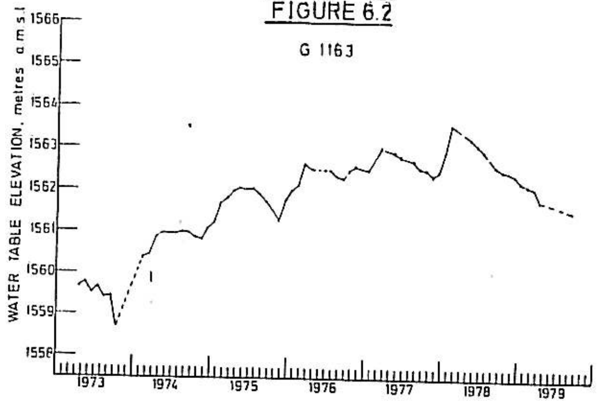


FIGURE 6.3

G 1169

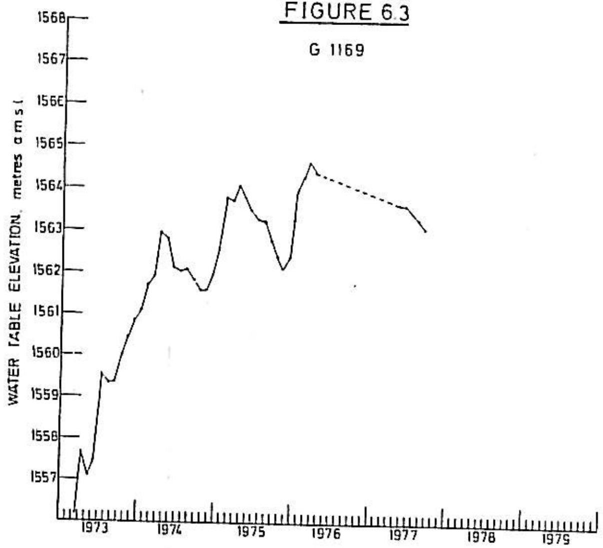


FIGURE 6.4

G 1137

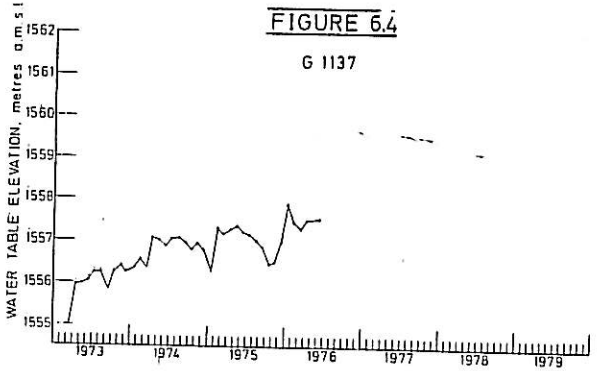


FIGURE 6.5

G 1128

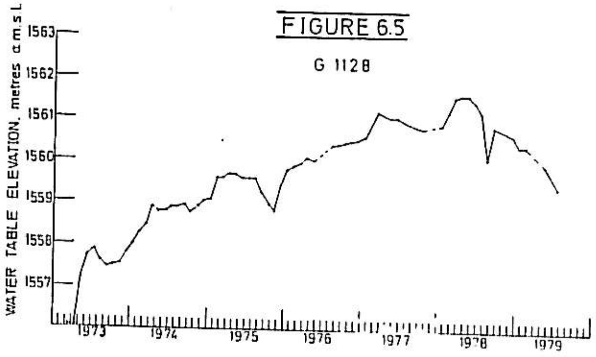


FIGURE 6.6

GM 5

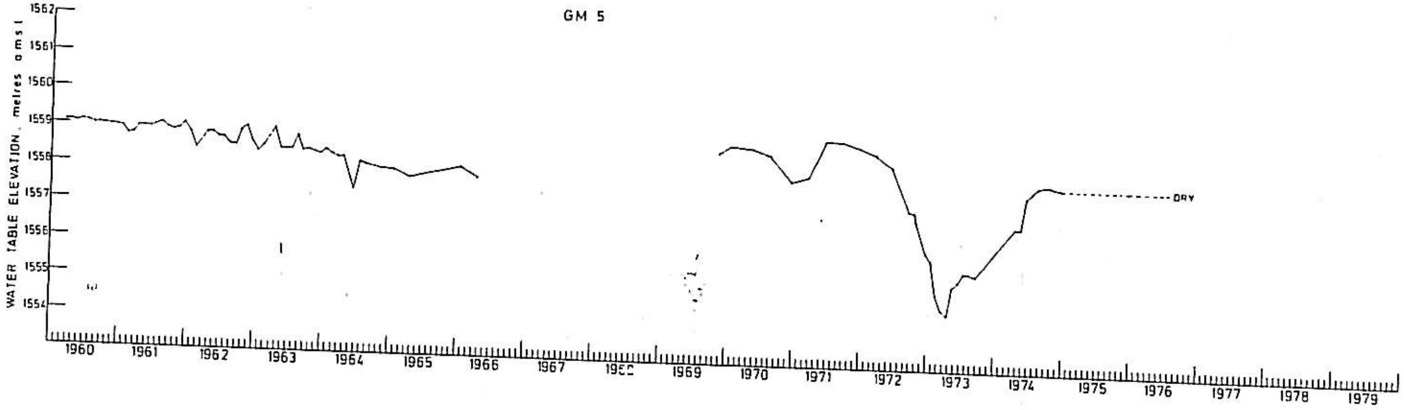


FIGURE 6.7

G 1140

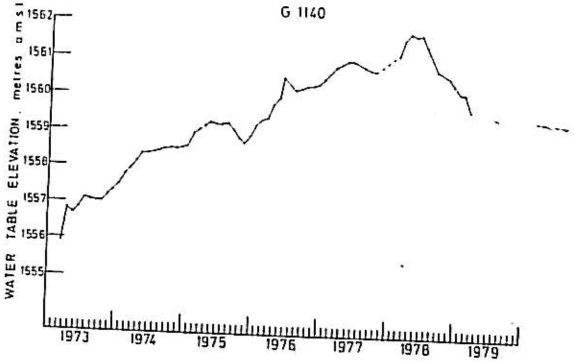


FIGURE 6.8

GB 1

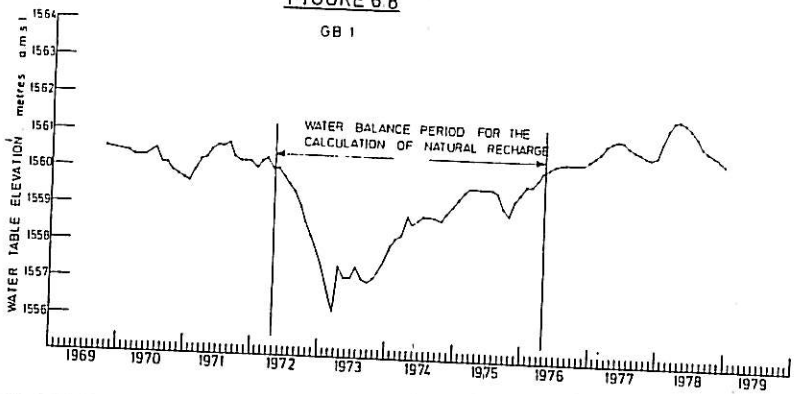


FIGURE 6.9

G 1133

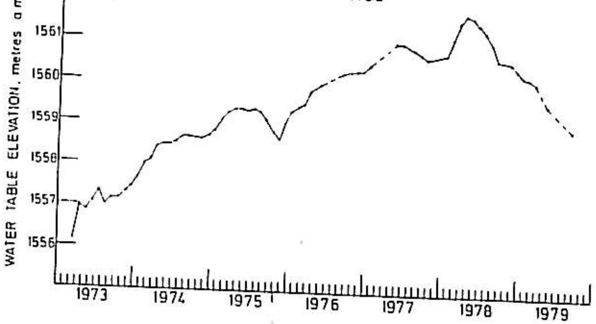


FIGURE 6.10

G 1111

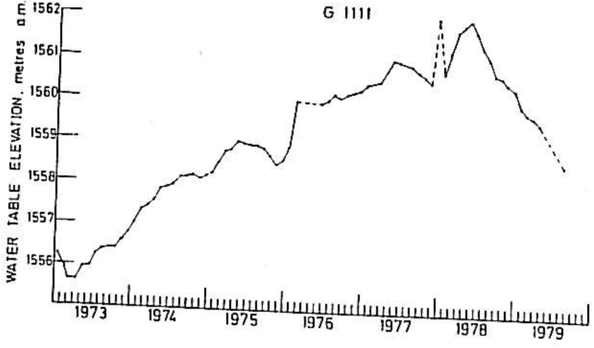


FIGURE 6.11

G 1112

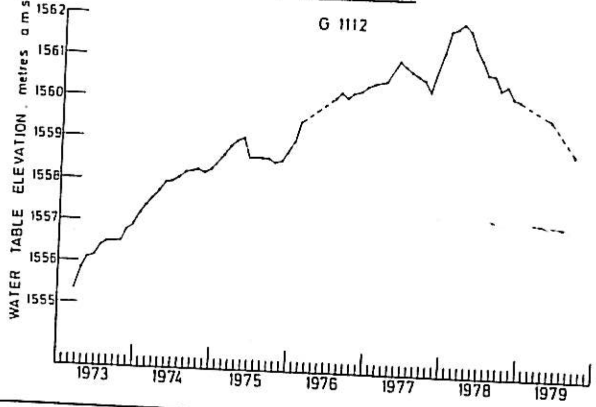


FIGURE 6.12

G 1107

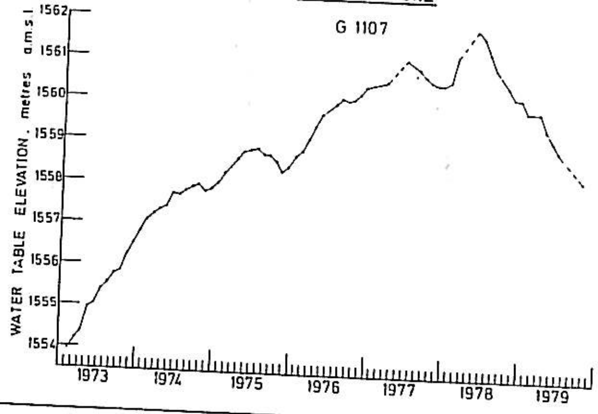


FIGURE-6.13

PV 37

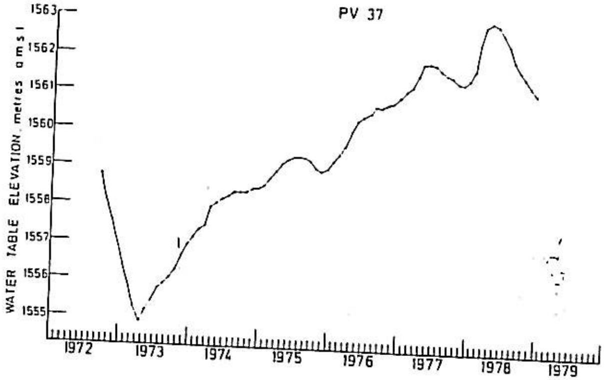


FIGURE-6.14

G 1110

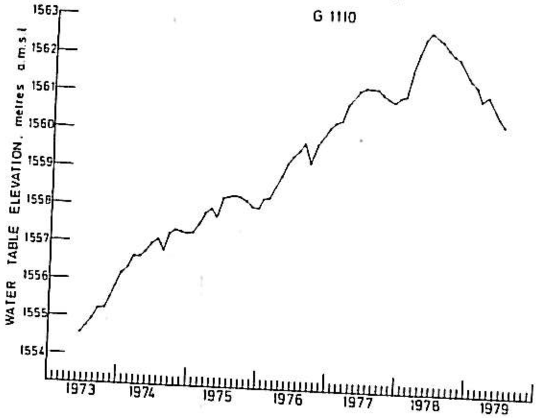


FIGURE-6.15

PV 13

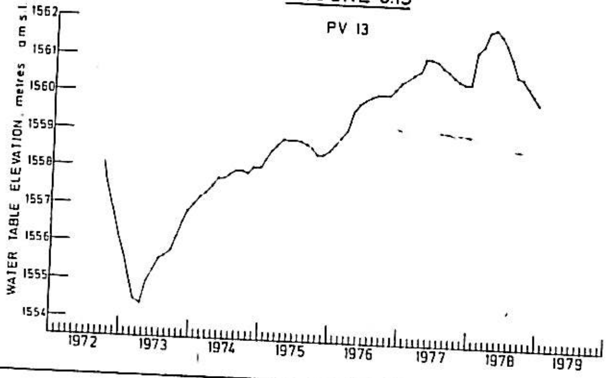
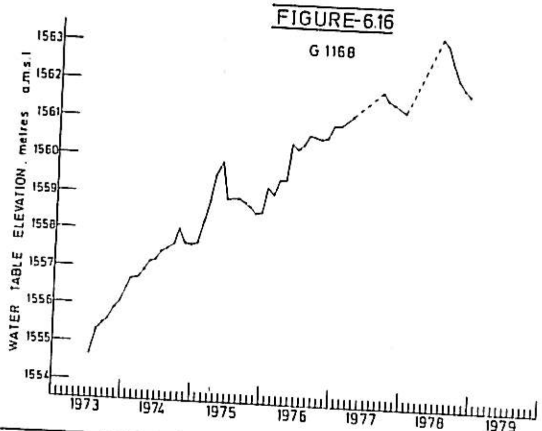


FIGURE-6.16

G 1168



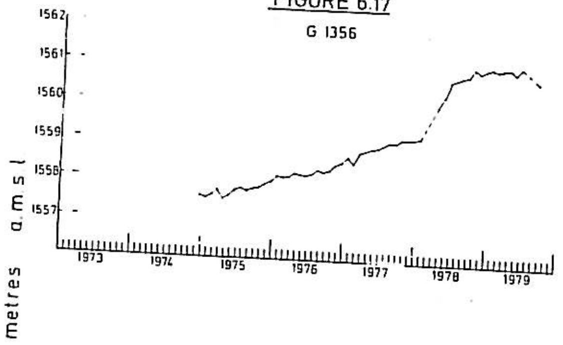


FIGURE 6.17

G 1356

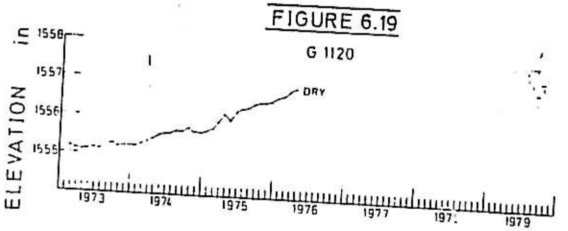


FIGURE 6.19

G 1120

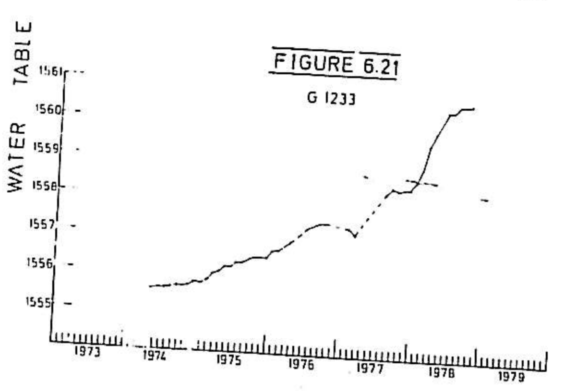


FIGURE 6.21

G 1233

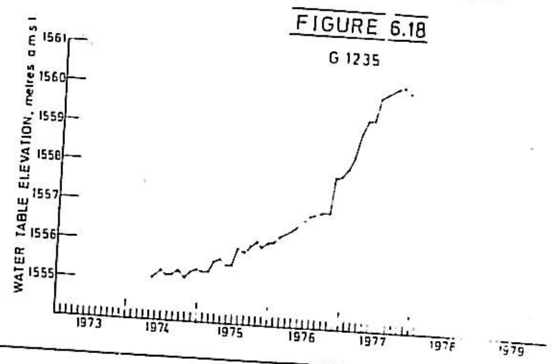


FIGURE 6.18

G 1235

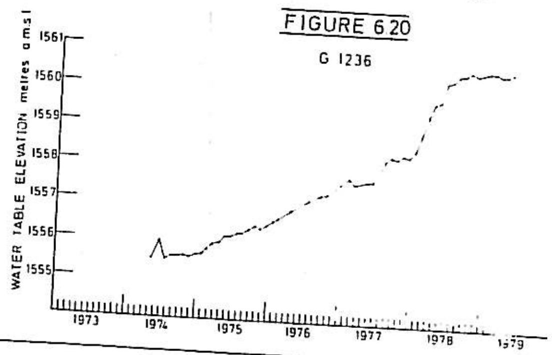


FIGURE 6.20

G 1236

FIGURE 6.22

MD 12

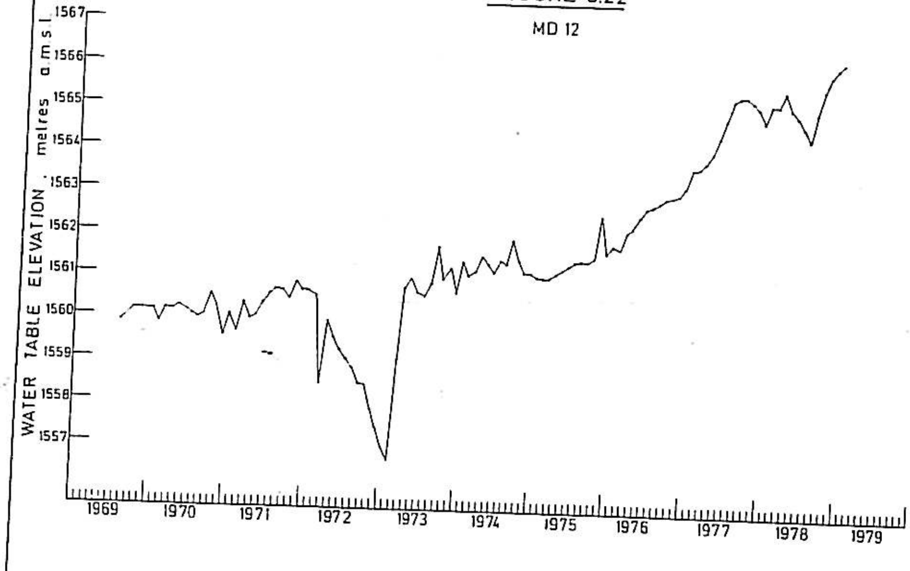


FIGURE 6.23

MD 34

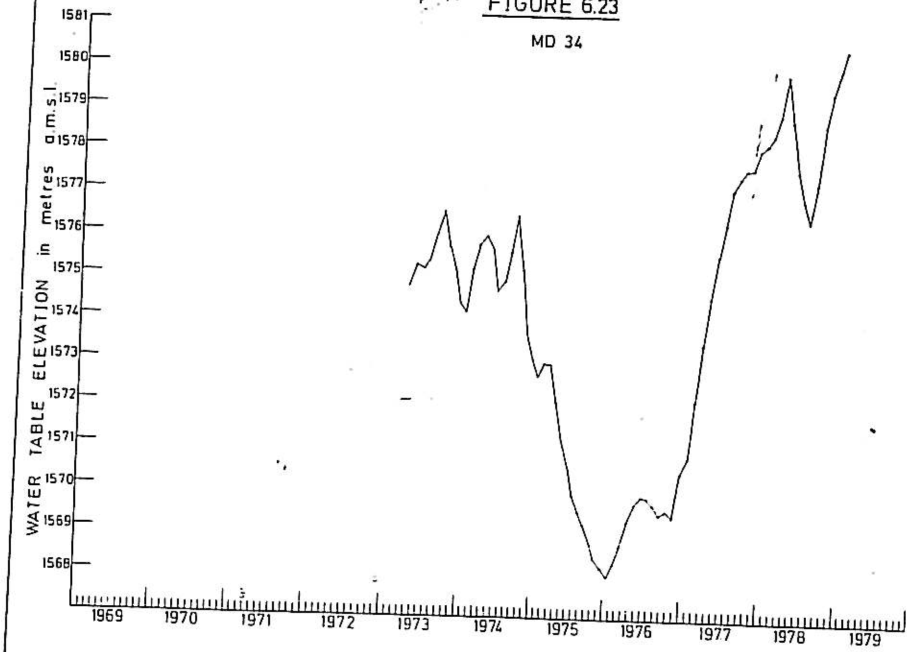


FIGURE 6.24

WP 24

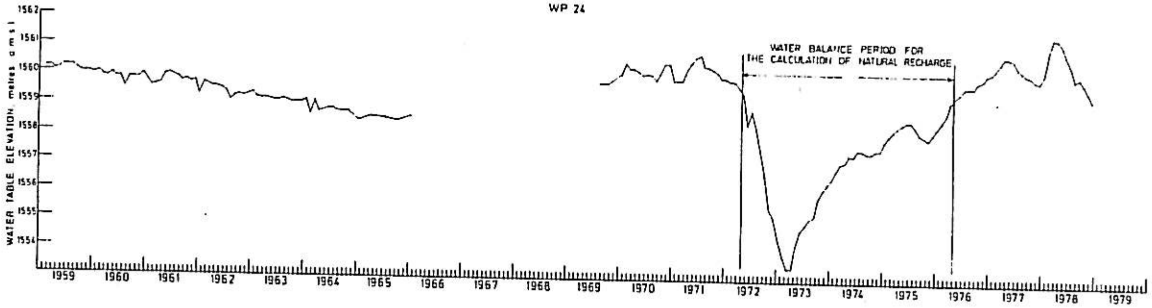


FIGURE 6.25

RW 461

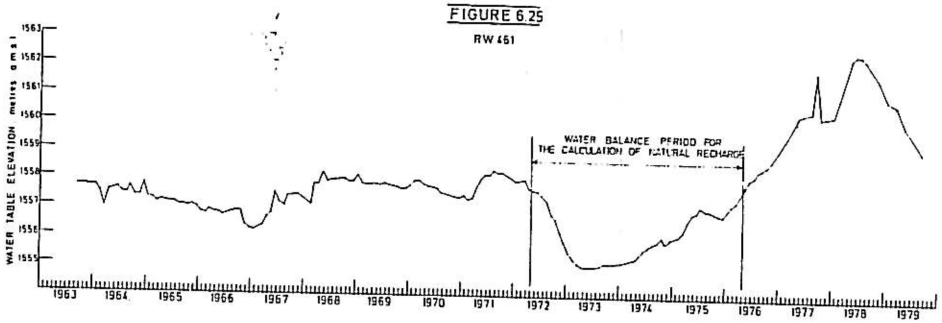
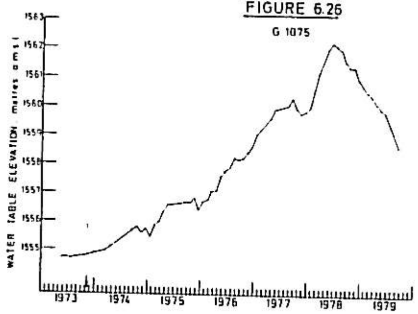


FIGURE 6.26

G 1075



Simultaneously, a detailed gravity survey was undertaken by the Geological Survey to delineate "weak" zones where subsidence might be expected. In the course of that survey, 76 boreholes were drilled in order to verify geophysical interpretations. In some of these boreholes casings were inserted so as to be used for water level observations (Folder 6.1). In a few of the observation boreholes, automatic recorders were installed. 30 Observation boreholes were operating in 1977.

No complete groundwater level records are available for the period preceding the overpumpage. The fluctuations expected in water table elevation over a period of many years, under normal natural conditions, do not exceed 2 metres, as may be observed in Figs. 6.25 and 6.24. More data are available concerning the behaviour of water levels in boreholes after the dewatering episode commenced, as shown in hydrographs (Figs. 6.2 - 6.26). A study of these hydrographs in comparison with the rainy seasons of 1974/75 and 1975/76 often reveals a rapid response of the groundwater level to precipitation.

The water level contour map for November 1975 (Fig. 6.27) represents the groundwater pattern which has prevailed since remedial measures, such as recirculation, were applied. The map is based on a rather limited number of observation points. Boreholes MD34 and WP7 were not considered in the construction of Fig. 6.27. Water levels observed in these boreholes were higher than the levels expected if only the regional aquifer was

WATER TABLE CONTOUR MAP.
NOVEMBER 1975.

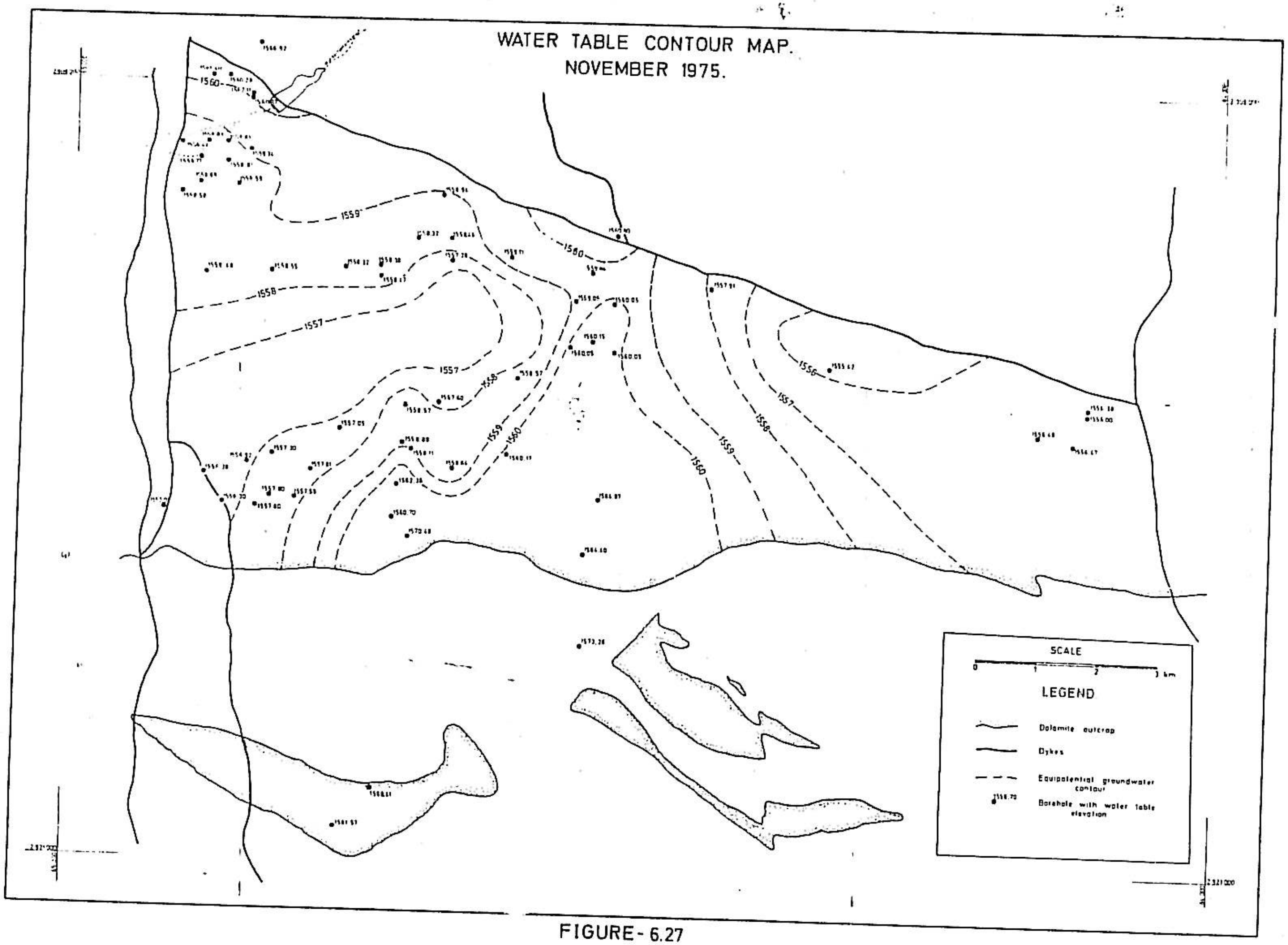


FIGURE- 6.27

penetrated, and could possibly represent a mixture of water from two aquifers. Borehole MD34 is however open to the regional aquifer as shown by the fact that between 3/1973 and 12/1974 an adjacent sinkhole had been recharged by an amount of $9{,}5 \times 10^6 m^3$, and the water levels in MD34 responded respectively, (Fig. 6.23).

It can be noticed in Fig. 6.27 that all through this period of restoration of hydrological conditions, distinct "highs" may be traced, one in the vicinity of Donaldson Dam, in the northwestern corner of the Compartment, and the other in the centre of the investigation unit. The central groundwater mound suggests the presence of a groundwater divide. Part of the underground flow drains accordingly eastwards. This interpretation is also backed by a possible extension of a dyke boundary, detected at Cooke Section Mine in Zuurbekom Compartment (Folder 6.1, Figs. 6.27 and 6.31). A comparison of hydrographs from boreholes on the eastern flank of this divide (Figs. 6.17, 6.21 and 6.20) with those on the western flank during 1977-1978 reveals a distinctly different behaviour. It is thus concluded that this compartment is subdivided into two separate geohydrologic units, the western part extending over a surface area of 64 km^2 and the eatern over 26 km^2.

Intricate geohydrologic conditions prevail in the northwestern corner of the compartment: Some groundwater flow, from Zuurbekom, sector A, towards Venterspost Compartment, has previously been mentioned. This was based on a groundwater contour map Fig. 5.5. It is not clear whether some part of this water also reaches Gemsbokfontein Compartment. From geohydrologic assessments in Venterspost Compartment, Section 7.4, it seems that the bulk of the overflow from Zuurbekom is taken into Venterspost Compartment.

Percolation of water stored at Donaldson Dam must be considered too, as confirmed by the chemical abalysis of a nearby borehole (G1130), and discussed later in Section 6.4.

Some small amount of groundwater could enter into Gemsbokfontein from Zuurbekom sector B, but this has not been positively proved.

The existence in places of Karoo sediments (Ecca shales), which are quite impermeable, will most probably affect the replenishment and circulation of groundwater. Fig. 6.28 provided base Karoo elevation a.m.s.l. and its thickness as penetrated in each borehole. An isopach map could not be attempted due to an inadequate number and unsatisfactory distribution of boreholes. Superimposing a groundwater contour map on Fig. 6.28 displays that the aquifer is phreatic, becoming confined in some parts. The presence of Ecca shales outliers generally does not practically restrict groundwater movement due to the extension of the aquifer below these shales. The aquifer may however, be of limited thickness below the shales.

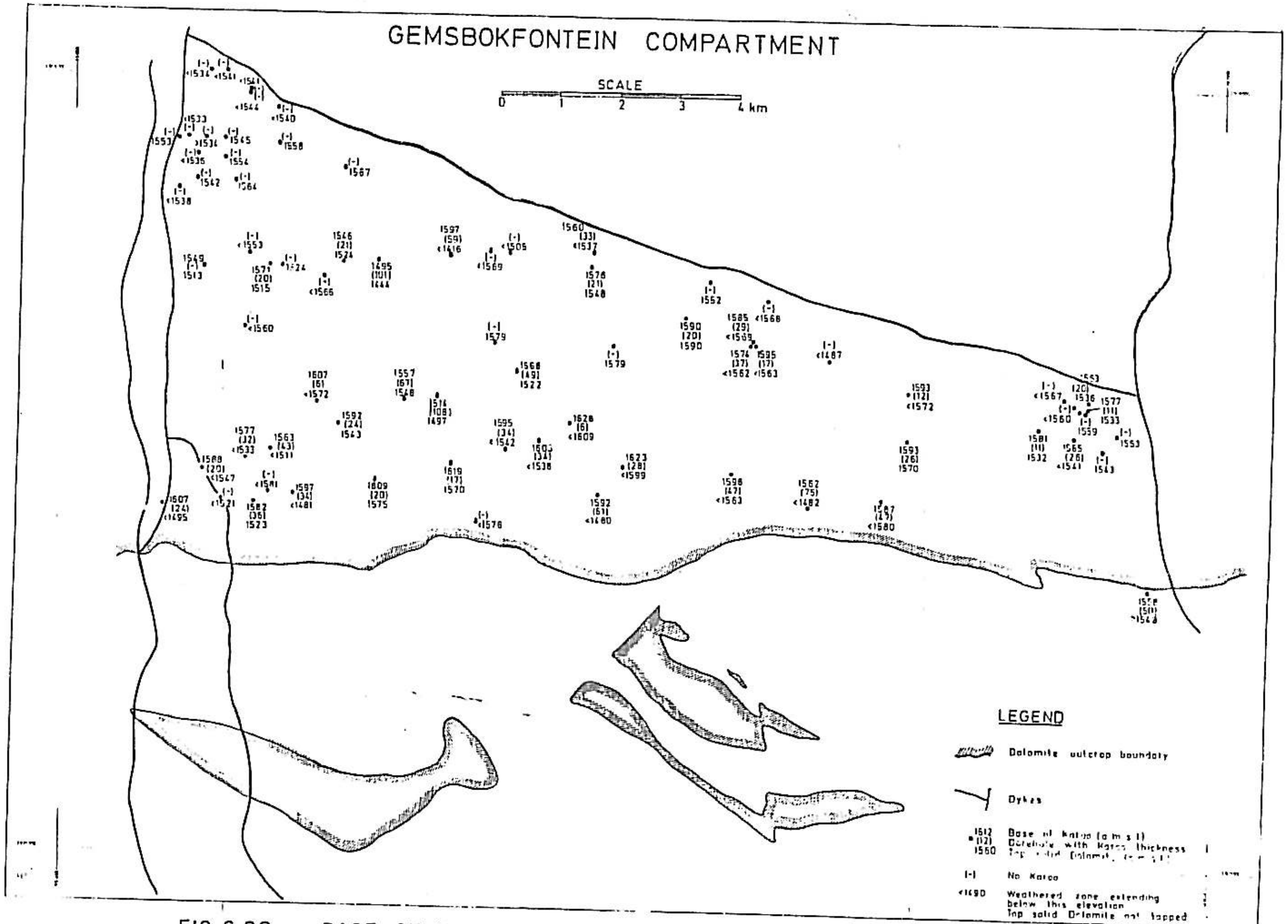


FIG. 6.28 BASE OF KAROO A.M.S.L

6.4 Water quality

Water samples (Table 6.1) were derived from four sources namely (a) Boreholes, (b) Water artificially recharged by Western areas G.M. through boreholes (recirculated water), (c) Water taken from Donaldson Dam sampled at Station C2M24, (d) Water samples taken at Station C2M25, which include a combination of overflow run-off from Donaldson Dam and discharge from Gemsbokfontein Eye.

There are no pumping boreholes in the compartment and in only five observation holes there is access to sample groundwater. Samples were also collected from three boreholes located in the western sub-compartment.

As stated before in Section 5.6, the sulphate ion concentration may quantitatively indicate the amount of contamination prevailing in the aquifer. This approach is based on the fact that mine effluents rich in sulphates constitutes the major contaminant. On the other hand groundwaters in the investigated area are undersaturated in respect of gypsum.

Samples 1, 2 and 3 (Table 6.1) of water being recharged through boreholes into the aquifer by western Areas G.M. are highly contaminated. Between 45% and 85% of the water brought to surface at the mine is artificially recharged. The recharged quantities involved are between 1,2 and $2 \times 10^6 m^3$ per month. Obviously in the long run, a serious contamination hazard can be expected.

TABLE 6.1: Chemical analyses of waters from Gemsbokfontein Compartment, in milligrams per litre

No.	Source	Date	TDS	pH	Ca	Mg	Na	K	Si	Cl	SO_4	HCO_3	NO_3
1	Artificial recharge	24.11.76	1220	6,4	227,0	62,0	32,0	3,8	7,9	18,0	810,0	0	59,3
2	Western Areas	17.1.80	1024	7,2	207,7	49,7	26,6	3,7	8,1	11,1	663,6	53,4	12,5
3	G.M.	10.3.80	1202	4,4	238,1	54,6	34,6	4,1	14,0	10,7	836,2	0	9,5
4	Borehole C.P.16	20.2.80	342	7,6	49,5	26,0	13,5	8,4	0	11,5	62,6	167,6	2,7
5	Borehole RW461	20.2.80	166	7,3	14,9	18,0	1,7	1,6	0	3,6	16,4	108,5	0,8
6	Borehole G1130	19.2.80	1041	7,8	72,8	92,5	41,9	29,5	0	25,2	40,7	735,9	2,8
7	Borehole G1130	20.2.80	1076	7,2	72,8	90,9	43,2	29,7	0	27,1	41,7	723,2	47,8
8	Borehole G1133	20.2.80	415	7,3	55,6	35,9	6,8	3,4	0	6,0	0,2	305,3	1,5
9	Borehole G1128	20.2.80	100	6,9	7,3	6,5	11,9	3,9	0	22,8	14,4	32,7	0,6
10	Borehole RW455	20.2.80	188	7,4	18,5	11,6	20,3	0,3	0	33,4	11,3	93,0	0
11	Borehole RW456	20.2.80	117	7,4	7,4	16,8	2,1	0,8	0	3,2	4,4	81,8	0
12	No. 1 Well	8.1.80	499	7,2	58,0	54,6	12,7	0,9	0,5	15,2	308,0	48,6	0
13	No. 1 Well	29.1.80	514	7,3	60,6	52,5	13,2	1,4	0,8	12,0	316,0	56,8	0,2
14	No. 1 Well	12.2.80	549	7,4	66,6	54,5	13,1	1,2	1,6	49,0	290,5	72,4	0
15	No. 1 Well	22.2.80	685	7,2	102,4	58,8	16,0	0,9	0	5,8	386,4	114,2	0
16	No. 1 Well	12.3.80	634	7,4	92,4	53,6	12,7	1,1	7,7	13,7	333,8	117,6	1,4
17	Donaldson Dam C2M24	24.11.76	1758	6,3	323,0	70,0	56,0	4,3	1,9	23,0	1250,0	0	29,4
18		29.1.80	1206	5,2	235,3	42,5	57,4	10,4	1,8	34,4	820,6	0	4,0
19		12.2.80	1312	5,0	238,4	47,5	75,0	9,5	1,5	32,4	902,0	0	5,8
20		27.2.80	1329	5,4	265,0	44,4	68,0	9,0	0	35,3	901,1	0	6,0
21	Gemsbokfontein Eye	24.11.76	1582	7,0	278,0	71,0	53,0	3,1	2,8	20,0	1120,0	18,0	16,3
22	C2M25	29.1.80	1195	5,8	232,5	43,2	57,4	10,2	0,3	34,7	813,9	0	2,8
23		12.2.80	1271	5,2	232,4	48,6	73,7	9,2	0,8	37,2	839,7	24,8	4,3
24		27.2.80	1347	4,7	266,5	46,4	68,1	8,9	0	35,8	914,9	0	5,9

Groundwater contamination may be detected in a sample from borehole CP16(4) and to a minor extent in borehole RW461(5).

The composition of Donaldson Dam water is demonstrated by samples 17-20 (Table 6.1). As mentioned before, it represents a mixture of mine effluents, reclaimed sewage water and catchment surface run-off. Some parts of the stored water constantly percolates into the subsurface. This assumption is backed by the composition of groundwater encountered at borehole G1130, samples 6 and 7.

The quantities of water gauged at Station C2M25 are since 12/1976 in excess of the overflow from Donaldson Dam, as gauged at Station C2M24. This indicates some discharge through the eye. It is assumed that groundwater discharged at the eye consists practically all of groundwater from Zuurbekom (sector A) together with some infiltrated dam water which re-appears at the eye outlet.

A series of samples from No. 1 well, located in the sub-compartment west of Gemsbokfontein (Folder 6.1) show a rather high sulphate concentration (Table 6.1, samples 12-16). Recalling that all water running west of Station C2M25 is intercepted and carried in pipes, it is concluded that the salinity observed at No. 1 well demonstrates groundwater inflow from Gemsbokfontein into Venterspost Compartment via the sub-compartment. The source of about a third of this inflow consists of percolated dam water.

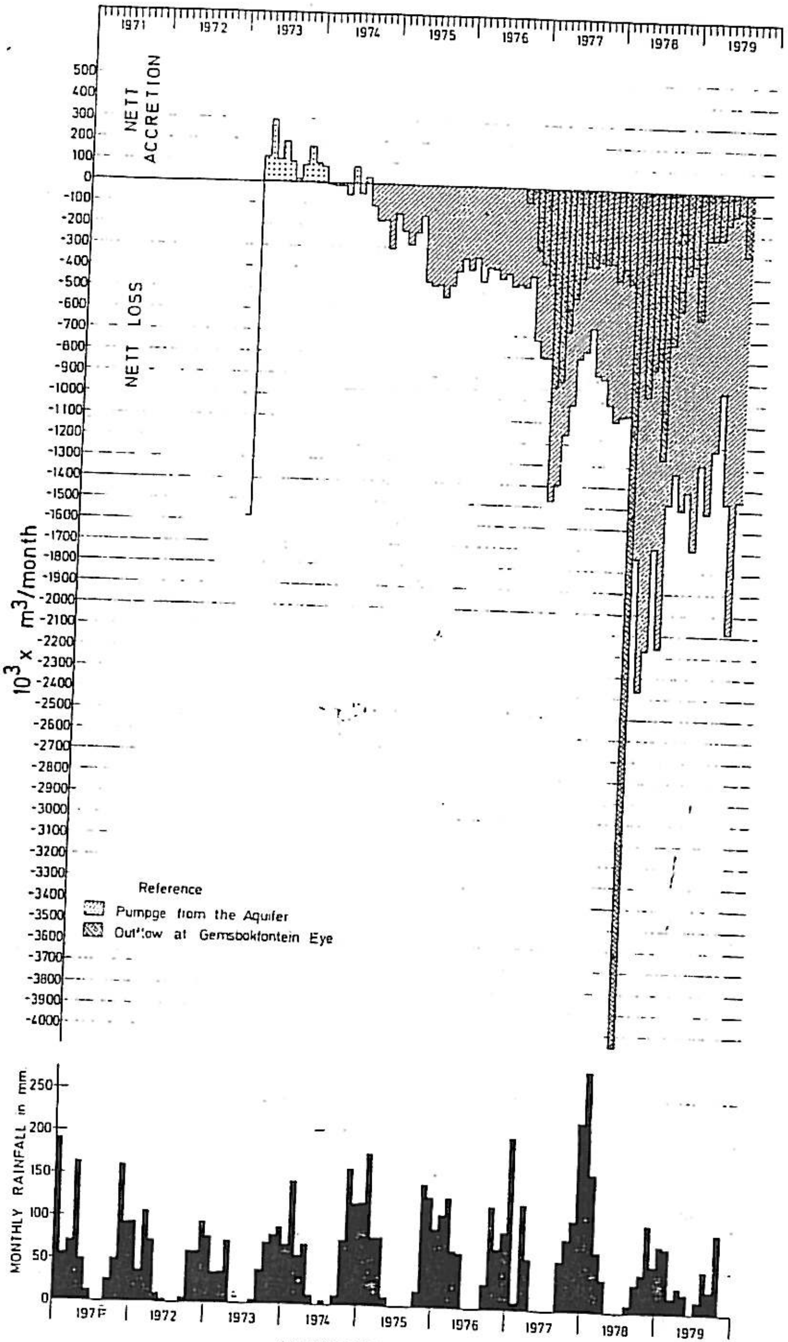
6.5 Quantitative estimations

In order to investigate the response of the aquifer to factors other than rainfall, a monthly water balance is presented in Figs. 6.29 and 6.30. In this balance, extraction through pumpage and spring flow are considered negative, while artificial recharge into the formation as positive. A horizontal line designates zero change while amounts shown above or below refer to changes of water volumes into and out of the aquifer respectively. Fig. 6.30 differs from 6.29 only in this respect that in Fig. 6.30 from 6/1976 onwards the negative amounts include abstraction due to pumping only, while in Fig. 6.29, during the corresponding balance period, outflow at the eye is also included.

Effects of renewed extensive pumpage, which started in 3/1978, may be traced on the hydrographs as abrupt drops. The result of the over-pumpage deficit is super-imposed on a slightly declining trend due to the low rainfall season of 1978/79. It is also remarkable that in 1976, during the dry season and despite a large deficit in the aquifer, water levels continued to rise. This would suggest that the period of replenishment is not confined to the rainfall season, but practically extends beyond it and considerable amounts reach the water table at a much later stage. The exceptionally wet season of 1975/76 reveals this rather prominently.

MONTHLY GROUNDWATER BALANCES
RECHARGE-(PUMPAGE+SPRING OUTFLOW)

Natural recharge not considered.

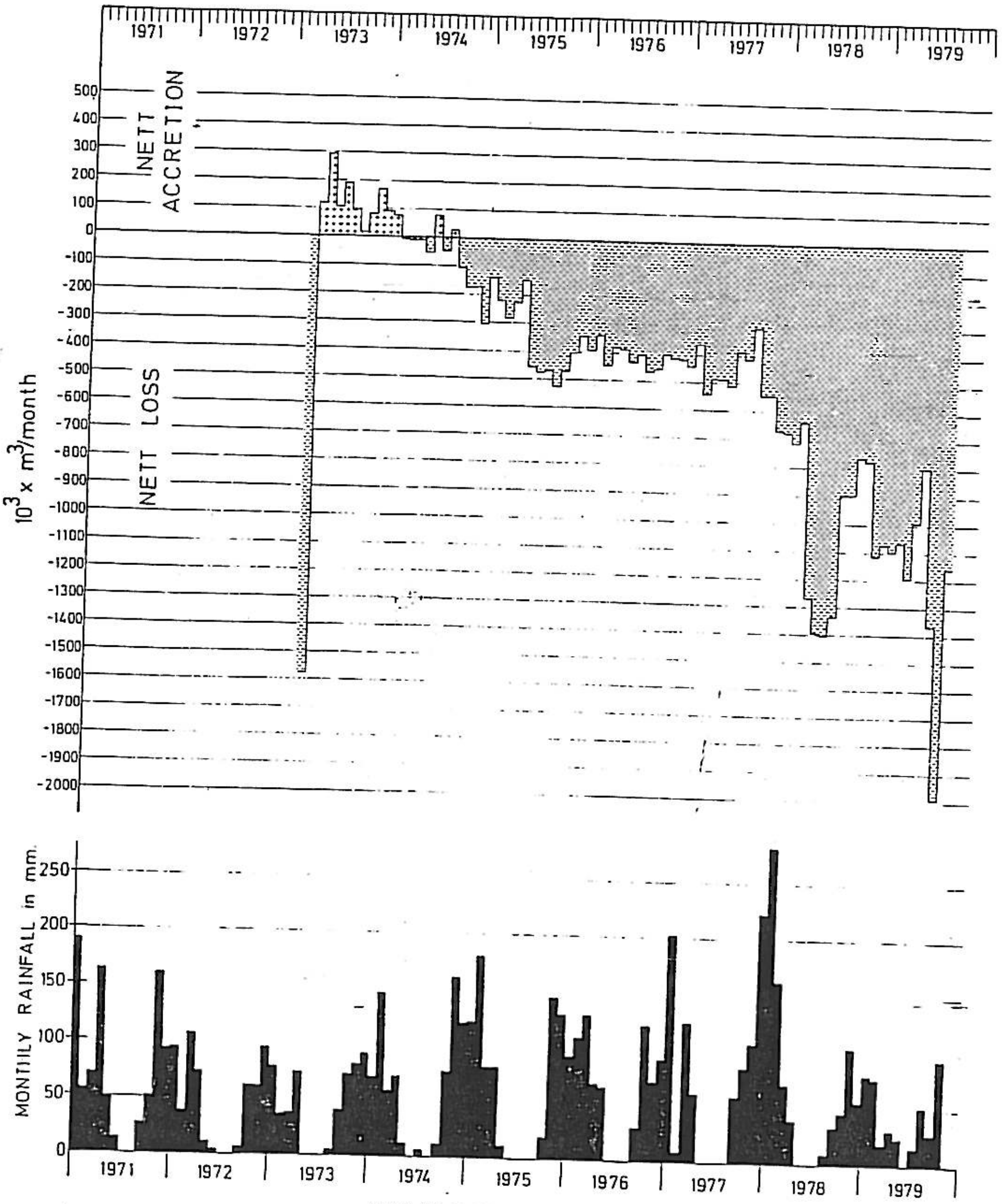


ZUURBEKOM 475/528

FIGURE - 6.29

MONTHLY GROUNDWATER BALANCES
(RECHARGE - PUMPAGE)

Natural recharge not considered.



ZUURBEKOM 475/528

FIGURE - 6.30

Three periods may be distinguished within the studied interval 1971-1979:

(a) 1/1971 - 2/1973: During which abstraction by far exceeded natural recharge and water levels dropped all over the compartment.

(b) 2/1973 - end of 1976: A combination of natural and artificial recharge succeeded in restoring hydrologic conditions in the aquifer. It is assumed that part of the natural recharge was due to groundwater inflow from Zuurbekom Compartment. Percolation from Donaldson Dam also contributed a certain unknown amount of recharge. On the other hand some groundwater outflow, the quantity of which is also unknown, drained out to Venterspost Compartment.

(c) The period later than 1976: Successive high rainfall seasons resulted in increased recharge rates. A rise of the water table above normal elevation is typical. Higher water levels at Donaldson Dam reservoir have, most probably affected the percolation rate and more influx of dam water has reached the aquifer. Groundwater inflow from Zuurbekom (sector A) has also been very high during this period, part of the water having been discharged at Gemsbokfontein Eye (Fig. 6.29).

By reducing the rate of recirculated water, Western Areas Mine increased the deficit in the aquifer, (Fig. 6.30), yet no descending trend is observed in water level hydrographs before 3/1978. Only at this stage has abstraction eventually exceeded total recharge. Unfortunately, doubtful flow data, supplied for stations C2M24 and C2M25, do not allow a proper quantitative study of this period.

Rate of natural recharge

From a few water level hydrographs of boreholes (Figs. 6.8, 6.25 and 6.24) where continuous records are available it may be observed that the period 30.4.72 to 30.4.76 includes a cycle of dewatering followed by a period of remedial recharge. Water levels at the beginning and at the end of this period are at the same elevation. This period was selected for water balance calculations, from which an estimate of the rate of natural recharge could be made. The quantities involved in this balance are as follows:

Discharge from the aquifer in $10^6 m^3$		Recharge into the aquifer in $10^6 m^3$	
Pumpage by Western Areas G.M.	91,494 377	Recharging boreholes	56,848 227
Pumpage by Elsburg G.M.	4,027,000	Recharge through sink=holes	9,566 017
Discharge from Eye area	0,373 245	Recharge through Eye area	7,310 682
TOTAL	95,894 622	TOTAL	73,724 926

95,894 622 - 73,724 926 = 22,169 696 x $10^6 m^3$ = The deficit fully accounted for by natural recharge. The estimated monthly natural recharge is therefore:

$$22,169\ 696 \times 10^6 m^3 : 48 = 0,461\ 869 \times 10^6 m^3$$

and the annual recharge, $0,460 \times 10^6 m^3 \times 12 = 5,5 \times 10^6 m^3$.

The average annual rainfall during the same period was 0,675 mm. The intake area is 64 km^2. Annual natural recharge expressed as percentage of rainfall is thus

$$\frac{5,5 \times 10^6 m^3 \times 100}{0,675\ m \times 64 \times 10^6 m^2} = \frac{5,5 \times 100}{43,2} = 12,8\%$$

Storage coefficient

Another balance period, 30.6.74 - 30.6.76, was selected to find the coefficient of storage:

Discharge from the aquifer in $10^6 m^3$		Recharge into the aquifer in $10^6 m^3$	
Western Areas G.M.	50,333 871	Recharging boreholes	43,687 045
Elsburg G.M.	3,353 000	Recharging through sink=holes	0,718 777
Discharge from the Eye area	0,373 245	Recharge through Eye area	2,360 665
TOTAL	54,060 116	TOTAL	46,766 487

The estimated natural recharge during the balance period is $0,462 \times 10^6 m^3 \times 24$ months = $11,088\ 000 \times 10^6 m^3$.

The amount of total recharge is thus:

46,776 487 + 11,088 000 = 57,854 487 x $10^6 m^3$.

The balance: 57,854 487 - 54 060 116 = + 3,794 371 x $10^6 m^3$.

The positive balance during this period, with surplus water introduced into the aquifer manifested itself by the rise of water levels. The difference in water levels observed in some 40 boreholes, between the beginning of the period and its end, were plotted in Fig. 6.31. Isopach contours were drawn. The total increase of aquifer volume during the balance period was computed by planimetering the various segments, west of the groundwater divide boundary (Fig. 6.31). The resulting volume is 168,4 x $10^6 m^3$. The storage coefficient may thus be derived:

$$\frac{3{,}8 \times 10^6 m^3 \times 100}{168{,}4 \times 10^6 m^3} = 2{,}26\%$$

6.6 Discussion

The results obtained should be regarded in the lignt of several factors which could introduce some inaccuracies: The dolomite area as a whole was treated as phreatic although in cases lateral transition to semi-confined and confined conditions may be expected. The unsatisfactory distribution and limited number of groundwater observation points do not enable a complete understanding of the investigated unit.

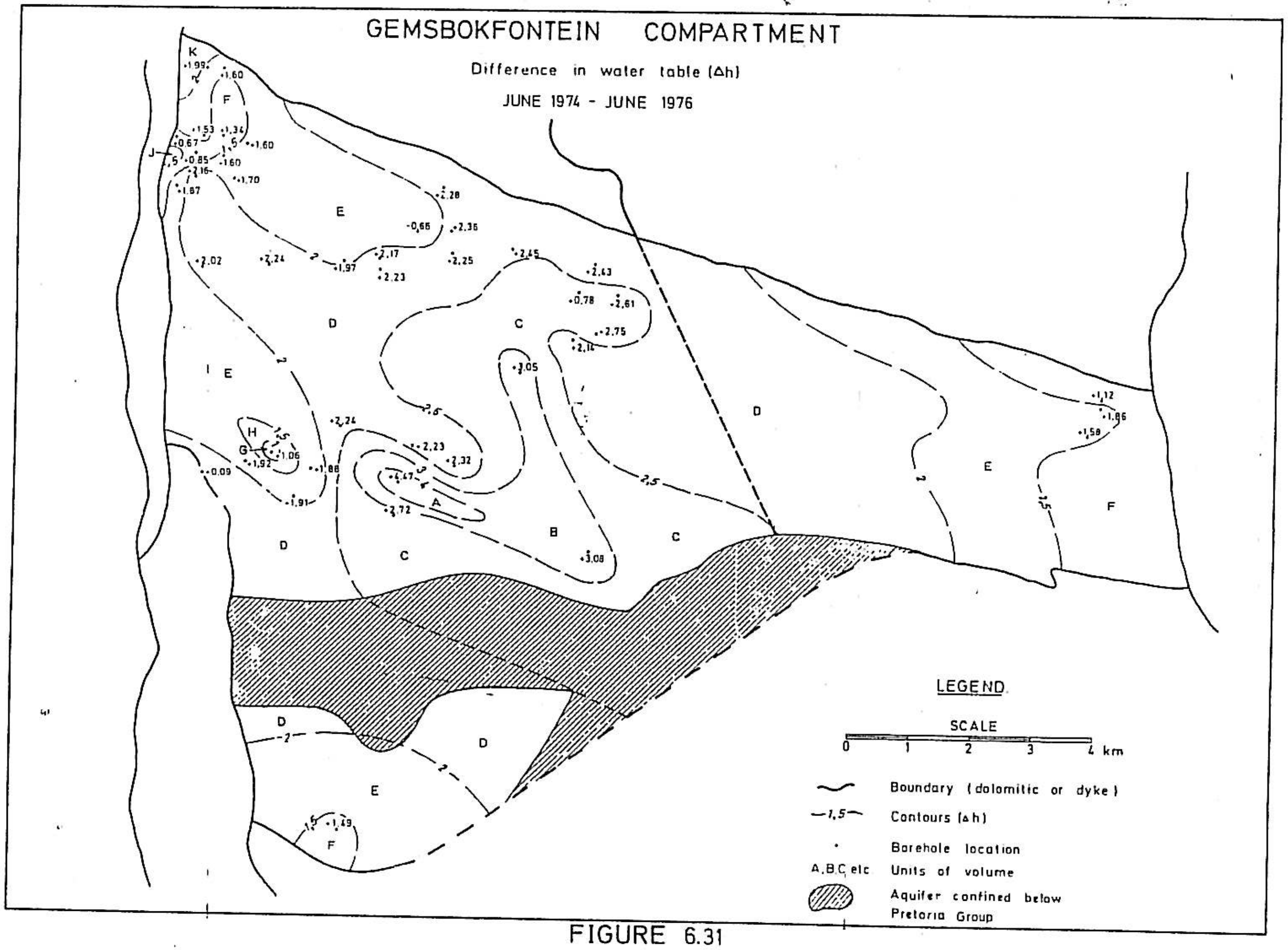

GEMSBOKFONTEIN COMPARTMENT
Difference in water table (Δh)
JUNE 1974 - JUNE 1976
K
1.99
2
1.60
F
1.53
1.34
0.67
1.5
1.60
J
1.5
0.85
1.60
2.16
1.70
1.87
E
2.28
-0.66
2.36
2.02
2.24
2
1.97
2.17
2.23
2.25
2.45
2.43
0.78
2.61
D
C
2.75
2.14
3.05
I
E
2
2.24
2.6
H
1.5
G
1.06
1.92
2.23
2.32
1.88
0.09
4.47
3
4
1.91
2.72
A
B
2.5
C
3.08
D
C
D
E
2
1.12
1.86
1.58
1.5
F
D
2
D
2
E
1.5
1.49
F
LEGEND
SCALE
0
1
2
3
4 km
Boundary (dolomitic or dyke)
1,5
Contours (Δh)
Borehole location
A,B,C etc
Units of volume
Aquifer confined below Pretoria Group

FIGURE 6.31

The major problem of uncertainty lies in the area of Gemsbokfontein Eye. In this area groundwater from Zuurbekom and from Donaldson Dam overflow into Venterspost Compartment (in the form of groundwater and surface water). Some of the replenishment of groundwater in Gemsbokfontein Compartment comes from this source too. It is however possible that this system, to the north and around the eye, is mainly feeding Venterspost Compartment. If this be the case, then water recharged or discharged at the eye, may have very little bearing on the balance of Gemsbokfontein Compartment. It may thus be speculated that artificially recharged water at the eye point during period (b), between 2/1973 and 1976, could have affected Venterspost rather than Gemsbokfontein Compartment.

By neglecting the discharge and recharge around the eye system, in the above water balances, one would get somewhat different results. In the first balance aimed at the estimation of natural recharge, the deficit will become $29,48 \times 10^6 m^3$ which divided by 48 months yields an amount of $0,614 \times 10^6 m^3$/month as natural recharge. This recharge includes a constant groundwater contribution from the eye system. The annual natural recharge will increase accordingly to $0,614 \times 10^6 m^3 \times 12 = 7,4 \times 10^6 m^3$. Expressed as percentage of the total rainfall volume $\frac{7,4 \times 10^6 m^3 \times 100}{168 \times 10^6 m^3} = 17,8\%$.

By similarly disregarding the quantities around the eye in the second balance, for the period 30.6.1974 - 20.6.1976, the accretion is $5,45 \times 10^6 m^3$ and the storage coefficient may therefore become:

$$\frac{5{,}45 \times 10^6 m^3}{168 \times 10^6 m^3} = 3{,}2\%$$

6.7 Conclusions

It is obvious as a result of the current study that Gemsbokfontein Compartment presents a much more complicated geohydrologic set-up than previously envisaged.

The boundary dykes initially assumed to be impervious, allow at certain parts an inflow from Zuurbekom Compartment and an outflow into Venterspost Compartment.

Surface water stored at Donaldson Dam plays an important role in groundwater replenishment both qualitatively and quantitatively.

The recharge of Gemsbokfontein Compartment consists of a complex combination of natural replenishment from rainfall plus inflow from the eye system area. The general rise of water levels during the period (c) on the one hand and heavy abstraction on the other, would induce a steeper gradient towards the mine, and hence increase the recharge.

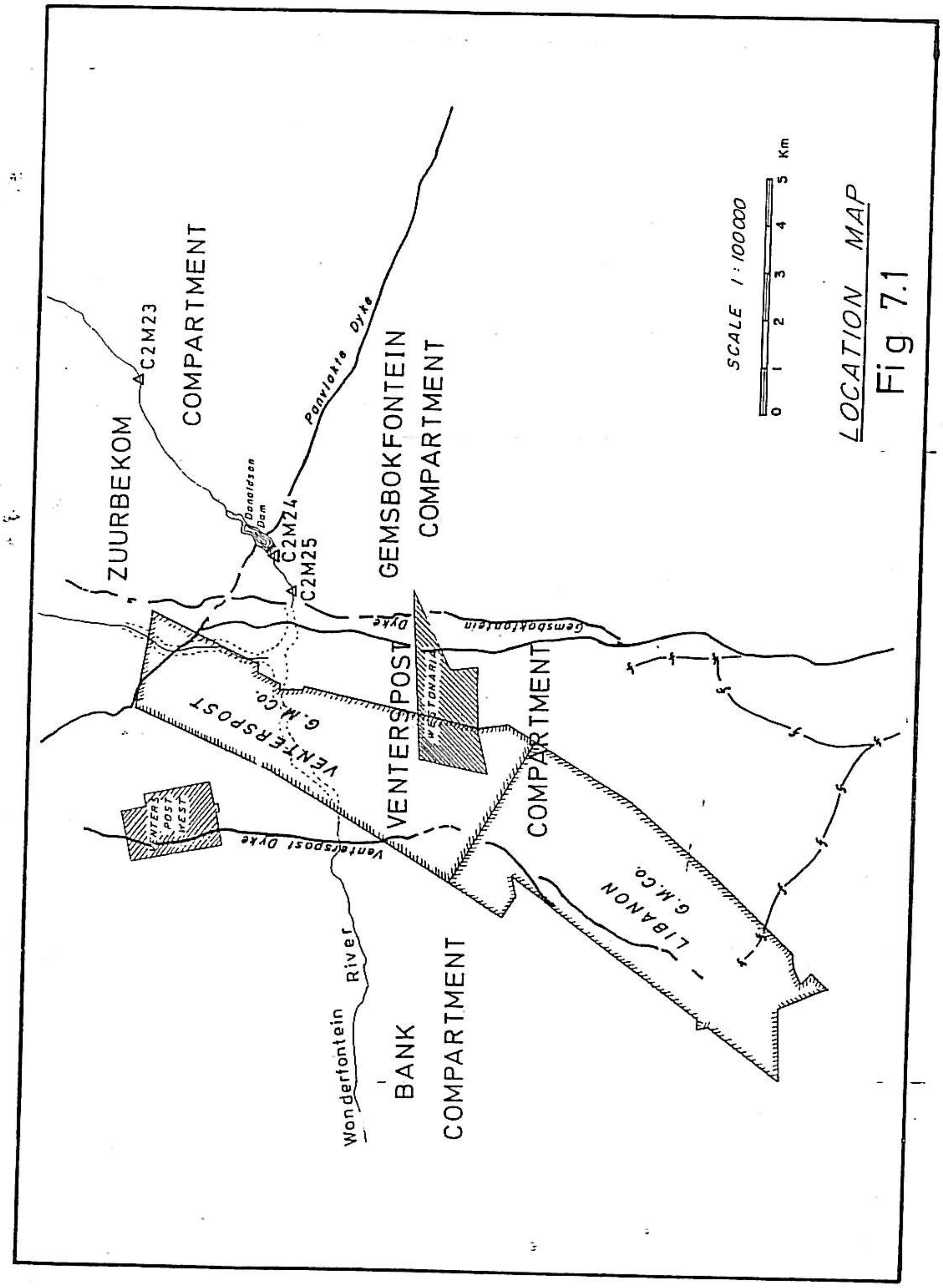
7. INVESTIGATION OF VENTERSPOST COMPARTMENT

7.1 Introduction :

Venterspost Compartment extends over an area of 54 km (Folder 7.1 and Fig. 7.1). Semi-vertical impermeable dykes to the east and to the west constitute hydrologic boundaries. To the north the Malmani Subgroup overlies rocks of the Witwatersrand Super Group and to the south the dolomite dips below the Pretoria Group.

The Wonderfontein River runs from east to west of the compartment in its central section (Fig. 7.1). Sinkholes, depressions and ground movements abound in this part of the compartment, as has been shown by a detailed investigation conducted by Venterspost Mine (Fig. 7.2).

Before man's interference through mining and pumpage the depth to water level in this central part used to be rather shallow. Natural discharge of groundwater from this compartment emanated through an eye, situated on the western boundary dyke, with an average annual discharge of $7,6 \times 10^6 m^3$, (Enslin and Kriel, 1967). This eye ceased flowing in 1947 as a result of pumpage. The average annual rainfall for the period 1965 - present is 690 mm.



LOCATION MAP

Fig 7.1

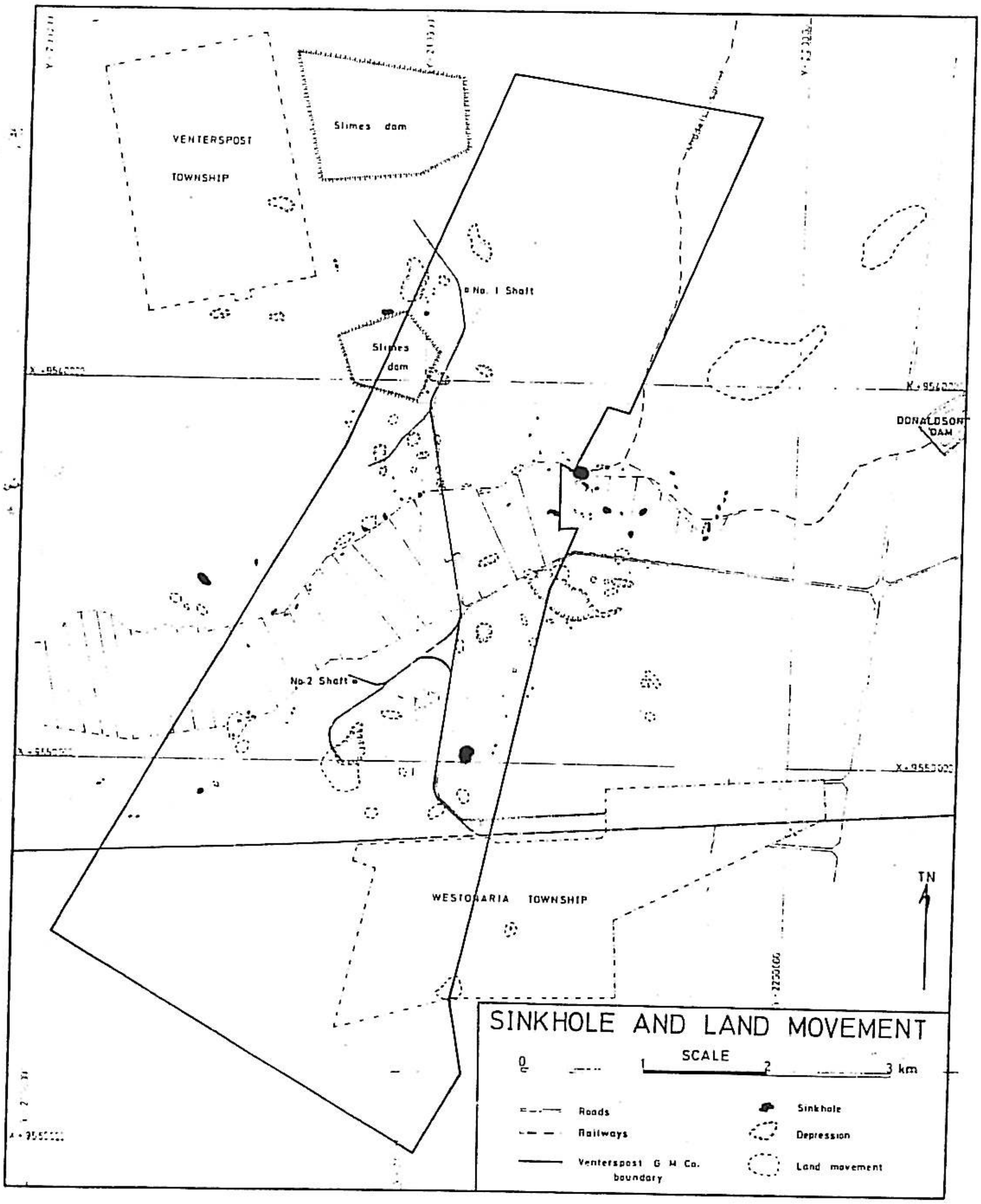

Slimes dam
VENTERSPOST
TOWNSHIP
No. 1 Shaft
Slimes
dam
DONALDSON
DAM
No 2 Shaft
WESTONARIA TOWNSHIP
TN
SINKHOLE AND LAND MOVEMENT
SCALE
0
1
2
3 km
Roads
Railways
Venterspost G M Co. boundary
Sinkhole
Depression
Land movement

FIGURE 7.2

Extensive gold mining is practised in the area by Venterspost, Libanon, and Kloof Mines. This activity necessitates pumpage of water from underground. The water pumped out by the mines originates from the upper weathered-rock-dolomite aquifer and reaches the underground workings through conduits such as faults, fractures, brecciated zones etc. Annual pumpage is listed in Table 7.1 and monthly figures appear in Fig. 7.4.

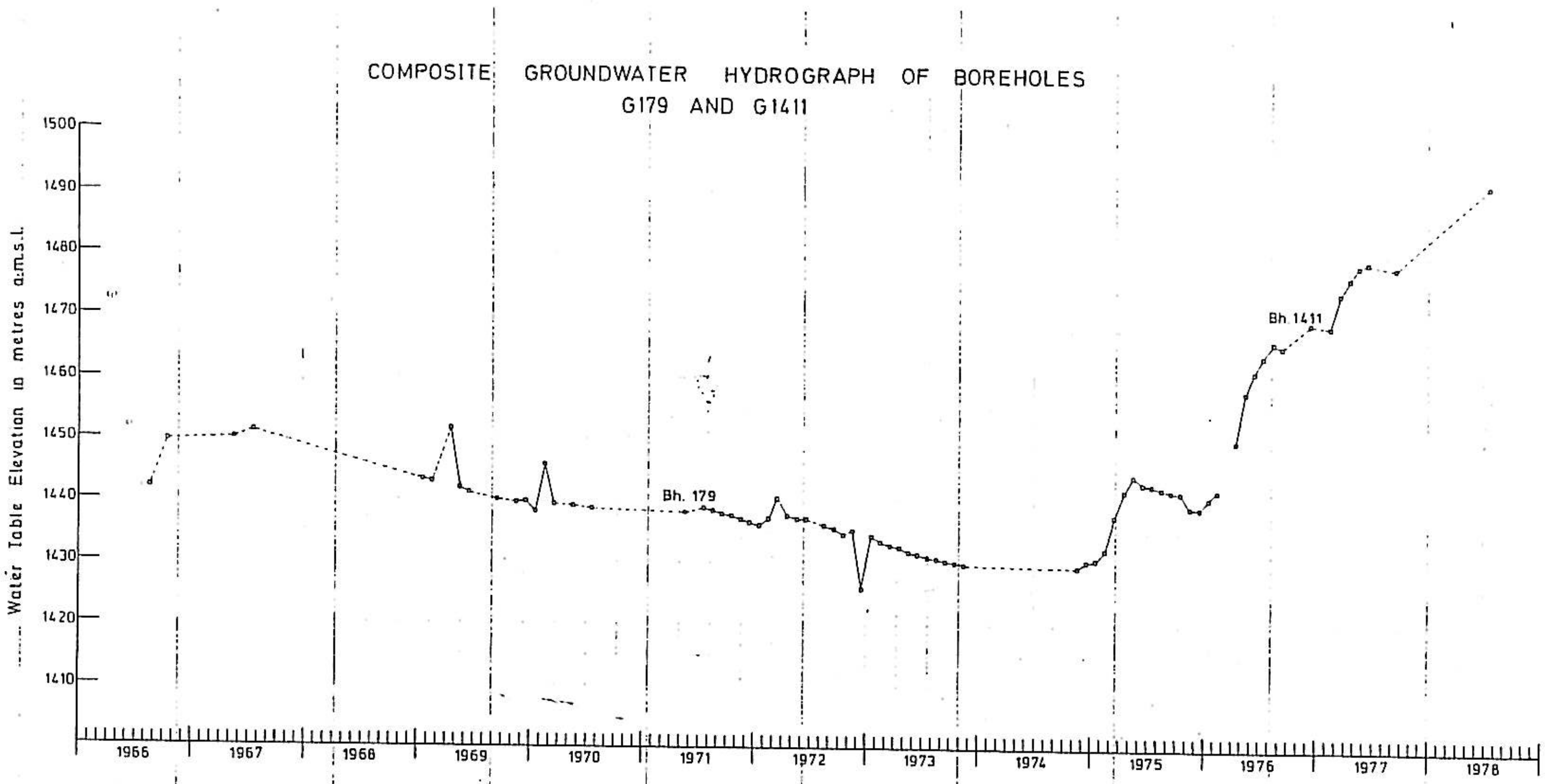
7.2 Previous work

Enslin and Kriel (1959) calculated storativity in this compartment by comparing drawdown against pumpage during periods of 100 days, in 1953-1958, when assumingly no recharge took place. The storativity determined in this way was between 8,75% to 9,06%. It was shown later, by the same authors (1967), that storativity decreases with depth from 9,1% to 1,3% at depths of 61 m to 146 m respectively. Enslin and Kriel determined the recharge during 1952-1958 from groundwater and surface water balances. The total annual recharge into the compartment was estimated at $9,5 \times 10^6 m^3$. Of this total, the recharge from rainfall only, was $5,6 \times 10^6 m^3$ per year. The total recharge expressed as percentage of the average rainfall was 25,3% and that part out of the total recharge which was due to rainfall only, amounted to 15%.

7.3 Geohydrology

Groundwater abstraction from this compartment has been going on for many years. Water is brought to surface through the shafts and is also being pumped from several boreholes. Records of pumping, monitored by the mines are available. Some inconvenience arises from the fact that at Libanon Gold Mine, part of the pumped water comes from Venterspost Compartment and part comes from Bank Compartment. Still another part of the water is seemingly derived from a small isolated unit. This division is clearly demonstrated when hydrographs are compared (Figs. 7.4 and 7.5). Venterspost No. 2 shaft and Libanon No. 1 shaft are in the same aquifer. Harvie-Watt shaft is in Bank Compartment and reflects the abstraction history at Bank, where maximum dewatering occurred in 1970. The water table at Libanon shaft No. 2 is unaffected by either of the dewatering processes. Quantitative differentiation between water derived from Venterspost Compartment and water from Bank Compartment is therefore a matter of guessing.

A continuous drawdown of the water table as a result of pumpage can be discerned during most of the observation period since the start of dewatering, Figs. 7.3, 7.4 and 7.5. The water table reached its lowest levels in 1974, some 120 m below the initial water elevation. It should however be noted that drawdown has not been uniform all over the compartment. Maximum drawdown occurred in the central part, while water levels remained high in the marginal areas. A substantial groundwater gradient from



COMPOSITE GROUNDWATER HYDROGRAPH OF BOREHOLES
G179 AND G1411

FIGURE 7.3

MONTHLY PUMPAGE AT VENTERSPOST MINE AGAINST GROUNDWATER LEVELS IN NO. 2 SHAFT.

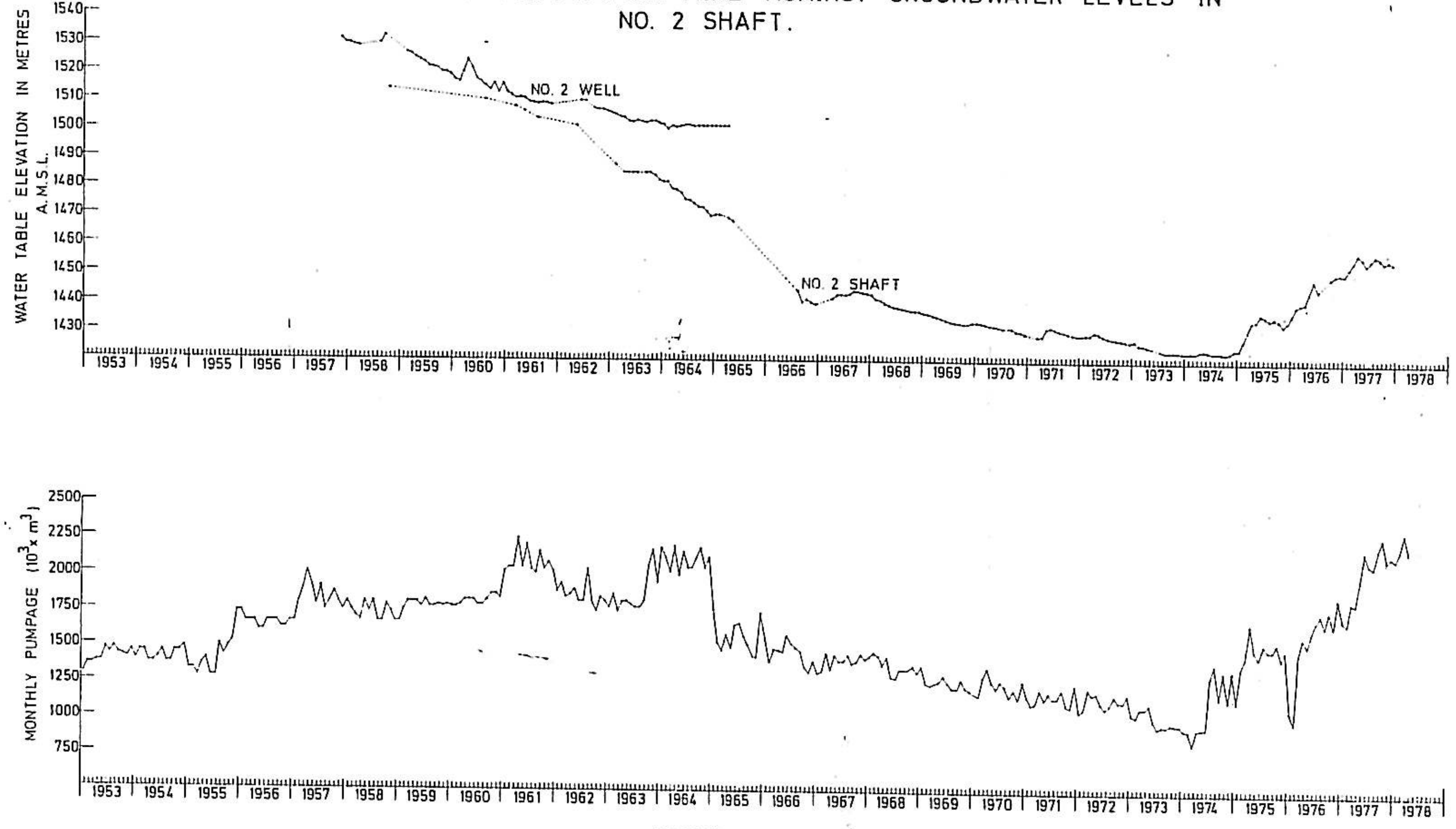


FIGURE 7.4

GROUNDWATER HYDROGRAPHS OF NOS. 1, 2 AND HARVIE-WATT SHAFTS
LIBANON GOLD MINING CO. LTD.

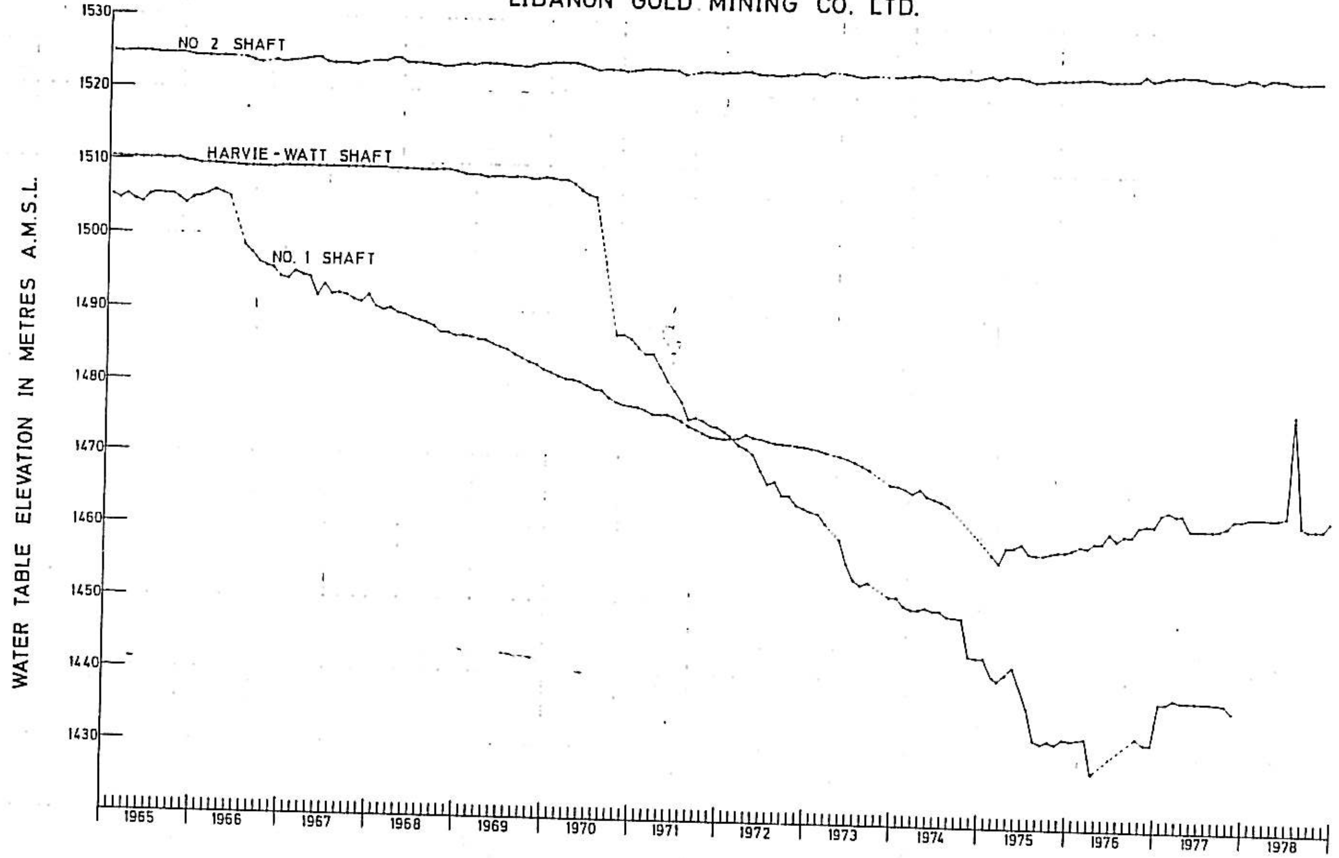
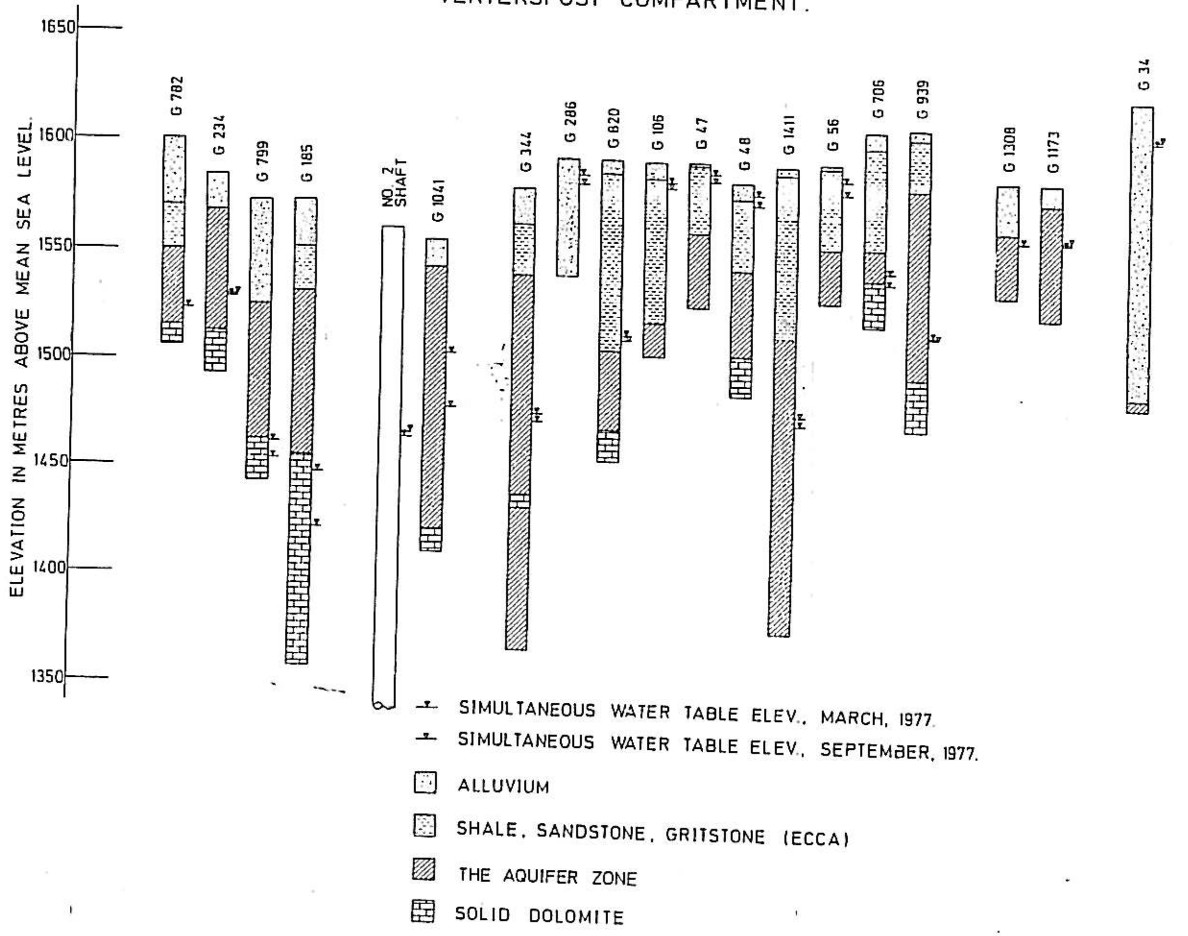


Fig. 7.5

the flanks to the central part characterises the trough. A steep rise in water levels, in spite of increased pumpage, is noticed during 1975-1977. However during 1966/67 which was an exceptionally high rainfall season, only a small rise was experienced.

Some fifteen observation boreholes are presently operating in this compartment. These boreholes were drilled to investigate sinkholes and land subsidences by the Geological Survey of the Department of Mines. Unfortunately, observations in the past were sparse and often irregular and did not cover the entire compartment. Also, many boreholes are not operating due to obstructions.

Condensed columnar sections of boreholes are shown in Fig. 7.6. Four units are distinguished: (a) alluvium, (b) Ecca Group (sandstone, shale grit etc), (c) Fluvio-glacial clastics and weathered chert and dolimite, (d) Malmani Subgroup (solid dolomite and chert). Information concerning rest water levels clearly indicate the presence of two aquifers, an upper but relatively shallow aquifer associated with beds of the Ecca Group or the alluvium, and a deeper regional aquifer comprising the fluvio-glacial clastic deposits and the weathered chert and dolomite of Malmani Subgroup. No information is available concerning the construction of the casings in the boreholes. Combined water levels representing more than one aquifer may also sometimes be expected. Isochronous water levels are shown



COLUMNAR SECTIONS OF BOREHOLES IN VENTERSPOST COMPARTMENT.

FIGURE 7.6

in Fig. 7.6 as for March 1977 and September 1977. It often happens, in the deep aquifer that the September water levels are higher than those of March. This phenomenon provides further evidence in support of the postulation that there is a delay in the arrival of recharge water into the aquifer. In this compartment however, it could also point to the partial replenishment due to underground inflow from the eastern boundary and/or infiltration of run-off from Donaldson Dam.

7.4 Evaluation of recharge

In Fig. 7.7 an attempt is made to calculate the total average natural recharge into this compartment. Annual drawdowns, h, are plotted against annual abstractions (Hill Method). An estimated annual amount of $3 \times 10^6 m^3$ was added due to withdrawal by Libanon Gold Mine. Drawdowns were calculated as a mean between water levels at No. 2 shaft Venterspost and No. 1 shaft Libanon (Table 7.1). Data from 1974/75, 1975/76, 1976/77 as well as from 1964/65 were left out. The scattering of the remaining points enables a line to be drawn which indicate an average annual recharge of $12,5 \times 10^6 m^3$. It is evident that during 1974/75, 1975/76 and 1976/77 recharge conditions were substantially different. The rise of water levels was only partly due to natural groundwater recharge. Surface water flow in the section of Wonderfontein River crossing Venterspost Compartment consisted of a combination of (1) Overflow from Donaldson Dam, (2) Discharge from Gemsbokfontein Eye and (3) flow coming from Middelvleispruit. Overflow from Donaldson Dam

ANNUAL PUMPAGE AGAINST ANNUAL CHANGE IN WATER LEVELS (HILL METHOD), VENTERSPOST COMPARTMENT.

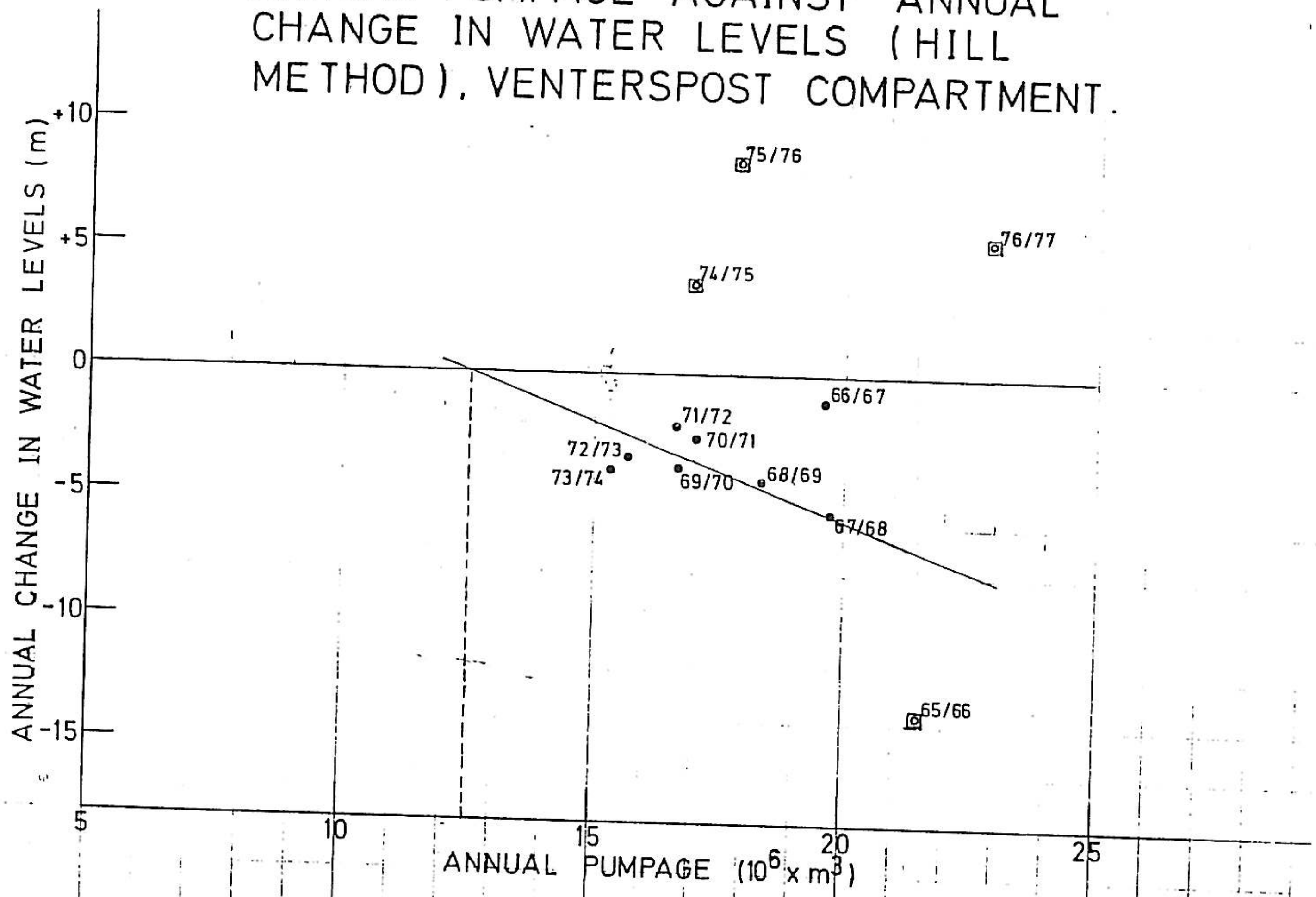


FIGURE 7.7

TABLE 7.1: Annual change in water level, Δh, and annual pumpage in Venterspost Compartment

Hydrological year Oct. - Sept.	Change in water level (m)	(m)	Mean (m)	Annual pumpage $10^6 m^3$	Remarks
	Venterspost No. 2 shaft	Libanon No. 1 shaft			
1963/64	-11,95			25,033	Venterspost + Libanon G.Ms.
1964/65	-12,30			22,755	
1965/66	-18,75	-8,50	-13,63	18,557	Venterspost G.M. only
1966/67	+ 2,50	-4,50	- 1,00	16,623	
1967/68	- 6,50	-4,50	- 5,50	16,697	
1968/69	- 4,50	-4,00	- 4,25	15,435	
1969/70	- 2,25	-5,30	- 3,77	13,683	
1970/71	- 0,75	-4,30	- 2,53	14,094	
1971/72	- 2,25	-1,80	- 2,03	13,683	
1972/73	- 4,00	-2,60	- 3,30	12,707	
1973/74	- 0,50	-7,20	- 3,85	12,385	
1974/75	+12,00	-4,60	+ 3,70	16,952	Venterspost + Libanon G.Ms.
1975/76	+14,50	+2,70	+ 8,60	17,881	
1976/77	+ 5,75	+1,50	+ 3,63	22,910	

was quantitatively dominant in the combined run-off. The increased inflow to Donaldson Dam was derived mainly from mine effluents upstream (3-5 x $10^6 m^3$/year) and reclaimed sewage water (2,5 x $10^6 m^3$/year). Fig. 5.3 illustrates the changes in surface flow at Station C2M23 higher upstream which affected Donaldson Dam. The annual run-off at this station used to be in the range of 4-6 x $10^6 m^3$, this amount has doubled since 1975/76.* It is claimed that increased percolation of run-off water into the aquifer affected the rise of water levels during 1974-1977. Since 1978 all surface water is collected and diverted from the compartment, hence no percolation of such water is possible after 1978.

A similar reasoning applies to data from 1965/66 where natural recharge was seemingly below average due to extremely low rainfall, Table 7.2.

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* It is most disappointing that records from station C2M25 are highly unsatisfactory as this station is situated at the upstream boundary of the investigated compartment, for which data is essential to derive quantitative estimates.

TABLE 7.2: Annual rainfall in mm (1/9 - 31/8)

Year	Randfontein		Zuurbekom
	475/338	475/370	475/528
1964/65	-	511*	700
1965/66	379	466	353
1966/67	1 063	991	700
1967/68	525	576	627
1968/69	601	640	495
1969/70	697	747	593
1970/71	986	974	761
1971/72	557	735	656
1972/73	951	590	452
1973/74	512	751	650
1974/75	799	703*	849
1975/76	809	-	756
1976/77	670	766	714
1977/78	896	927	931*
1978/79	480	549	534

*Rainfall record incomplete.

The figure arrived at for total recharge namely 12,5 x $10^6 m^3$/year is rather high. Considering an area of 54 km^2 and a mean 690 mm rainfall, the recharge expressed as the percentage of total rainfall volume is:

$$54 \times 10^6 m^2 \times 0{,}69\ m = 37 \times 10^6 m^3 = \text{Total rainfall volume}$$

$$\frac{12{,}5 \times 10^6 m^3 \times 100}{37 \times 10^6 m^3} = 33{,}8\%$$

Part of the above recharge is however due to groundwater inflow through a contributing boundary as will be discussed in the following chapter.

7.5 Chemistry of water

The composition of Donaldson Dam water can be seen in Tables 7.3 and 7.4. This type of water most probably contributed to groundwater recharge prior to 1978, and simultaneously also contaminated the aquifer. It is assumed that the chemical composition of the groundwater has been restored to normal during 1978-1980. Water analyses of No. 1 Well, No. 1 Shaft, No. 2 Shaft and No. 4 Well (Table 7.4) reveal a rather constant concentration in each case, no dilution with time process can be traced. It is therefore acceptable to assume that the system has reached a steady state. The salinity pattern presently observed could thus reflect, constant conditions.

TABLE 7.3: Partial analyses of water from Donaldson Dam in milligrams per litre

Date	pH	TDS	SO_4
22.1.75	8,2	1965	670
18.4.75	7,1	1925	1160
10.7.75	7,0	1960	1250
10.9.75	7,4	1975	1160
8.12.75	7,9	1425	880
24.3.76	5,2	1530	840
23.7.76	5,5	1970	1000
23.9.76	7,2	2015	1100
6.1.77	7,2	2070	1150
7.4.77	5,3	1930	1200
16.8.77	6,2	1850	1100
7.10.77	6,9	2040	1180
8.2.78	4,7	1325	860
4.4.78	8,3	2020	1200
5.10.78	7,0	1885	1100
6.12.78	5,3	1934	1200
1.2.79	6,4	1885	1100
1.5.79	5,8	1855	1000
1.8.79	7,0	1780	850

TABLE 7.4: Chemical analyses of waters from Venterspost Compartment in milligrams per litre

Source	Date	TDS	pH	Ca	Mg	Na	K	Si	Cl	SO_4	HCO_3	NO_3
Donaldson Dam	24.11.76	1758	6,3	323,0	70,0	56,0	4,3	1,9	23,0	1250,0	0	29,4
	29.1.80	1206	5,2	235,3	42,5	57,4	10,4	1,8	34,4	820,6	0	4,0
	12.2.80	1312	5,0	238,4	47,5	75,0	9,5	1,5	32,4	902,0	0	5,8
	27.2.80	1329	5,4	265,0	44,4	68,0	9,0	0	35,3	901,1	0	6,0
No. 1 Well	8.1.80	498	7,2	57,9	54,6	12,7	0,9	0,5	15,2	308,0	48,6	0
	29.1.80	514	7,3	60,6	52,5	13,2	1,4	0,8	12,0	316,0	56,8	0,2
	12.2.80	549	7,4	66,6	54,5	13,1	1,2	1,6	49,0	290,5	72,4	0
	22.2.80	685	7,2	102,4	58,8	16,0	0,9	0	5,8	386,4	114,2	0
	12.3.80	634	7,4	92,4	53,6	12,7	1,1	7,7	13,7	333,8	117,6	1,4
No. 1 Shaft	22.2.80	334	7,8	43,9	35,0	8,9	0,9	0	13,1	97,3	133,0	2,0
	12.3.80	345	8,0	45,0	33,9	11,5	1,0	6,5	14,3	100,0	133,2	0
No. 2 Shaft	22.2.80	490	7,7	76,7	41,9	11,8	1,3	0	7,2	215,4	134,1	1,3
	12.3.80	503	7,6	79,5	39,6	12,7	1,1	8,3	7,8	212,2	140,1	1,6
BH16	22.2.80	178	7,3	13,7	13,6	14,4	15,2	0	36,8	4,8	79,9	0
	12.3.80	196	7,4	14,8	12,7	15,0	15,4	1,0	40,2	15,3	81,9	0,1
No. 4 Well	8.1.80	289		41,2	25,4	4,8	0,5	6,7	19,3	68,7	121,9	0,8
	29.1.80	276	7,7	39,8	24,5	5,2	0,7	7,8	6,1	71,9	119,4	0,77
	12.2.80	269	7,6	38,2	24,0	4,9	0,7	8,1	4,7	65,8	121,7	0,6
	22.2.80	297	7,1	39,5	27,2	9,3	7,5	0	5,4	72,1	136,3	0
	12.3.80	276	7,4	41,3	23,4	6,9	0,6	6,9	6,2	66,4	123,6	0,3

The eastern sub-compartment (Folder 7.1 and Fig. 7.1) serves as an intermediate underground reservoir which spills into Venterspost Compartment, itself being recharged by groundwater from Gemsbokfontein and Zuurbekom Compartments. Samples from No. 1 well demonstrate the salinity in this unit. The salinity is derived from Gemsbokfontein groundwater Compartment.

Groundwater in the dolomite aquifer, under natural conditions, contains negligible amounts of sulphate ion. Moreover, due to the fact that most waters in the studied area are unsaturated in respect of sulphate, this ion can be used for quantitative monitoring of contamination.

It is thus suggested that groundwater at Venterspost Compartment consists of mixed water where the two end-members are on the one hand water of the type in No. 1 well, and on the other hand rain recharge water containing no sulphate. The product of mixing is reflected in water from No. 4, located on the western boundary of the compartment.

The contaminating end-member contributes about 20% of the total recharge. The average annual amount of recharge derived by the Hill method is $12{,}5 \times 10^6 m^3$, so that $2{,}5 \times 10^6 m^3$ constitute the inflow through the eastern boundary.

7.6 Discussion

Because of heterogenic properties of the studied aquifer, it is not desirable to use the composition of the contaminating end-member based on one point only. The sulphate concentration of the inflow groundwater could on the average be less concentrated than that shown by No. 1 well water, so that the estimate of 2,5 x $10^6 m^3$ is more likely a minimum figure foi the inflow through the eastern boundary.

If the amount of inflow via the eastern boundary is subtracted from the total recharge, 12,5 - 2,5 = 10 x $10^6 m^3$, the in situ recharge is obtained. The in situ recharge expressed as percentage of the rainfall volume still remains surprisingly high: $\frac{10 \times 100}{37} = 27\%$.

It is suggested that as a result of the dewatering of this compartment, additional storage was created in the aquifer underlying the area of the river course. Previously the natural groundwater level was close to ground surface and prevented extensive intake due to lack of storage. It is also inferred that potentially the permeability is rather high in this central area due to sinkholes, depressions, etc. Very similar recharge conditions prevail in Bank Compartment (Part 8). The percentage of recharge out of the total rainfall in Bank Compartment was calculated to be 24%. In both cases the high recharge rates are due to accelerated percolation through the river course under the new artificial conditions.

The expected amount of annual in situ recharge at Venterspost Compartment, by analogy to Bank Compartment would be $\frac{37 \times 10^6 m^3 \times 24}{100} = 8,9 \times 10^6 m^3$. It appears that in Venterspost Compartment an additional intake component was active. An extra contribution to the total annual recharge could come from infiltrated run-off, the sources of which were: Gemsbokfontein Eye and moderate overflow from Donaldson Dam. The order of magnitude of this component used to be about 1,1 x $10^6 m^3$/year.

7.7 Conclusions

The total recharge into Venterspost Compartment amounts to 12,5 x $10^6 m^3$/year. 2,5 x $10^6 m^3$ of this amount flows into the compartment from adjacent compartments via the eastern boundary. The in situ recharge therefore is 10 x $10^6 m^3$/year. A considerable part of the in situ recharge is due to the creation of additional storage as a result of the artificial process of dewatering. Under the specific circumstances in Venterspost Compartment, a rather high rate of recharge has been noticed due to surface water percolation (up to mid-1977).

The main source of error in the aforegoing calculations may arise from the application of the Hill method. Firstly, the drawdowns and water levels, which appear in Table 7.1 and Fig. 7.7, do not represent proper averages over the compartment. Secondly, pumpage amounts at Libanon Gold Mine are estimated.

It should also be borne in mind that the recharge figures obtained refer to "average" rainfall years. It has however been found that fluctuations in annual rainfall substantially affect the amount of replenishment, as will be discussed later.

8. INVESTIGATION OF BANK COMPARTMENT

8.1 Introduction :

The compartment includes some 154 km^2 (Folder 8.1), and impermeable boundaries delineate the compartment on all sides. Syenite dykes striking approximately NNE comprise the eastern and western boundaries. Relatively impervious rocks of the Black Reef Group form a rather irregular boundary to the north. In the south the dolomite dips below the impervious shales of Pretoria Group and the aquifer probably extends only a short distance beyond the line of outcrops.

The Wonderfontein River crosses the compartment in an east-west direction. The ground surface slopes gently towards the river and westwards.

Outcrops of pre- and post-dolomitic rocks outside the compartment form a hilly topography in contrast to the even dolomite terrain.

Outliers of Karoo beds are commonplace on the dolomite, and may reach a considerable depth. The area is soil covered, the thickness of the cover varying considerably. The residual gravity map presented in Folder 8.2 provides a useful means of indicating the distribution of low gravity rock units below the regional groundwater level. This includes shaley Ecca beds and the Pre-Ecca fluvio-glacial aquifer down to the basal karstic zone. Younger karst and weathered dolomitic rock, if thick enough, manifests itself in the same way (see also Section 5.5).

8.2 Geohydrology

Under natural conditions the dolomitic aquifer in the Bank Compartment was replenished through the percolation of a certain amount of the summer rainfalls, run-off in the river bed and overflow from the Venterspost Compartment upstream.

Discharge from the Bank Compartment took place mainly through the spring and through seepages from the effluent section of the river bed.

Because of the shallow depth to the water level in the vicinity of the river, it is assumed that under changing annual rainfall, alternating effluent and influent conditions must have prevailed.

Outflow from the spring did not include any surface run-off because the spring issued about 1 km south of the river course.

Some change in the natural hydrologic regime occurred when dewatering commenced in the neighbouring Venterspost Compartment. The outflow from the Venterspost Spring diminished, and eventually it dried up in 1947.

A profound change happened towards the end of 1968. Mining by West-Driefontein Gold Mine was extended to the Bank Compartment across the dyke separating Bank and Oberholzer Compartments. In October 1968 inflow of enormous amounts of groundwater threatened the workings and the miners. The inflow was eventually overcome and controlled. Details of the three weeks human and technical efforts were described by Cartwright (1969) and Cousens and Garrett (1969).

In the wake of the 1968 events, and in order to provide for safe mining, the Interdepartmental Committee on Dolomite Mine Water approved the dewatering of the Bank Compartment. Pumpage figures are given in Tabel 8.1 and 8.2.

Simultaneously a gravity survey was carried out by the Geological Survey to investigate sinkhole formation and subsidences anticipated as a consequence of the dewatering. In the course of this survey some 500 boreholes were drilled. Out of the total number of drilled holes, 90 were used for groundwater observation.

The general geology and the flow of groundwater to the mine workings is schematically demonstrated in Fig. 8.1. It should be noted that interconnected faults and fissures transmit water from the actual water bearing zone, which is rather limited in

BANK COMPARTMENT
Schematic Hydrologic Cross-section

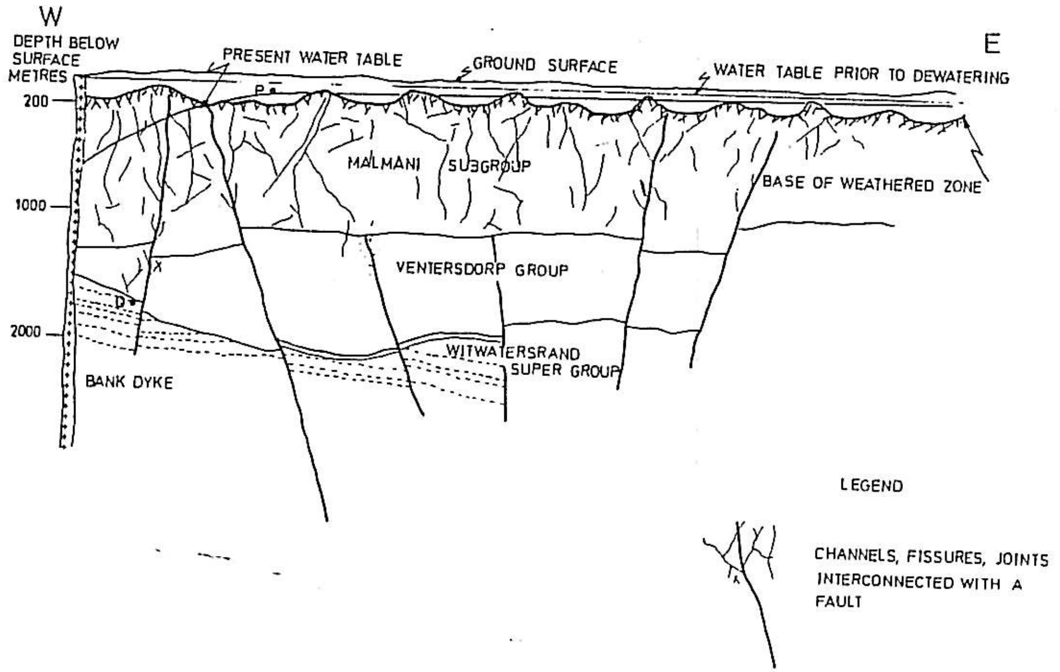


Fig. 8.1

TABLE 8.1: Monthly pumpage from Bank Compartment in $10^3 m^3$

Month Year	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
1969						907	1 633	2 342	3 236	3 197	3 150	3 517
1970	5 112	6 393	8 122	9 384	9 963	10 297	10 349	10 156	9 903	9 837	9 577	9 470
1971	9 204	9 074	8 735	8 548	8 346	8 233	7 938	8 281	7 283	7 204	6 875	6 139
1972	6 200	5 499	5 956	5 240	4 984	4 815	4 702	4 642	4 537	4 439	4 394	4 318
1973	4 893	3 503	4 122	4 089	3 921	3 977	3 820	3 727	3 758	3 665	3 485	3 419
1974	3 405	3 210	3 136	2 968	2 891	2 926	2 927	2 882	2 962	2 847	2 963	2 704
1975	2 950	2 600	2 394	2 432	2 503	2 456	2 516	2 400	2 311	2 391	2 395	2 400
1976	2 386	2 860	2 767	2 738	2 902	2 899	2 906	2 842	2 927	2 534	2 855	2 799

TABLE 8.2: Annual amounts of pumpage from Bank Compartment

Year (1/10-30/9)	Q in $10^6 m^3$
1968/69	44,290
1969/70	89,543
1970/71	104,526
1971/72	66,793
1972/73	48,961
1973/74	37,876
1974/75	31,076
1975/76	32,413

thickness, down to the mine. The major part of the dolomite, Ventersdorp volcanics and the Witwatersrand Super Group are actually impermeable. The amount of influx into the mine depends on the potential difference between say, points P and Q and on the specific permeability of the conduits (fissures, faults etc.). Actual flow occurs entirely due to underground excavations, while faults and joints facilitate to a certain extent the descending flow. The water table has dropped considerably since the early seventies and the amount of inflow has diminished accordingly (Fig. 8.2). The pumpage is however still in excess of the average natural intake from rainfall. With the dewatering process going on for nine years it is to be expected that part of the permeable aquifer has been drained. The irregular base of the aquifer as seen in Fig. 8.1 enables groundwater accumulation in the deeper troughs. Most of these lows are hydrologically interconnected as proved by the response of water levels to dewatering.

8.3 Previous Work

Enslin and Kriel (1959) concluded on the basis of gauged run-off loss and estimated evapotranspiration over a period of eleven months, that direct percolation from water channels and the river does take place in this compartment.

Monthly amounts of groundwater extracted from
BANK COMPARTMENT.

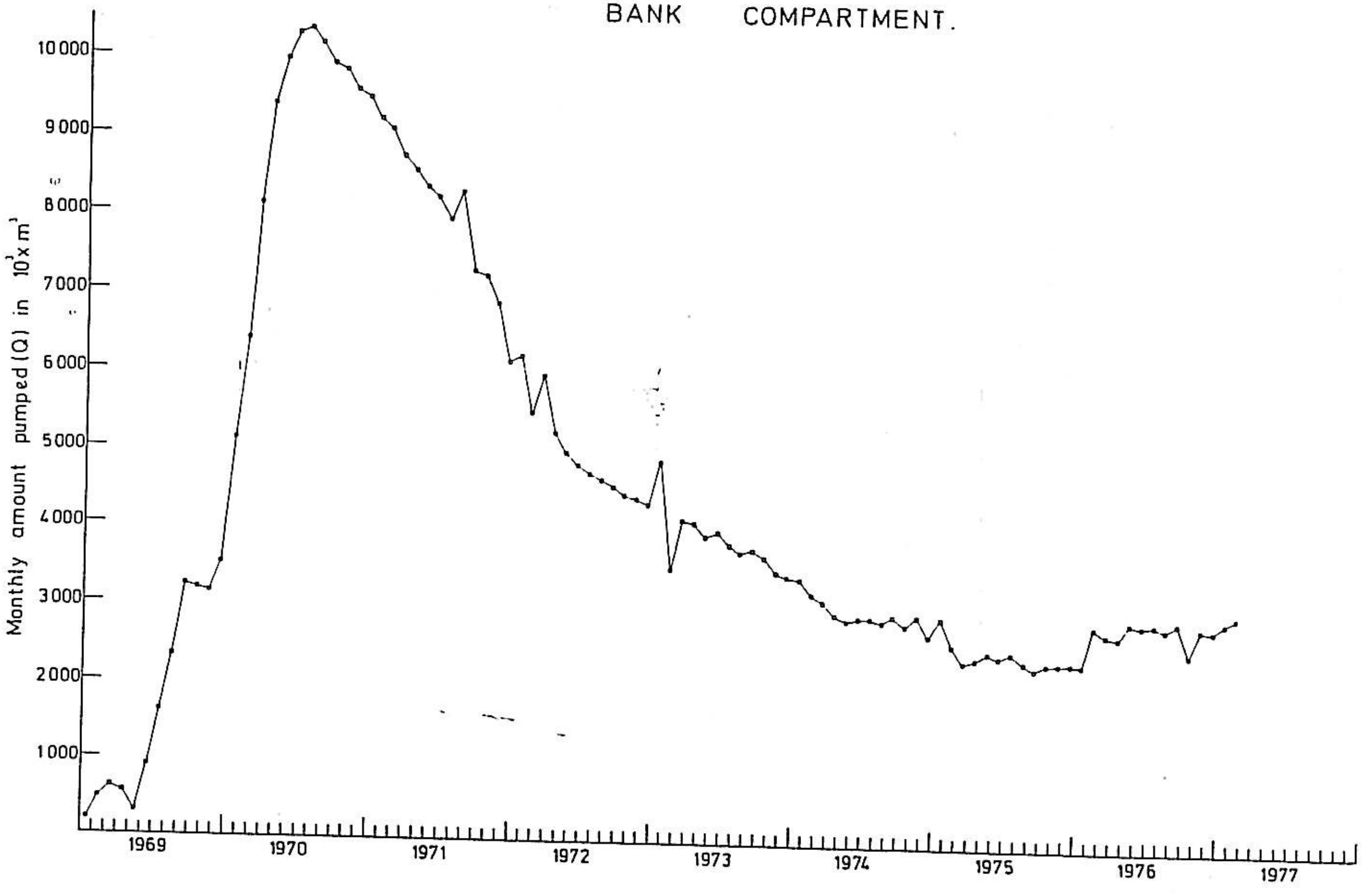


FIG. 8.2

Schwartz and Midgley (1975) made use of water table observations taken at 17 boreholes during the groundwater inflow episode of 1968. They applied the Theis non-equilibrium equation, and by using several assumptions, arrived at a transmissivity constant of 7 000 m^2/day, and a storage coefficient of 1,5%. The bulk of stored groundwater in the Bank Compartment down to a depth of 1 000 m, according to the above authors, was estimated at 2 000 x $10^6 m^3$.

8.4 The Mechanism of Replenishment

Monthly discharge figures from the spring for the period 1957 to 1969 are available. The annual amounts of discharge observed in this period are in the range of 16-22 x $10^6 m^3$, Table 8.3 and 8.4. Later outflow figures no longer represent the natural discharge.

A comparison of monthly discharges at the Spring, Fig. 8.3, with monthly rainfalls, reveals a marked systematic delay of about 6 months, when peaks are matched. The annual spring minima, generally in February, often appear simultaneously with maximum rainfall. On the whole the minima are not repeated exactly at the same month, small variations do occur, but the delay is nevertheless clear. It should however be borne in mind that the replenishment mechanism in these aquifers involve a two-phase percolation system. One is the delayed phase and the other is a nearly immediate phase (refer also to section 5.5). The delay is roughly assumed to originate from late arrival of replenishment water down to the saturated zone. Depth to water level seems to be the main cause for the delay. This would

Monthly discharge and rainfall at BANK SPRING.

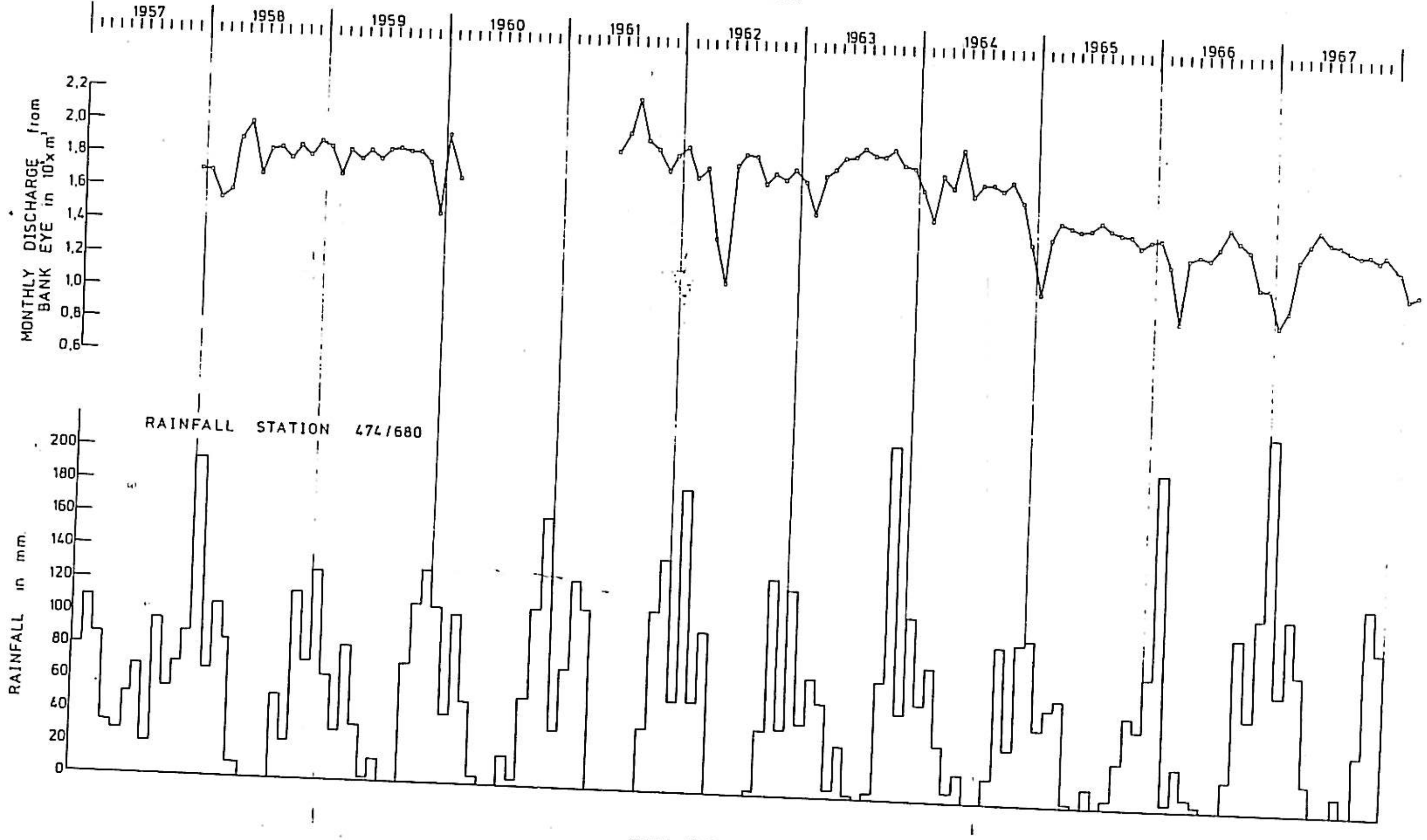


FIG. 8.3

TABLE 8.3: Monthly discharge amounts from Bank Spring in $10^6 m^3$

Month Year	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
1957												1,71
1958	1,70	1,54	1,59	1,90	2,00	1,69	1,84	1,85	1,79	1,87	1,81	1,90
1959	1,87	1,70	1,85	1,80	1,85	1,80	1,86	1,87	1,85	1,85	1,79	1,48
1960	1,96	1,70										
1961						1,89	2,00	2,21	1,96	1,91	1,79	1,88
1962	1,93	1,75	1,81	1,39	1,12	1,83	1,90	1,87	1,73	1,79	1,76	1,82
1963	1,75	1,55	1,79	1,83	1,90	1,91	1,96	1,92	1,92	1,96	1,87	1,83
1964	1,72	1,54	1,81	1,74	1,77	1,70	1,77	1,77	1,74	1,79	1,67	1,42
1965	1,12	1,45	1,55	1,53	1,51	1,52	1,56	1,52	1,49	1,49	1,42	1,46
1966	1,47	1,31	0,97	1,36	1,38	1,36	1,43	1,55	1,47	1,42	1,19	1,19
1967	0,97	1,06	1,37	1,49	1,55	1,48	1,47	1,44	1,41	1,42	1,38	1,42
1968	1,31	1,15	1,19	1,15	1,18	1,14	1,16					

TABLE 8.4: Annual discharge amounts from Bank spring

Year (1/10-30/9)	Discharge Q in $10^6 m^3$
1958/59	22,03
1961/62	16,86
1962/63	21,90
1963/64	21,22
1964/65	18,13
1965/66	16,67
1966/67	16,04

imply that the delay time varies from place to place. The relative significance of the two phases in each particular hydrograph depends on the physical conditions in the vicinity of the borehole. Most of the boreholes, shown in Fig. 8.4 are located near the river course, a fact which may have a bearing on the recharge. In other words, immediate recharge (shallow water levels) is dominant in these cases as compared say, to conditions in Steenkoppie Compartment, where most of the replenishment is due to delayed recharge.

The behaviour of water levels in a number of boreholes in Bank Compartment, during the pumpage of the reservoir, is shown in Figures 8.5-8.22.

In the course of the severe pumpage most of the boreholes gradually dried up. Several reasons account for the abandonment of observation:

(a) Shallow boreholes where the depth of penetration was too small became dry with the drop of the regional water table (saturated aquifer still existing beneath).

(b) Boreholes which locally penetrated solid dolomite, at rather high elevations, dried up, though other boreholes in the name area which encountered pervious material at a greater depth, remained in operation.

(c) In many cases gauging stopped due to the blocking of boreholes which is expected where no pumpage is practiced.

Hydrographs of boreholes prior to de-watering, BANK COMPARTMENT.

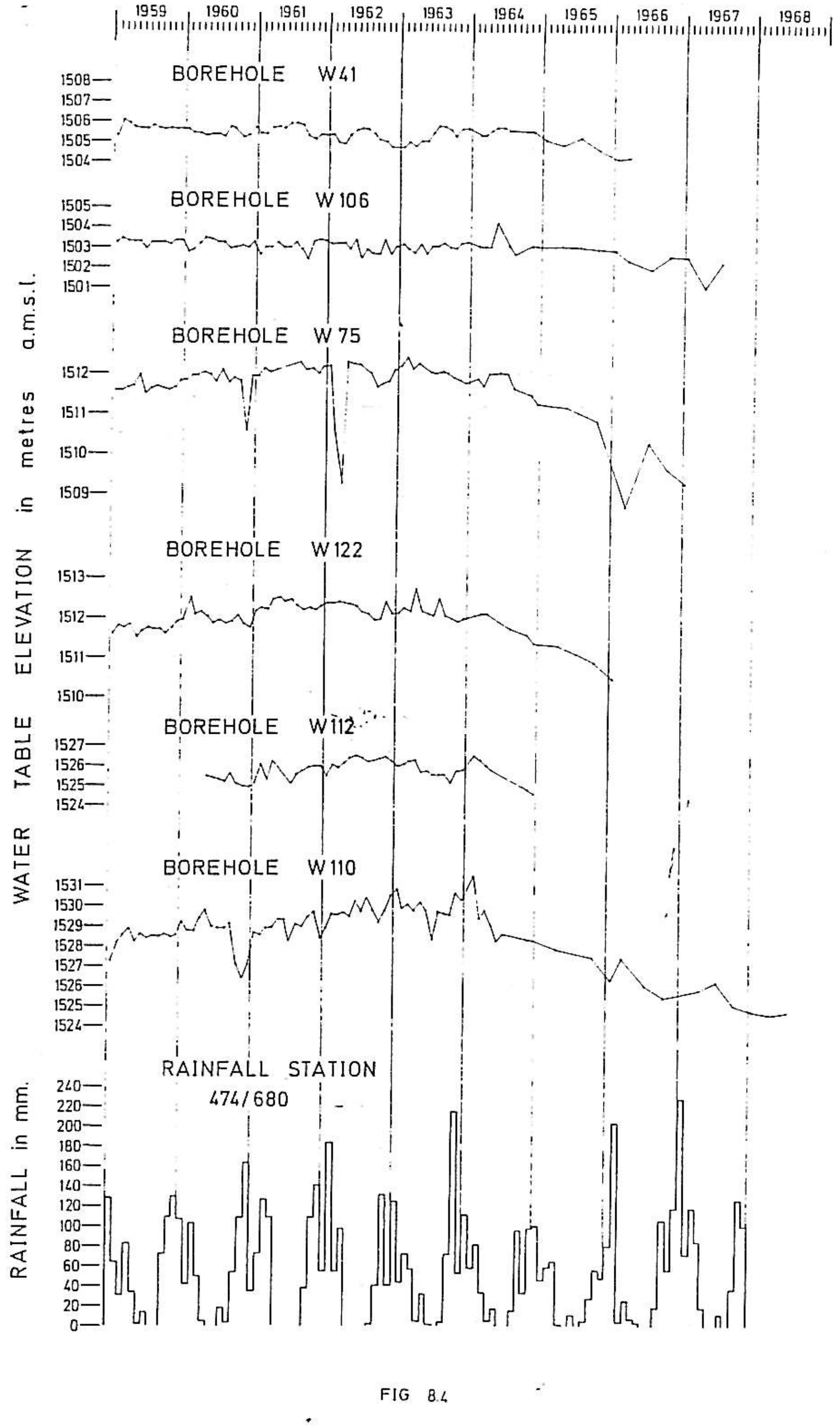


FIG 8.4

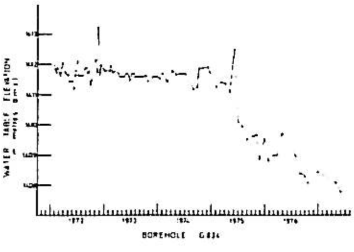


FIG 8.5

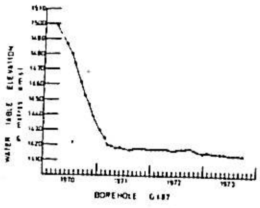


FIG 8.6

FIG 8.9

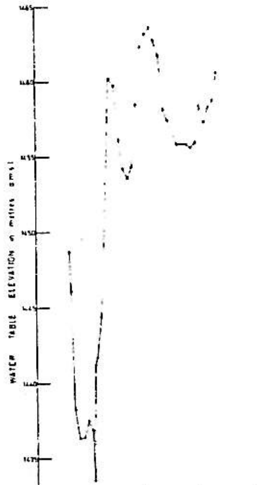


FIG 8.7

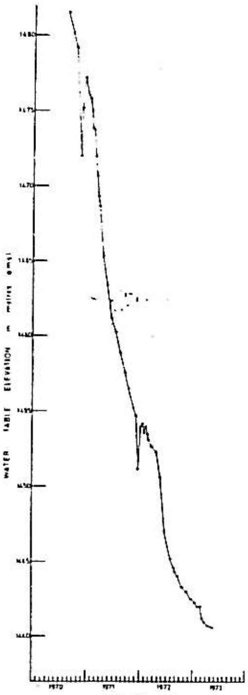


FIG 8.8

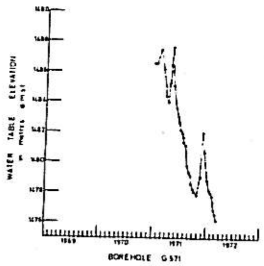


FIG 8.11

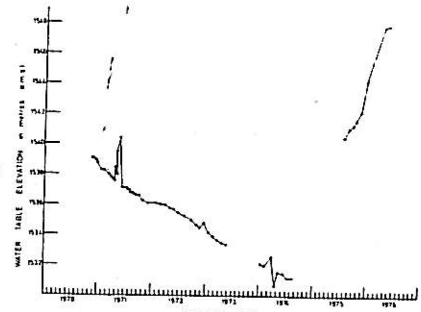
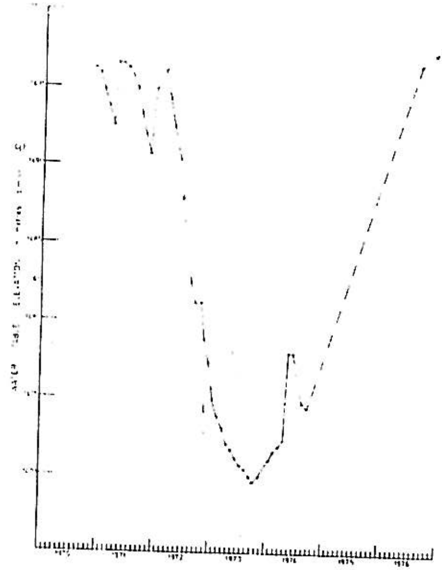
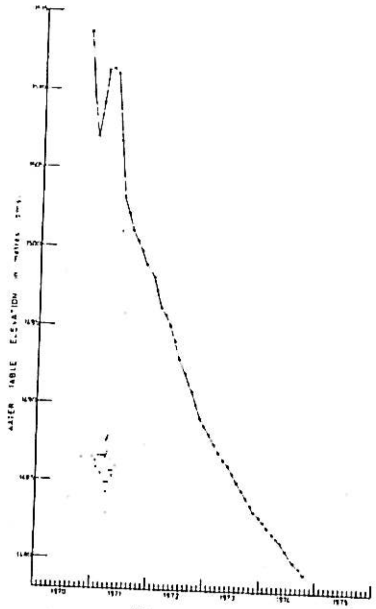


FIG 8.10



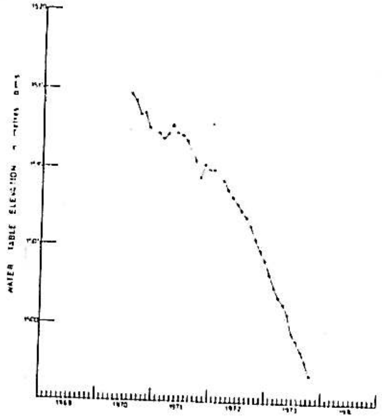
BOREHOLE G 592

FIG B 12



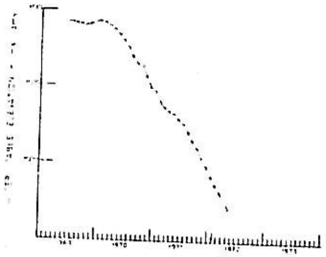
BOREHOLE G 435

FIG B 13



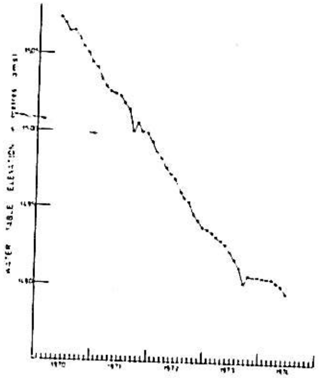
BOREHOLE W 129

FIG B 14



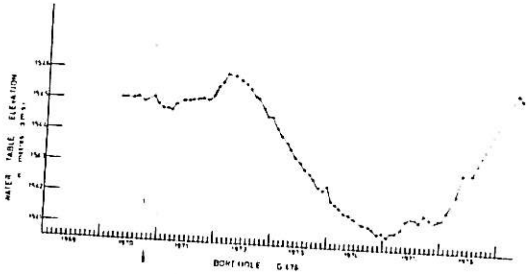
BOREHOLE W 125

FIG B 15



BOREHOLE G 511

FIG B 16



BOREHOLE G 476

FIG B 17

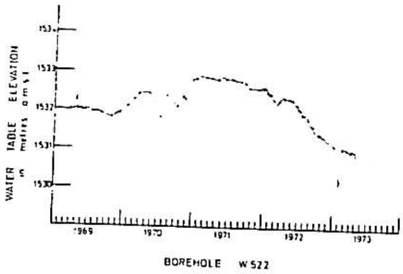


FIG 8.18

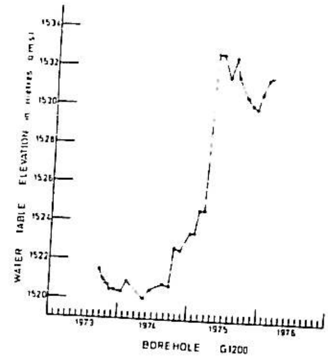


FIG. 8.19

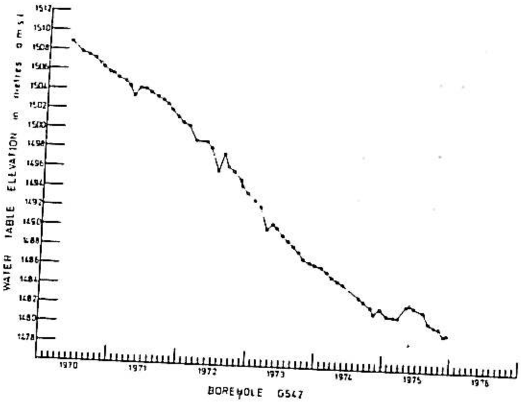


FIG 8.20

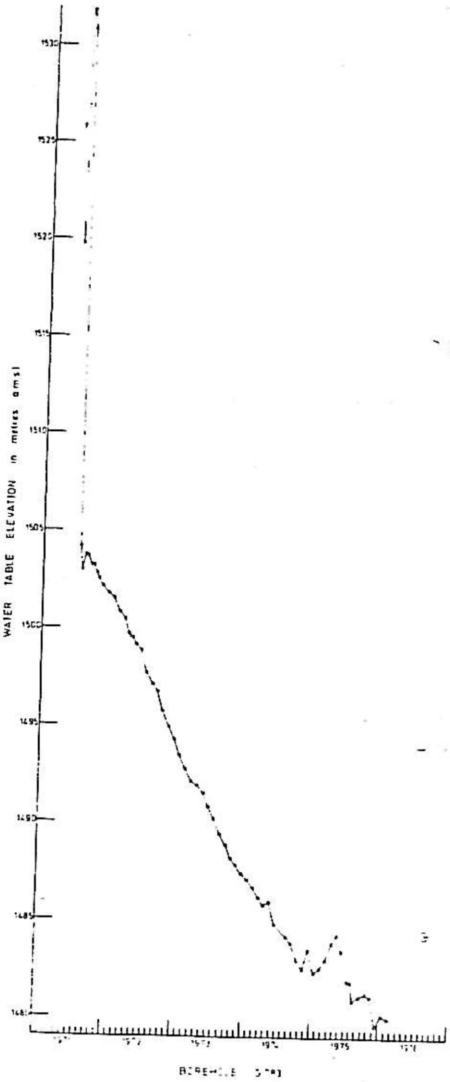


FIG 8.21

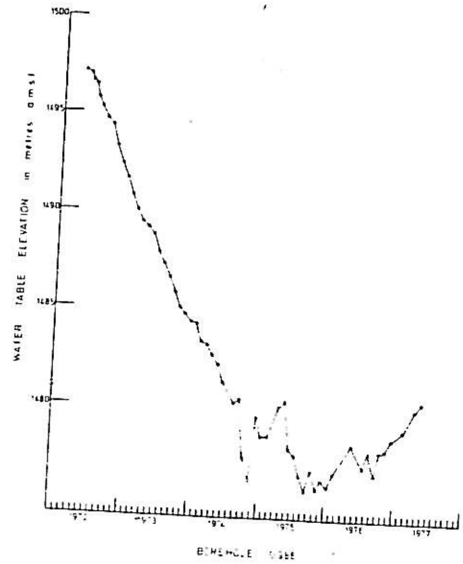


FIG 8.22

Table 8.5 includes relevant information of all available observation holes such as period of observation, nature of the aquifer, elevation and depth.

The drastic drawdown which developed with the large scale pumpage can be observed in Fig. 8.8; 8.9; 8.10; 8.13; 8.15; 8.16; 8.20; 8.21; 8.22. In some of the boreholes seasonal recharge is discernable, superimposed on the otherwise steeply declining water level, Figs. 8.14 and 8.22.

The north-eastern sector of the compartment has been-affected rather late (1972), Figs. 8.17 and 8.18. The water level tends to rise in this part in 1975/76 only due to a temporary decrease in the rate of extraction, combined with a good rainfall season. This area constitutes for all practical purposes an integral part of the Bank Compartment.

The Hill method, an empirical approach for the rough estimation of safe yield in a basin where overpumpage has been practiced and the corresponding drawdowns monitored over a long enough period, has been applied. In Fig. 8.23, annual drawdowns in borehole G783 were plotted against pumpage, and a line fitted to cut the zero drawdown. The safe yield which in this case equals natural recharge, was found to be 23 x $10^6 m^3$/year. Fig. 8.24 includes three boreholes where the same method has been applied. In two of the boreholes, G635 and G511, the drawdown corresponding to 1970/71 was apparently anomalous and had to be eliminated. The recharge figures obtained were 23 and 25 x $10^6 m^3$/year respectively. In the case of borehole G986

Annual pumpage figures against the corresponding drawdowns in borehole G783.

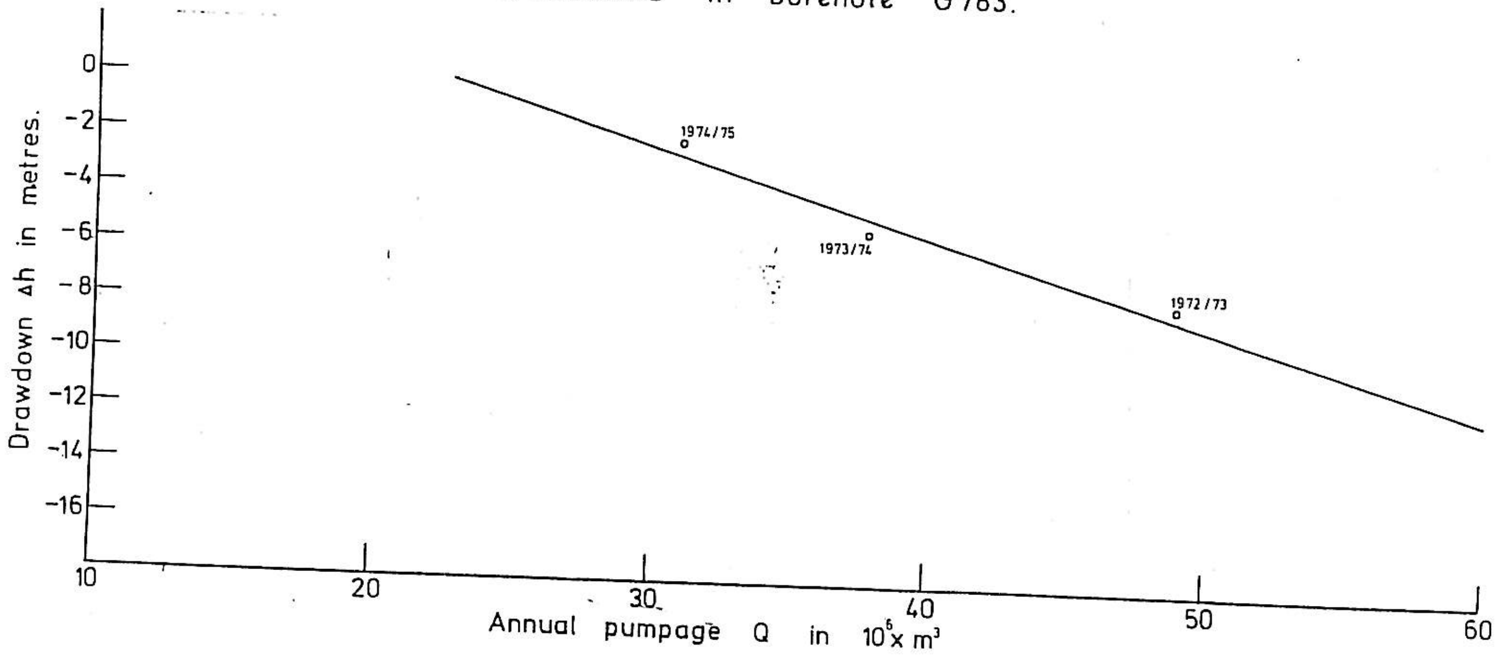


FIG. 8.23

Annual pumpage figures against the corresponding drawdowns in boreholes G511, G986 and G635

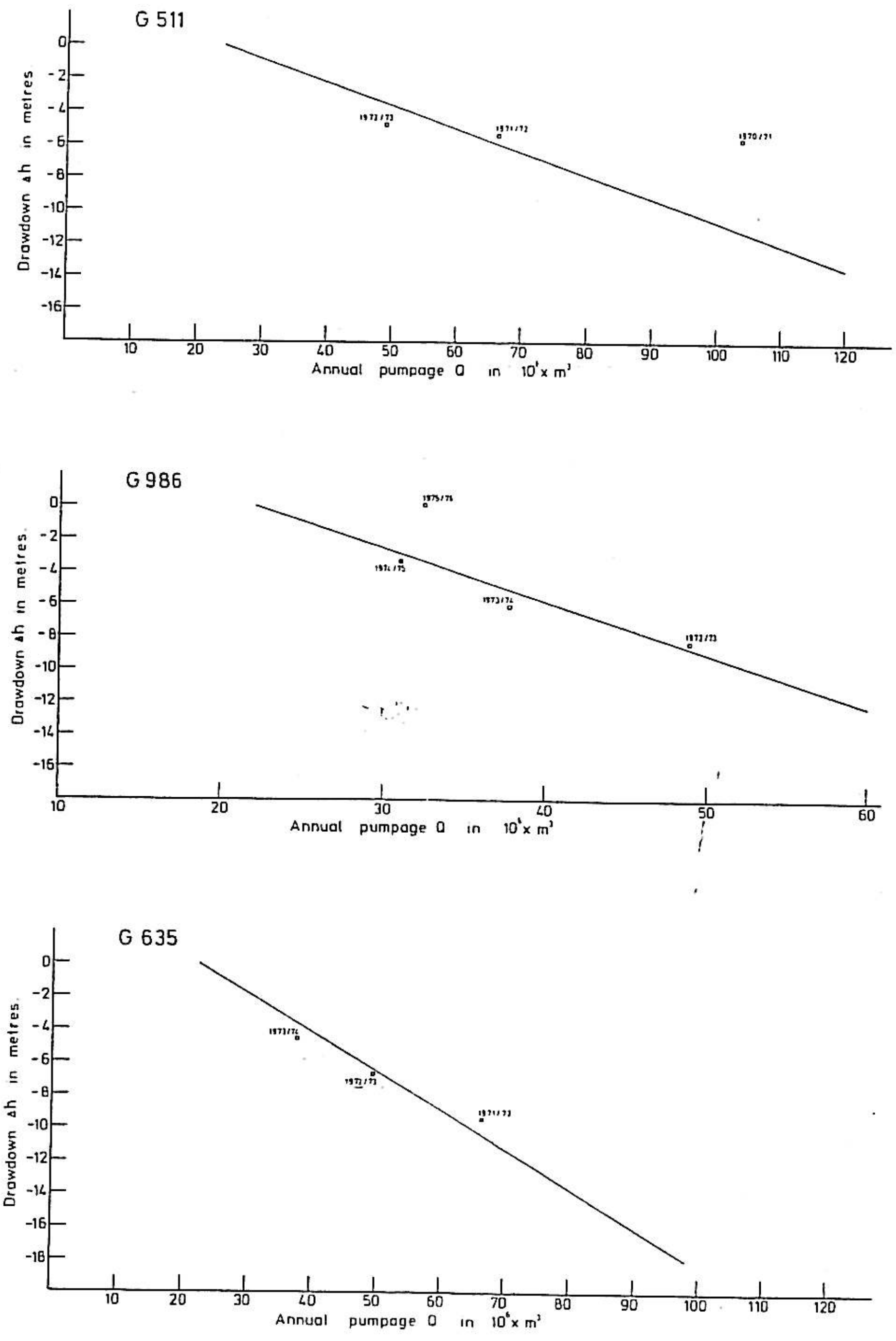


FIG. 8.24

TABLE 8.5: Observation boreholes in the Bank Compartment (all figures in metres)

Borehole number	Collar elevation a.m.s.l.	Depth	Aquifer*	Karoo**	Period of observation***
G455	1591,92	213,4	P	-	7/1969-9/1970
MW1	1576,86	-	-		1/1969-4/1970
G456	1582,16	213,4	P	-	8/1969-11/1970
G457	1564,79	213,4	P	-	4/1970-9/1970
MW2	1559,56	-	-	-	5/1969-3/1970
UD5	1645,07	-	-	-	5/1969-6/1971
E2E	-	-	-	-	1/1969
E2A	1571,07	-	-	-	1/1969-6/1971
G402	1557,79	129,5	C	50	5/1969-3/1970
E2G	1557,4	-	-	-	6/1969-2/1970
G438	1555,26	79,3	P	-	4/1969-7/1970
UD8	1626,63	-	-	-	1/1969-3/1971
E2J	-	-	-	-	1/1969
G439	1566,67	86,9	P	41	6/1969-8/1969
E2H	1564,82	-	-	-	12/1968-11/1970
G449	1556,13	213,4	C	90	6/1969-10/1970
G363	1540,99	169,2	P	47	1/1969-11/1970
G403	1523,63	157,9	P	-	3/1969-1/1971
G421	1521,69	91,4	P	-	3/1969-1/1970
G564	1516,94	29,6	P	-	6/1970-2/1972
G501	1516,33	103,6	P	-	4/1970-1/1971
G409	1514,72	48,8	P	-	4/1969-3/1970
G405	1510,66	50,3	P	-	3/1969-4/1971
W41	1510,36	-	-	-	10/1957-3/1966
G470	1519,39	56,4	P	-	9/1969-Present
UD7	1605,17	-	-	-	5/1969-7/1970
E1M	1585,90	-	-	-	5/1969-5/1970
G441	1581,56	91,4	P	26	4/1969-11/1969
G445	1568,14	59,4	P	-	
W60	1522,03	-	-	-	10/1957-1/1970
G446	1522,18	146,3	P	-	6/1969-1/1971
G454	1520,06	32	P	-	4/1969-9/1969
G414	1519,87	121,9	P	-	6/1969-10/1979

Borehole number	Collar elevation a.m.s.l.	Depth	Aquifer*	Karoo**	Period of observation***
G834	1517,02	120,4	P	-	1/1972-Present
G487	1524,25	141,7	P	-	3/1970-10/1973
G534	1537,67	91,4	P	-	1/1971-9/1971
W606	1535,21	-	-	-	4/1969-4/1973
W601	1557,44	-	-	-	4/1969-12/1970
W602	1566,45	-	-	-	4/1969-4/1975
W598	1570,91	-	-	-	4/1969-1/1972
W600	1562,33	-	-	-	4/1969-Present
E1D	1634,64	-	-	-	1/1969-3/1969
G750	1572,11	-	Perched	23	11/70-Present
G610	1572,11	-	P	15	8/70-9/1974
G452	1562,96	-	C	75	11/69-9/1970
E1Q	1541,52	-	-	-	12/1968-2/1971
G416	1532,73	213,4	P	-	6/1969-9/1970
G407	1525,38	79,3	P	-	1/1969-9/1969
G411	1524,39	158,5	P	-	4/1969-1/1971
W62	1525,3				9/1957-2/1970
G431	1524,27	79,3	P	-	4/1969-8/1970
G797	1522,15	195,1	P	-	9/1971-6/1974
G408/2	1521,36	50,3	P	4	3/1969-2/1970
G408/1	1520,92	56,4	P	12	1/1969-5/1970
G504	1525,19	61	P	-	10/1969-6/1970
G676	1523,34	48,8	P	-	7/1970-2/1972
G660	1524,25	45,7	P	-	6/1970-11/71
G415	1514,07	208,9	C	9	6/1969-9/1970
E1N	1597,84				1/1969-10/1971
G590	1573,63	153,9	C	50	11/1970-12/1971
W102	1546,43				10/1957-1/1963
G486	1541,46	140,2	C		2/1970-8/1970
W97	1522,35				11/1957-4/1962
W98	1539,38				1/1958-9/1969
G413	1520,68	96	P	-	6/1969-11/1970
G591	1573,63	146,3	C	58	8/1970-10/1974
EM13	1553,38	-	-	-	1/1971-4/1972
W106	1550,4	-	-	-	10/1957-9/1969

Borehole number	Collar elevation a.m.s.l.	Depth	Aquifer*	Karoo**	Period of observation***
W131/1	1547,38	–	–	–	3/1969-1/1970
W108	1550,61	–	–	–	4/1969-8/1970
W100	1545,91	–	–	–	10/1957-1/1962
G506	1534,62	88,4	P	–	11/1969-4/1972
G507	1537,06	82,3	P	–	5/1970-4/1972
G563	1525,17	61	P	–	5/1970-3/1972
G571	1533,70	70,1	P	–	1/1971-3/1972
MW3	1586,44	–	–	–	6/1969-4/1972
MW4	1567,72	–	–	–	6/1969-4/1972
G592	1572,11	121,9	P	49	11/1970-Present
G451	1566,62	213,4	C	88	11/1969-Present
EM12	1559,51	–	–	–	6/1970-7/1971
G488	1542,85	83,8	P	–	5/1970-5/1971
G508	1539,19	50,3	P	–	5/1970-Present
G579	1536,75	74,7	P	–	6/1970-2/1972
W339	1549,80	–	–	–	11/1968-10/1970
W525	1531,01	–	–	–	1/1971-12/1971
G632	1561,74	100,6	P	27	11/1970-11/1976
W534		–	–	–	1/1971-9/1971
W510	1551,95	–	–	–	3/1969-9/1970
G674	1541,63	32	P	–	8/1970-11/1976
W337	1602,73	–	–	–	1/1957-12/1970
W595	1643,26	–	–	–	3/1969-10/1971
MW6	1556,26	–	–	–	8/1969-4/1972
G510	1552	42,7	P	–	5/1970-2/1972
W610	1539,19	–	–	–	6/1970-1/1971
G635	1527,30	77,7	P	–	10/1970-Present
W45	1563,12	–	–	–	6/1957-11/1960
G436	1566,64	89,9	P	–	4/1969-8/1972
W75	1553,49	–	–	–	11/1957-10/1970
G432	1552,25	90,5	P	–	3/1969-4/1970
G511	1547,11	59,1	P	–	5/1970-Present
W125	1540,54	–	–	–	10/1957-5/1972
W124	1542,01	–	–	–	3/1969-10/1971
W129	1535,91	–	–	–	1/1958-11/1976

Borehole number	Collar elevation a.m.s.l.	Depth	Aquifer*	Karoo**	Period of observation***
W122	1540,34	-	-	-	10/1957-3/1966
W123	1539,86	-	-	-	10/1957-7/1967
G523	1531,66	160,9	P	-	4/1970-10/1974
W571	1610,01	-	-	-	3/1969-Present
G1160	1617,31	33,5	P	-	4/1973-Present
W333	1623,62	-	-	-	3/1969-7/1971
G987	-	167,6	P	-	6/1972-11/1973
MW5	1599,85	-	-	-	9/1969-6/1971
G761	1610,01	128	P	30	3/1971-Present
W46	1571,30	-	-	-	3/1969-8/1970
MW7	1565,70	-	-	-	9/1969-12/1971
W509	1558,92	-	-	-	3/1969-10/1970
W73	1559,12	-	-	-	11/1957-5/1968
G512	1550,12	64	P	-	11/1969-10/1972
W70	1549,91	-	-	-	11/1957-10/1965
W114	1543,29	-	-	-	3/1969-9/1970
W420	1544,07	-	-	-	7/1970-1/1971
W115	1543,52	-	-	-	3/1969-9/1971
W118	1543,33	-	-	-	10/1957-6/1968
G762	1611,82	128	-	47	3/1971-5/1974
G986	1573,68	135,6	P(?)	56	4/1972-Present
G783	1570,13	183,8	P	-	6/1971-7/1976
G582	1553,82	53,3	C	27	6/1970-7/1972
G513	1555,65	140,2	P	-	6/1970-2/1972
G542	1544,53	93	C	24	4/1970-8/1976
G605	1544,70	64	P	-	6/1970-9/1971
G604	1544,52	39,6	P	-	6/1970-3/1972
W425	1538,47	-	-	-	3/1969-3/1972
G535	1543,60	35,1	P	-	4/1970-5/1974
W112	1542,88	-	-	-	5/1960-9/1968
W111	1542,36	-	-	-	3/1969-10/1971
G1134	1534,70	41,5	P	-	4/1973-Present
G1200	1535,05	59,4	P	-	9/1973-2/1976
G1198	1536	-	-	-	7/1973-Present
G1135	1541,09	37,2	P	-	4/1973-12/1975

Borehole number	Collar elevation a.m.s.l.	Depth	Aquifer*	Karoo**	Period of observation***
W428	1549,03	-	-	-	3/1969-1/1972
G1293	1559,97	57,9	P	-	3/1974-6/1976
G522	1563,54	-	-	-	3/1969-1/1975
G1294	1562,35	39,6	P	8	3/1974-2/1976
G1152	1566,64	50,3	P	-	4/1973-Present
G476	1570,14	91,4	P	-	4/1970-Present
G1218	1578,14	45,7	P	-	8/1973-Present
W331	1574,59	-	-	-	10/1958-9/1968
G1159	1594,01	36,6	P	-	4/1973-Present
MW8	1583,08	-	-	-	10/1969-10/1971
G796	1573,03	-	-	-	6/1971-Present
G1042	1569,28	79,3	P	11	7/1972-Present
G514	1559,92	71,6	P	-	6/1970-Present
W110	1546,41	-	-	-	10/1957-12/1973
G1153	1537,80	38,1	P	-	4/1973-Present
G1292	1548,91	42,7	P	-	3/1974-Present
G1185	1562,8	76,2	P	-	7/1973-6/1976
W567	1591,84	-	-	-	3/1969-Present
G516	1565,09	-	P	10	7/1976-7/1976
G524	1544,98	161,5	P	-	4/1970-Present
G1341	1552,32	128	P	-	12/1974-Present
G1184	1551,65	539	-	-	6/1973-Present
G98	1567,93	-	-	-	11/1965-3/1975
G1221	1577,25	-	-	-	9/1973-Present
G1219	1587,53	48,8	P	-	8/1973
B1	1585,21	-	-	-	6/1965

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* The type of the aquifer before dewatering
P = Phreatic; C = Confined

** Penetrated thickness of Karoo Beds

*** The period may include intervals of no records and different frequencies in measurements the drawdown for 1975/76 did not fall in line with the rest of the data and was left out. Here the recharge was 22 x $10^6 m^3$/year. An acceptable average amount of natural recharge is therefore 23 x $10^6 m^3$/year.

The average annual rainfall for the period 1971/72–1974/75 (4 years), based on five gauging stations in the studied area, amounts to 636 mm, Table 10.2. The annual natural recharge expressed as percentage of the rainfall may thus be calculated as the following:

$$\frac{23 \times 10^6 m^3 \times 100}{154 \times 10^6 m^2 \times 0,636\ m} = \frac{23 \times 100}{97,9} = 23,5\%$$

The somewhat high figures for the average natural recharge arrived at in Figs. 8.23 and 8.24 as compared to spring discharge records can be explained if conditions in the aquifer are examined: During the said period 1969–1976, and due to dewatering, a considerable part of the aquifer volume practically became empty. The creation of excess storage in the central sector of the compartment, along the river and in the area where natural discharge previously took place, is of special importance. In this area before dewatering groundwater level used to be very shallow and any intake would spill over to the Oberholzer Compartment. Under the new artificial conditions an increase in the rate of recharge could be expected. Similar results were obtained in Venterspost Compartment, where very much the same conditions prevail.

As stated before the Hill method is only applicable where mean annual recharge is the case. Regional rainfall data, based on five gauging stations, confirms beyond doubt that 1970/71 and 1975/76 were high rainfall seasons with 800 mm and 833 mm respectively. The above average rainfall contributed to a much larger intake. In a detailed study of springs in the dolomite aquifer, elaborated on in Part 10, it could be demonstrated that certain rain seasons differ very much from the average and the annual recharge in cases such as 1970/71 and 1975/76 is outstanding. The fact that data from 1970/71 and 1975/76 had to be discarded in the above analysis provides a clue that much higher annual recharges than 23 x $10^6 m^3$ may occur.

8.5 Storage Evaluation

Two methods have been employed to calculate the storage: the bookkeeping balance and a spring analysis.

Bookkeeping method

Two water balances were prepared to calculate the storage coefficient in the compartment. For each balance period a set of two water level contour maps were prepared, for the beginning and the end of the period. These maps were superimposed on each other and a third map produced, showing Δh, the thickness of the dewatered aquifer. The volumes of the dewatered rock material were calculated with the aid of a planimeter. The volume of groundwater extracted through pumpage, during the balance period, was compared to the dewatered aquifer volume. Allowance was made in each case for natural replenishment during the balance period.

Application

The selection of balance periods had been complicated mainly by the insufficient coverage of the area with boreholes. To a certain extent inadequate depth of boreholes was also an obstacle. With the development of pumpage, boreholes in the vicinity of the pumping mine went out of operation rather rapidly. Upstream and in the eastern three quaters of the compartment, very few boreholes were available. Drilling which commenced in the area for geophysical purposes was applied generally for ad hoc engineering problems. No monitoring net was laid out for groundwater investigation.

The rate of drawdown in an area with a radius of about 4 km from the mine can be seen on the key map (Folder 8.1), where the date at which the water table dropped to the datum of 1 440 m a.m.s.l. is shown.

Water balance A covers the period 6/1969-6/1970. It includes a full rain season. The water table contour map at the beginning of the balance period A is shown in Folder 8.3 and at its end in Folder 8.4. Folder 8.5 represents the difference ~~of~~ one map from the other. The volume of dewatered rock material has been calculated by planimetration and amounts to $3322 \times 10^6 m^3$. The total amount of groundwater extracted during the said period from the compartment was $61,655 \times 10^6 m^3$. An allowance has however to be made for a full season of natural replenishment say, about $23 \times 10^6 m^3$. The net extraction was therefore:

$$61,655 \times 10^6 m^3 - 23 \times 10^6 m^3 = 38,655 \times 10^6 m^3$$

The storage will thus be $\frac{38,655 \times 10^6 m^3 \times 100}{3322 \times 10^6 m^3} = 1,16\%$

Water balance B, which includes the period 1/1971-1/1972, was calculated in a similar way. At the beginning of the period (1/1971), the water levels in boreholes E1N, E1Q and G403, (Folder 8.1), reached depths of 248 m, 190 m and 150 m respectively. This would suggest that the area delineated between E1N, E1Q and the dyke, where the water table dropped below 200 m, could for all practical purposes be neglected in the storage considerations. Balance B covers therefore a somewhat reduced area. In the selection of this balance period, availability of water level records was the main problem.

The natural recharge during this period includes two incomplete rainy seasons. The first wet months of 1970/71 season are excluded while 1971/72 season includes only the first months. As mentioned before, the recharge mechnism is not simple and involves two phases. In accordance with this setting, the recharge during balance period B will be a combination of the delayed phase of recharge from rainfalls during 11-12/1970, the total recharge from 1-4/1971 and the immediate phase of recharge from 11-12/1971. It can thus be assumed that the intake during the said period included a full one year recharge.

Folders 8.6 and 8.7 demonstrate the water table contour maps at the beginning and at the end of the balance period. The volume of dewatered aquifer, 1836,73 x $10^6 m^3$, was calculated from Folder 8.8. The total pumped volume of water during balance period B was 97,458 x $10^6 m^3$. The estimated natural recharge per year derived in section 8.4 is 23 x $10^6 m^3$. The net pumpage is accordingly 97,458 x $10^6 m^3$ - 23 x $10^6 m^3$ = 74,458 x $10^6 m^3$.

The storage is therefore: $\frac{74,458 \times 10^6 m^3 \times 100}{1836,73 \times 10^6 m^3} = 4,05\%$

Spring Analysis

The discharge pattern shown in Fig. 8.3 is rather typical of the summer rain climate and the dolomitic aquifer involved. Recharge of the aquifer extends over the greater part of the year. Sometimes the delayed phase at the end of one rainy season may coincide with the start of the next season's rainfall. It is therefore only during a limited period of two to three months that a recession curve may follow.

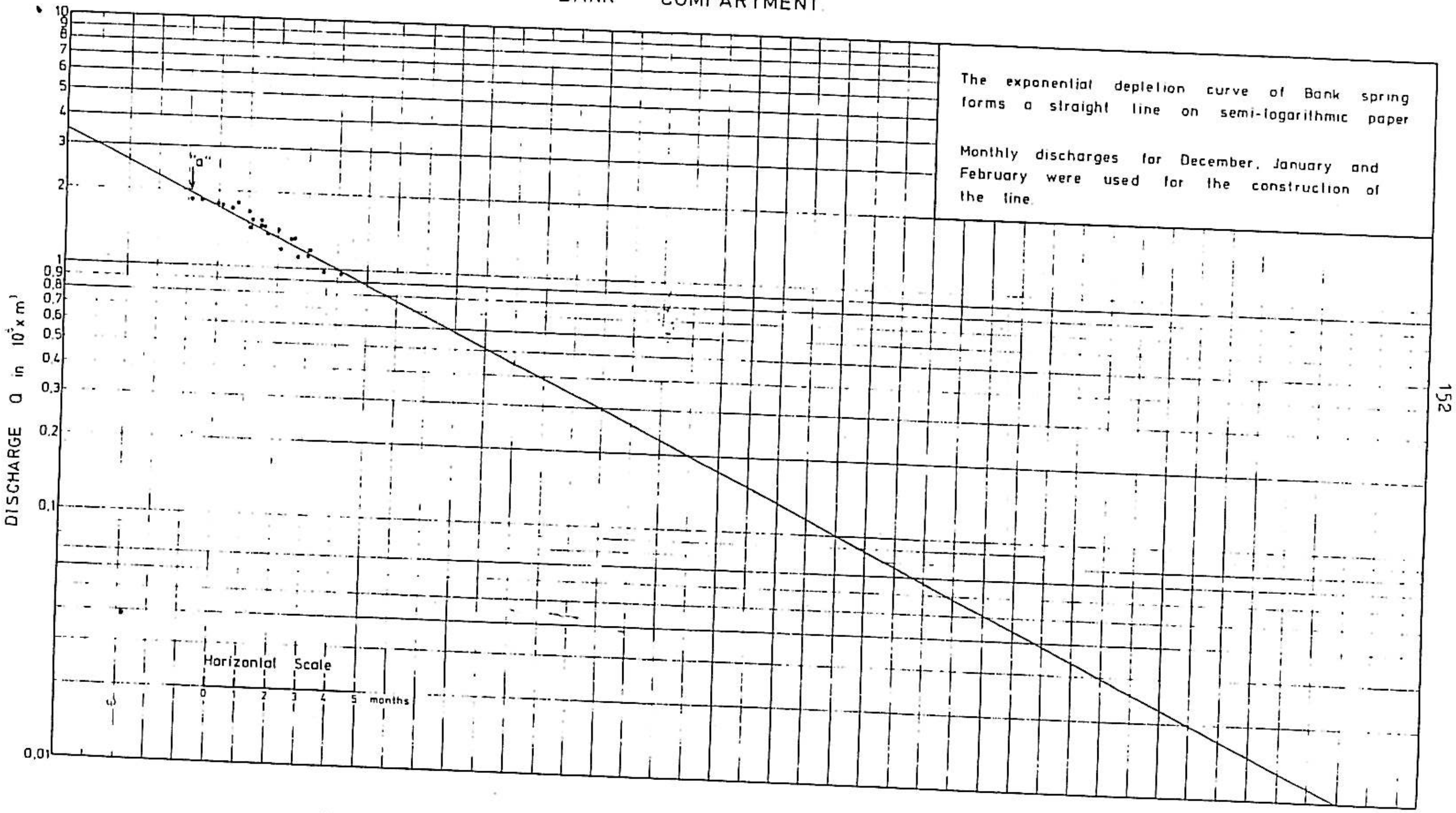
Depletion curves of discharge through a spring system, during a non-replenishment period, can be approximated very closely by an exponential function, sometimes with more than one exponential function (Mero, 1963). Discharge-storage relationship can thus be studied by analyses on semi-logarithmic paper.

Monthly discharges from the short periods of assumed no intake in every year (December, January, February) have been compiled and plotted together in Fig. 8.25. The result is a straight line which represents the free drainage through the spring, provided no recharge takes place. The time units on the horizontal (arithmetic) scale indicate months. By selecting a starting point of discharge on the logarithmic scale, and assuming no intake occurs, it is possible to calculate successive monthly discharges of free drainage. Several practical applications may be worked out, based on the depletion line in Fig. 8.25.

The time interval measured in months, on the horizontal scale, between a starting point "a" and the point where the sloping line intersects the zero discharge represents the time required for the complete drainage of the storage in the reservoir. The reservoir is defined as the mass of aquifer between the water table surface and a horizontal plane, the elevation of which corresponds to the outflow point of the spring. In the case of Bank Compartment, the time required to drain the reservoir would be about 40 months.

Records from the few observation holes which had been in operation during 1959-1967 allow for the construction of a rough water table contour map, (Folder 8.9). The aquifer volume of the reservoir has been calculated for October 1963, and the spring outflow altitude was taken as the base of the reservoir. The aquifer volume, (Folder 8.9, totals $1519 \times 10^6 m^3$. The groundwater storage retained in the aquifer, on the above data,

Spring Discharge and Storage Relationship in
BANK COMPARTMENT



The exponential depletion curve of Bank spring forms a straight line on semi-logarithmic paper

Monthly discharges for December, January and February were used for the construction of the line.

FIG. 8.25

has been read from the depletion line, Fig. 8.25, in monthly portions of discharge up to the complete drainage of the reservoir. This volume of water amounts to 15,6 x $10^6 m^3$. The storage coefficient obtained is:

$$\frac{\text{Groundwater storage x 100}}{\text{Reservoir volume}} = \frac{15,6 \times 100}{1\ 519} = 1\%$$

8.6 Recharge - Rainfall relationship

In order to investigate the relationship between recharge and rainfall, annual net recharge has to be compared with rainfall. The annual discharges at Bank Spring have been corrected in the following way: For every year, starting in October, the monthly discharges of twelve months were read-off from the depletion line and summed up. This amount represented the assumed free drainage which would have issued if no recharge had taken place. Each annual free drainage was then substracted from the corresponding recorded gross annual outflow. Thus corrected, annual recharge figures have been arrived at (Table 8.6). In Fig. 8.26, corrected annual discharge figures have been plotted against total annual rainfall. The linear relationship is clearly observed. This relationship enables the forecast of the net recharge for the given annual rainfall amounts. An additional parameter which can be deduced from Fig. 8.26 is a threshold value of rainfall, 200 mm, below which apparently no recharge will occur.

Rainfall-recharge relation in
BANK COMPARTMENT.

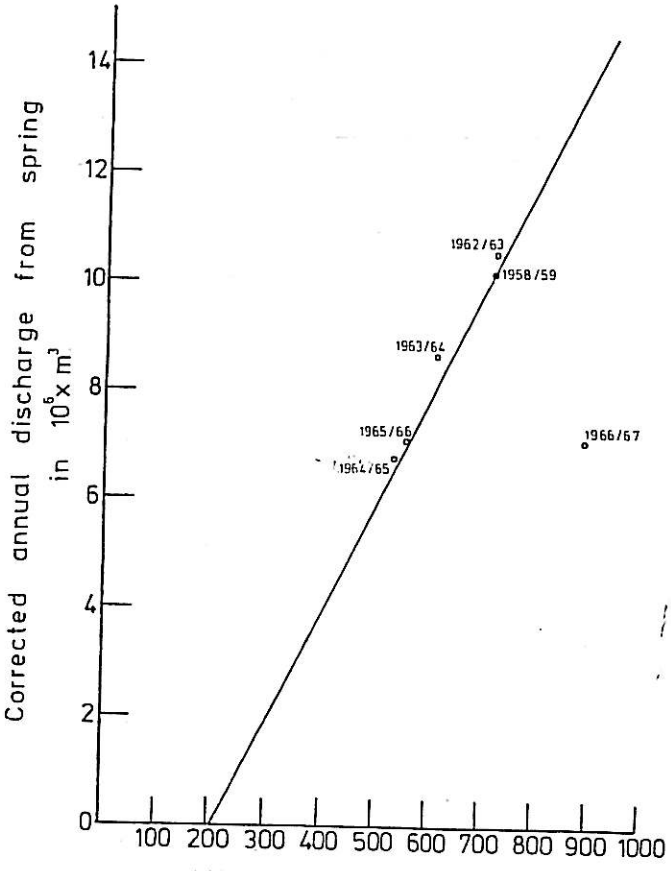


FIG. 8.26

TABLE 8.6: Calculation of the annual natural recharge
All amounts in $10^6 m^3$. Rainfall in mm

Year (1/10-30/9)	Q1	Q2	Q3	Rainfall
1958/59	22,03	11,89	10,14	712
1961/62	16,86	12,55	4,31	773
1962/63	21,90	11,39	10,51	713
1963/64	21,22	12,55	8,67	608
1964/65	18,13	11,39	6,74	530
1965/66	16,67	9,55	7,12	553
1966/67	16,04	9,00	7,04	897

Bank spring: Total annual discharge (Q1), calculated annual free drainage (Q2), corrected annual discharge (Q3 = Q1 - Q2)

The corrected annual discharge is equal to the annual natural recharge.

The 1960/61 season was discarded in Fig. 8.26 as the discharge data do not seem plausible. The 1966/67 season does not fall in line with the rest, and no explanation is postulated to account for this discrepancy. It will be shown later, in the study of springs (Part 10) that the replenishment all over the studied area during 1966/67 was lower than the expected.

8.7 Discussion

Some inaccuracies in the above calculations are due mainly to the lack of a proper net work of observation holes. This is also the reason that an investigation of a vertical change in storage was not applicable. Another shortcoming is inadequate simultaneous rainfall gauging points, which is essential for a detailed hydrometeorologic study.

Out of the three water balances carried out to determine the storage, two yielded closely-related figures, namely, 1% and 1,2%. A higher figure of 4,05% was found through balance B. It is however noted that each of these balances has its drawbacks and should be evaluated accordingly: In balance A, due to the configuration of the depression cone, deeper parts of the aquifer are involved in the dewatered volume. Porosity is expected to decrease with depth (Enslin and Kriel, 1967), consequently the calculated storage coefficient is too low. In balance B an amount of $23 \times 10^6 m^3$, which equals the natural recharge of one year, has been introduced to the calculation. This figure however represents an average which is not applicable for the 1970/71 season. During this exceptionally wet season, the recharge may have been twice as much, a fact which is confirmed by analyses of springs located in other geohydrologic units. The calculation may thus be revised as follows: $97{,}458 \times 10^6 m^3 - 46 \times 10^6 m^3 = 51{,}458 \times 10^6 m^3$

$$\frac{51{,}458 \times 10^6 m^3 \times 100}{1836 \times 10^6 m^3} = 2{,}8\%$$

The storage coefficient obtained from the spring analysis is most probably an under-estimation. In this case the weak points are the highly conjectural nature of the reservoir volume and a possible built-in inaccuracy of the depletion line. The use of the depletion line is justified where a no-recharge period is assumed. Whether this requirement is completely satisfied has not been proved.

9. INVESTIGATION OF TURFFONTEIN AREA

9.1 Introduction

Turffontein Area, as compared to previously discussed geohydrologic units, had not been geophysically surveyed. The occurrence and nature of significant sub-surface structural elements such as igneous dykes are still missing. The area covers some 400 km^2 of Malmani Subgroup outcrops, mostly concealed below younger decomposed rocks and soil. The Wonderfontein River crosses the area along its central part, and on the whole, geohydrologic conditions in the Turffontein Area are similar to those described before farther upstream. The dolomite dips regionally southwards where it is overlain by sediments of the Pretoria Group. These sediments stand out topographically as a hilly crest bordering the area to the south (Folder 9.1).

Preliminary sampling and chemical analysis of surface-waters were done in May 1977. A full scale sampling programme of groundwaters was carried out in late 1978.

As it was found that mine effluents play a major role in the hydrologic setting in the Turffontein Area, a closer follow-up of surface-water quality has been undertaken. Some 17 stations were selected where water has regularly been monitored since the end of 1979. At the beginning, samples were collected every fortnight, but this has later been changed to a monthly frequency.

9.2 The impact of gold mining activities on the quality of water

Uncontaminated genuine aquifer water in the studied area is generally of low mineral concentration, typically 100 to 500 milligram per litre total dissolved salts. The major ions being HCO_3^-, Ca^{++} and Mg^{++}.

Under the present circumstances however, the quality of groundwater in this area no longer reflects purely natural conditions. Although the sources of contamination include the use of fertilizers, manure from cattle farming, urban sewage effluents, air-borne salts of industrial origin, by far the dominant factor affecting groundwater is due to the extensive and prolonged mining activity in the Far West Rand.

A close inspection of routine water use by the gold mines immediately reveals that the general trend is one of a constant deterioration in the quality of the available water.

The influx of originally fresh dolomitic water, derived from the overlying aquifer, descends hundreds of meters and remains in contact for a considerable time with a different type of newly excavated rock material, which is commonly rich in sulfide minerals, mostly pyrite. These are easily oxidized and dissolved. As a result, the water is enriched in sulphuric acid. Water is practically used in all underground processes and is stored in underground reservoirs. Explosives commonly used down the mine also contribute chemicals to the water. To neutralise the acidity of the water it is often treated with lime. Water in excess of the underground requirements is pumped to the surface. Most of this amount is disposed of away from the mine as effluents.

Up on the ground surface a certain amount of water is essential in the process of the extraction of the gold. Crushing and grinding of rocks in reduction plants are wet processes. Water is however recycled in a closed circuit. In the process of cyanidation gold enters into solution as cyanide complexes and the fine-grained rock residue mixed with water is boostered to the slime dams and allowed to settle. Under normal conditions this too is a closed system where water is recirculated. Generally no serious contamination hazards to groundwater are expected in connection with these closed systems. Occasionally, for instance during storm spells, slime dams may become flooded or the walls may yield, stored fluids thus spill out and the mineralized water may percolate to the aquifer.

Piles of mined and crushed rock material dumped around mine shafts are exposed to rainwater for long periods of time, it undergoes a similar leaching process as described in connection with the underground workings. This source of salinity may contribute directly to the underlying groundwater.

Leakage from slime dams is another possible source of contamination to be considered although it is assumed that such leakage is usually significant only during the initial stages of operation of a slime dam, while later on the bottom layer is sealed off by fine grained sediments.

9.3 Geohydrologic setting

Turffontein Area is bounded on the east by a major dyke which separated Oberholzer Compartment from the Turffontein Area. A strip of several dykes probably faulted and discontinuous forms the western boundary (Folder 9.1).

Groundwater drains through Gerhardminnebron and Turffontein Springs. These springs are advantageously located away from the Wonderfontein stream bed and the flows gauged at the points of issue consist of groundwater discharge only.

Nearly all available boreholes are concentrated along the river courses. Data is insufficient to present a water level contour map. Groundwater flows in a south-westerly direction, as is inferred from the limited information on water levels from boreholes (Folder 9.1). A further sub-division of the area into smaller geohydrologic units may be expected but with the lack of a geophysical survey, this cannot be positively demonstrated.

Two separate groundwater depressions exist on either side of Oberholzer Dyke, a deep one resulting from the dewatering of Oberholzer Compartment by West Driefontein and Blyvooruitzicht Mines, and a shallower one which is due to abstraction of groundwater by Doornfontein Mine.

9.4 Disposal of water from the gold mines

Groundwater abstracted from the dolomite aquifer by gold mines has been diverted as effluents into the studied area. The effluents are discharged west of Oberholzer Dyke.

Two groups of mines may be distinguished in this respect: Group I includes Venterspost, East Driefontein and West Driefontein Mines. Group II includes Blyvooruitzicht, Western Deep Levels and Doornfontein Mines. As from mid-1977, intercepted Donaldson Dam and Gemsbokfontein Eye water are also included in the flow coming from Group I mines.

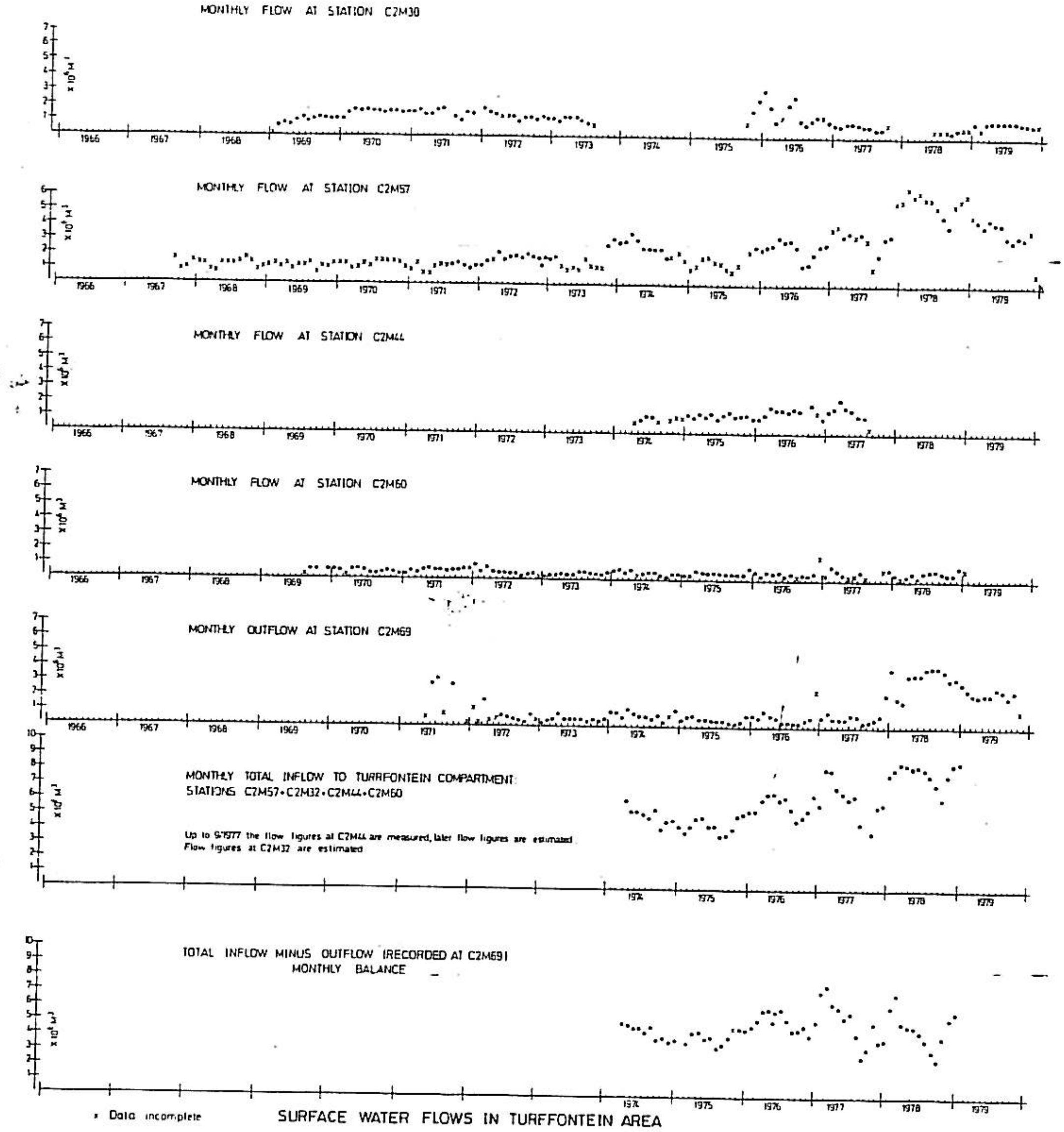
Effluents from both mine groups flow in water proof pipes and concrete canals up to the eastern boundary of Turffontein Area, so as to avoid leakage. In the studied area however, west of Carletonville, the effluents are carried in a combination of earth furrows, concrete canals and the river course. The water is also temporarily stored in earth dams and regularly overflows to resume its course downstream in the river bed. Obviously, percolation down to the saturated zone is expected in the studied area.

The surface water flow pattern in the area is schematically demonstrated in Folder 9.1: Water from Venterspost No. 2 Shaft arrives at point C, (Former Bank Eye), where the flow is automatically recorded at Station C2M30 (Fig. 9.1). From Point C the water is divided into two carriers. One of the canals arrives at the dividing box point F, and the other, which also runs across Oberholzer Compartment, extends beyond it into the Turffontein Area. The flow in this second canal is supposed to be gauged at Station C2M44, point L (Folder 9.1 and Fig. 9.1). Most of the data from this station was technically unsatisfactory.

Another carrier, a 1 meter pipe, delivers a combination of water from Venterspost Mine Shaft 1 plus the water intercepted at Gemsbokfontein Eye. This pipe discharges into a canal which leads to the dividing box.

Effluents from West and East Driefontein Mines enter the dividing box at point G.

The water entering the dividing box mixes and leaves the box in two canals going westward beyond the boundary dyke. Flow in the northern canal is automatically recorded at Station C2M57, point J (Folder 9.1). Flow in the southern canal is supposed to be measured respectively at Station C2M32. Unfortunately all data from C2M32 was worthless and had to be rejected. A few manual measurements were carried out during 1980 at Station C2M32 which enable a rough estimation of the average flow.



SURFACE WATER FLOWS IN TURFFONTEIN AREA
Fig. 9.1

In the Turffontein Area the water flows in two parallel courses. One water carrier enters Carletonville Nature Reserve Dam and the other by-passes this Dam. It is worth mentioning that occasionally when large volumes of effluents are involved, part of the water is diverted into an abandoned quarry and a cave system on the northern bank of the river (Folder 9.1). Water leaving the above mentioned nature reserve dam continues westwards to Welverdiend Dam. Shortly before the dam the two water carriers join together. From Welverdiend Dam the water flows downstream in the river. On its route, the river collects the spring flows from Turffontein and Gerhardminnebron, and residual amounts to surface-waters from the studied area, eventually reach Boskop Dam.

Effluents from Group II mines also enter Welverdiend Dam and the flow amounts are automatically recorded at Station C2M60 (Fig. 9.1). Water leaving Welverdiend Dam is automatically monitored at Station C2M69 (Fig. 9.1).

The total monthly amounts of inflow to Turffontein Area are shown in Fig. 9.1. This could however be worked out for a relatively short period of time and the calculation is subject to some inaccuracies due to the lack of measured data at Stations C2M44 and C2M32.

By substracting the flow at C2M69 from the total inflow (Fig. 9.1) an approximate idea may be formed concerning the magnitude of the combined components: Artificial groundwater recharge, evapotranspiration and consumption. These figures however are valid for part of Turffontein Area only as Station C2M69 is not located on the western boundary.

The uncertainities introduced in the graph which described the monthly total inflow (Fig. 9.1) renders it impractical for comparison with the monthly total amounts of groundwater pumped by the mines (Fig. 9.2). Such a comparison could indicate the rate of consumption of irrigation water east of Oberholzer Dyke. Nevertheless, a similar general trend can be observed during 1974-1978, when the amounts of water discharged into Turffontein Area (Fig. 9.1) are compared with amounts pumped by the mines (Fig. 9.2). The total annual amounts pumped by Group I mines, less the water consumed on the mines, increased during the said period from some 48 x $10^6 m^3$ to about 80 x $10^6 m^3$. The total annual amounts of groundwater pumped by Group II mines, and diverted to Turffontein Area remained more or less constant, and is in the range of 6 x $10^6 m^3$.

9.5 Reaction of the groundwater system to artificial recharge

A major dewatering episode of the Oberholzer Compartment occured during the period 1954-1967. The abstracted water was discharged into the Wonderfontein River and this manifested

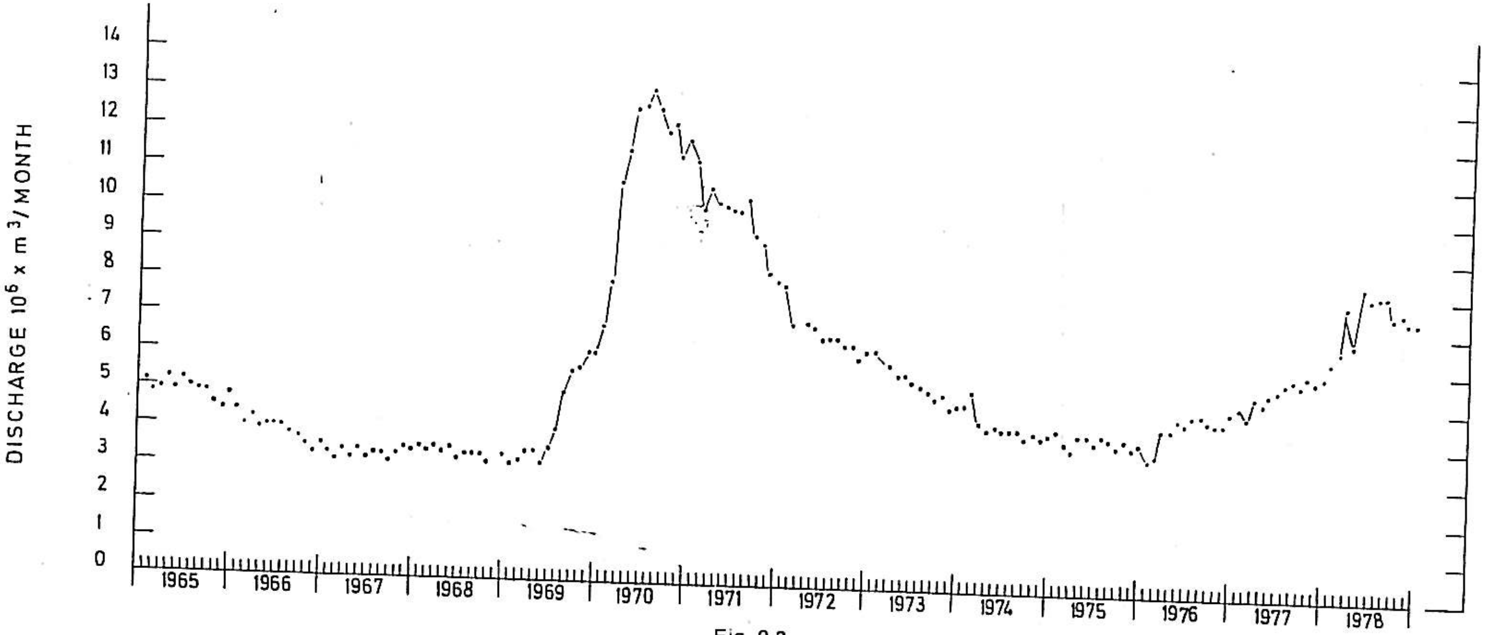


Fig. 9.2

MONTHLY AMOUNTS OF GROUNDWATER PUMPED BY VENTERSPOST, EAST AND WEST DRIEFONTEIN GOLD MINES AND DIVERTED TO THE WONDERFONTEIN RIVER COURSE, WEST OF CARLETONVILLE. WATER CONSUMED ON THE MINES NOT INCLUDED.

itself in the increase in Turffontein Spring discharge, demonstrated in Fig. 9.3. Also shown in Fig. 9.3, as a reference for comparison, is the discharge hydrograph of Maloney's Spring, the outflow of which represents drainage from a compartment completely unaffected by artificial interference. The diverse trends observed in the discharges of the two springs, under identical climatic conditions, suggests that at Turffontein the reaction of groundwater is due to artificial recharge by the effluents.

A similar dewatering episode occured during the years 1970 and 1971, as seen in Fig. 9.2, where monthly amounts of water abstracted by Group I gold mines, during the period 1965-1978, are shown. In these figures, consumption on the mines is excluded, but no records are available for amounts utilized for irrigation. Most of the abstracted water has been discharged as effluents onto the dolomite terrain beyond Oberholzer Dyke (Folder 9.1). In this case however, the natural replenishment pattern somewhat complicates the picture. From Maloney's Spring discharge hydrograph (Fig. 9.4) it appears that 1970/71 was an exceptionally wet season which contributed to an increased outflow. Water levels observed in two mine shafts and a borehole (Fig. 9.5) reveal a rise in the beginning of 1970. This rise most probably reflects the response to artificial recharge, because the outstanding wet season only started later, namely at the end of 1970.

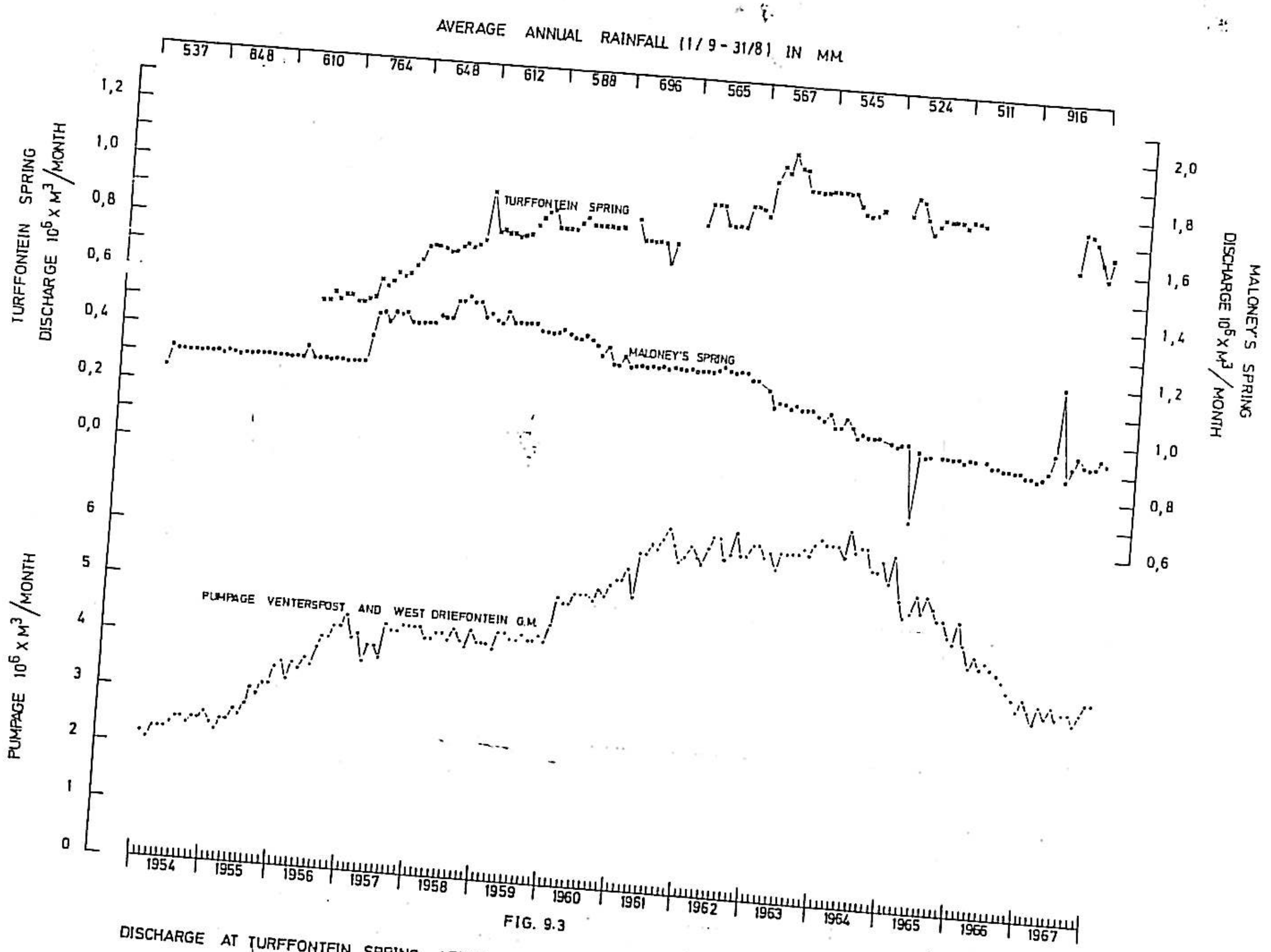


FIG. 9.3

DISCHARGE AT TURFFONTEIN SPRING, AFFECTED BY ARTIFICIAL RECHARGE FROM EFFLUENTS SPREAD IN THE RIVER COURSE COMPARED TO NATURAL DISCHARGE AT MALONEY'S SPRING.

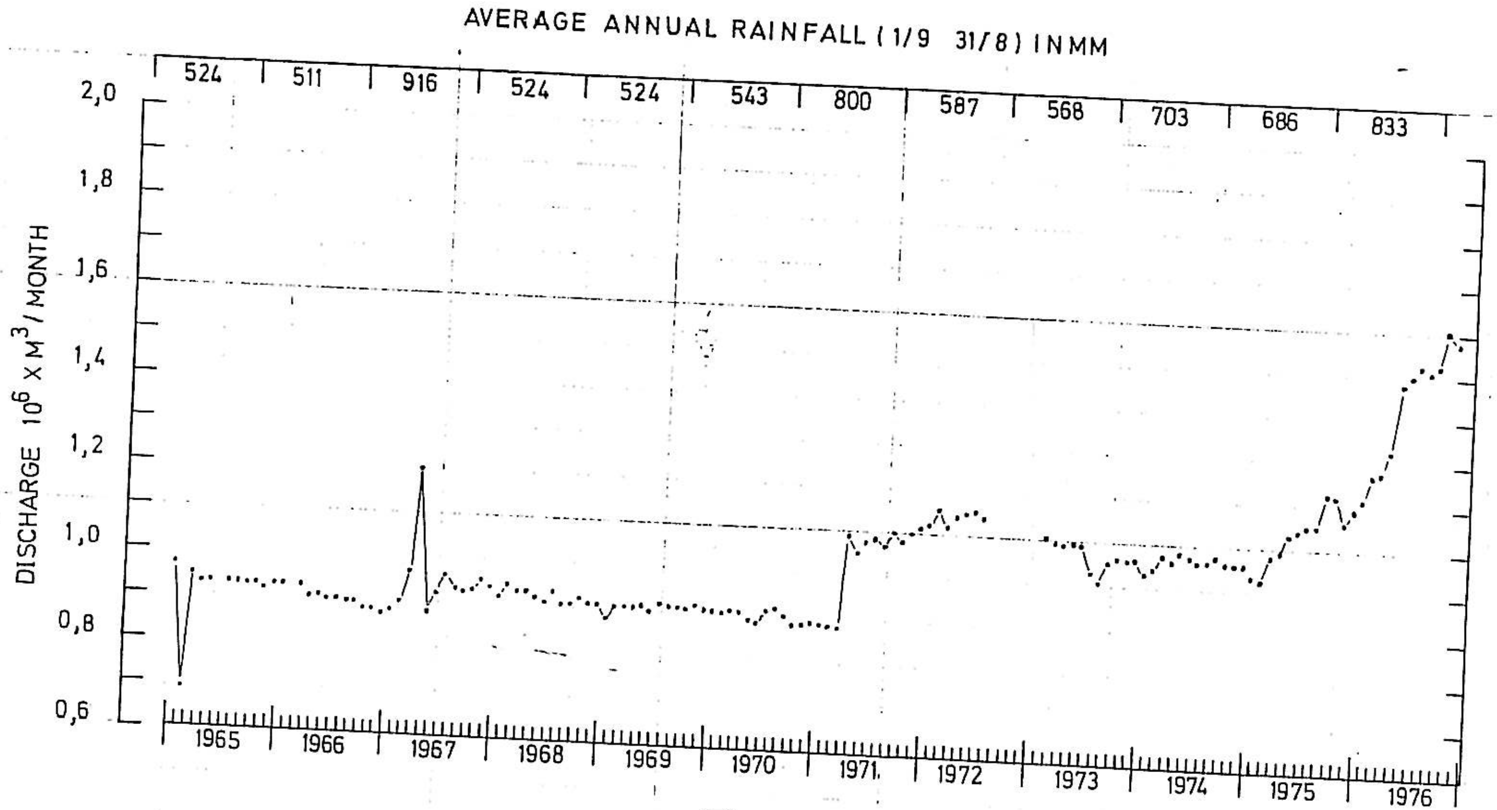


Fig. 9.4
MONTHLY DISCHARGE AT MALONY'S SPRING

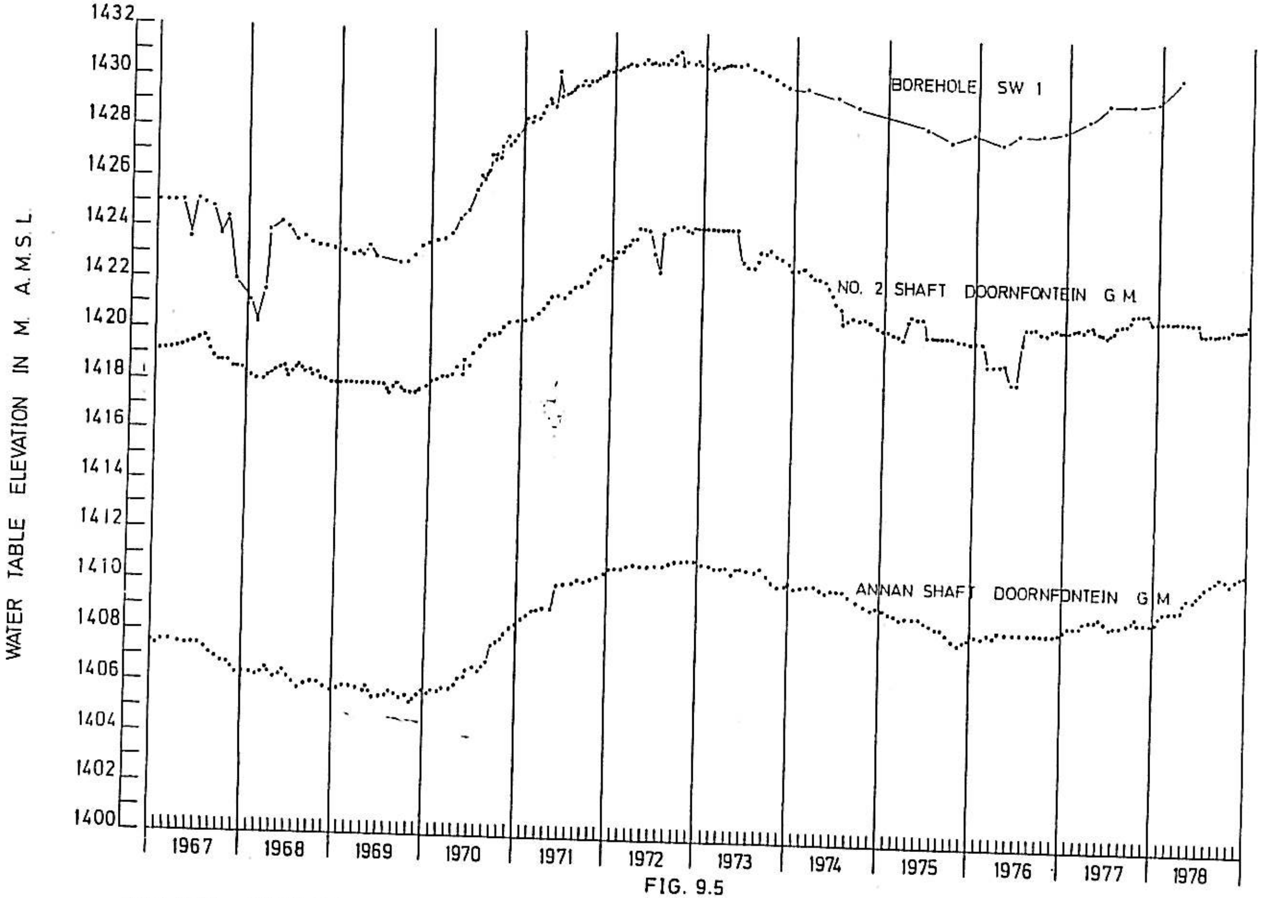


FIG. 9.5

ARTIFICIAL RECHARGE REFLECTED ON GROUNDWATER HYDROGRAPHS BY A RISE OF WATER LEVELS AT THE BEGINNING OF 1970

This correspondence between recharge due to effluents and groundwater behaviour can be observed simultaneously on the Turffontein Spring hydrograph (Fig. 9.6) where an increase in discharge started here too prior to rainfall. The rather high discharge, maintained later on, consists assumingly of a combination of artificial and natural recharges. The correlation found also indicates that the groundwater system of Turffontein Spring reacts rather rapidly to recharge.

Inspection of the discharge hydrograph of Gerhardminnebron Spring (Fig. 9.7) does not clearly reveal such a correlation between artificial recharge and outflow. The small increase in September 1970 is too ambiguous to be substantiative. A significant increase occurs in this case in April 1971, which of course could be interpreted as the response to natural replenishment. It is plausible that the larger size of Gerhardminnebron groundwater system, with an annual discharge of 20-29 x $10^6 m^3$, as compared to Turffontein with 14 x $10^6 m^3$, is the reason for the vague impression of the comparatively small quantities involved in the artificial recharge.

9.6 Hydrochemical Aspects

Simultaneous water sampling has been undertaken during late 1978, and full analyses are presented in Table 9.1. Occassionally repeated samples were taken. Water samples in the

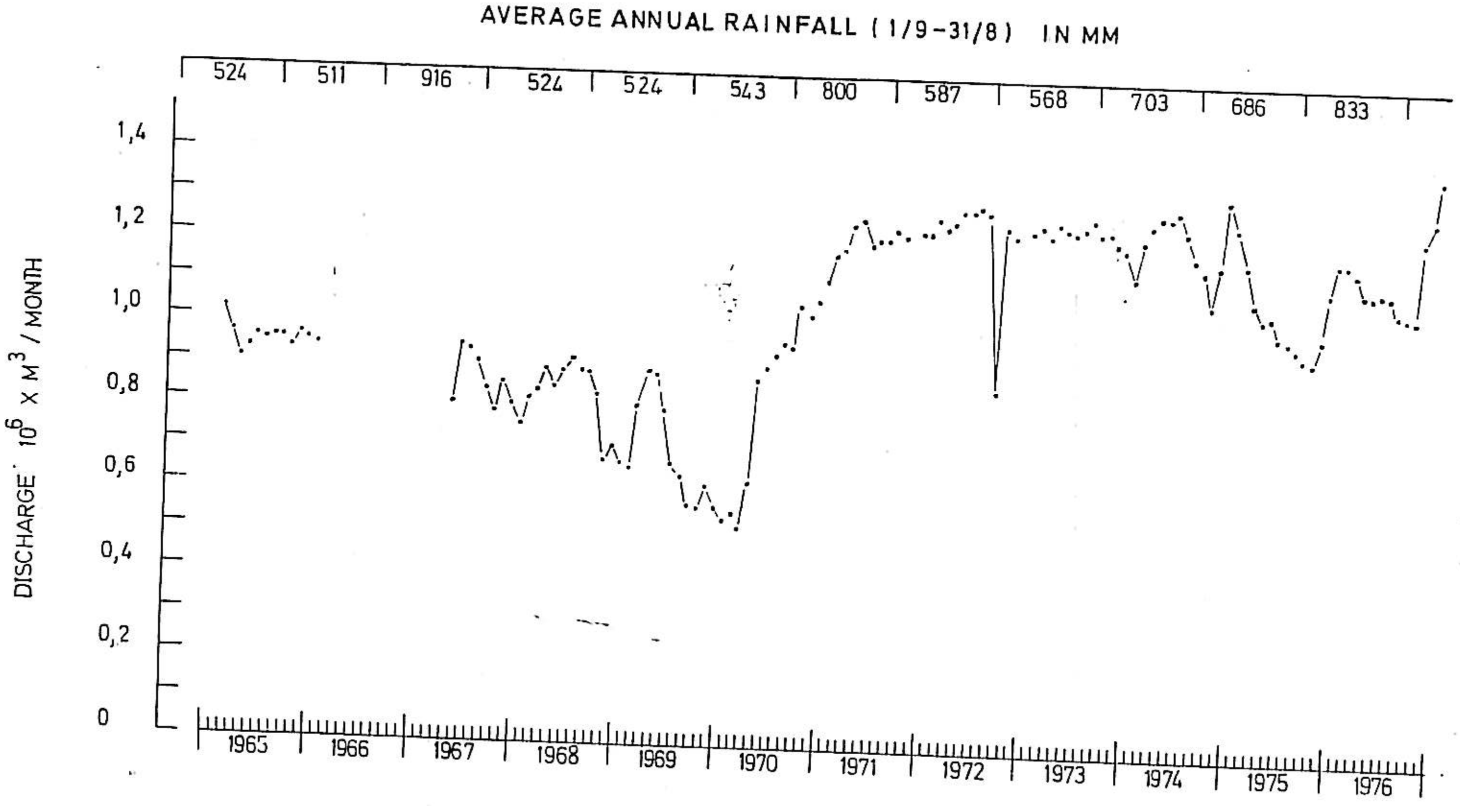


Fig. 9.6
MONTHLY DISCHARGE AT TURFFONTEIN SPRING C2M13

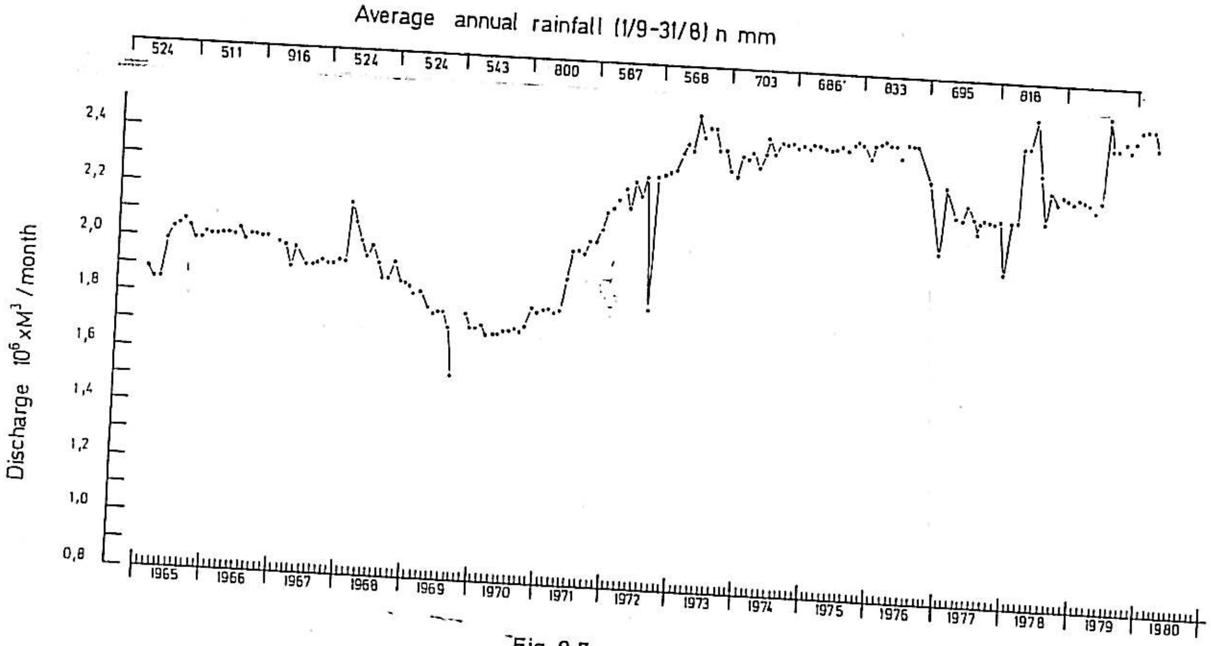


Fig. 9.7
Monthly discharge at gerhardminnebron spring C2M11

TABLE 9.1: Chemical analyses of waters from Turffontein Area, in milligrams per litre

No.	Source	TDS	pH	Ca	Mg	Na	K	Si	Cl	SO_4	HCO_3	NO_3
	SPRINGS											
1	Turffontein	604	7,70	73,3	42,7	29,6	1,2	8,4	25,4	156,8	256,4	10,4
2	Gerhardminnebron	405	7,80	52,6	32,1	7,8	0,5	7,8	8,3	48,8	237,7	8,9
3	Maloney	212	7,90	26,0	15,4	2,3	0,5	6,7	2,0	2,0	155,8	1,1
	EFFLUENTS											
4a	H	500	7,60	56,9	32,7	32,8	3,1	4,8	17,6	179,5	151,4	21,8
4b	K	512	7,53	57,9	33,5	34,0	3,1	4,9	18,5	190,0	145,6	24,4
4	J	510	7,29	55,7	34,4	31,9	3,1	5,7	18,0	188,5	152,9	19,4
5	Q	1 094	6,80	124,9	50,8	131,8	10,2	5,7	101,8	588,2	41,2	44,9
6	S	1 356	6,69	152,0	56,6	180,3	13,8	4,2	135,0	740,2	33,4	40,3
7	T	1 536	6,65	180,8	62,8	183,5	16,2	4,4	152,9	851,6	45,4	42,6
	BOREHOLES AND SHAFTS											
8	RH Geo 1	629	7,40	76,3	49,2	21,1	1,5	8,3	15,4	94,9	349,2	21,1
9	WN3	531	7,45	67,0	40,9	18,8	1,2	9,5	12,9	133,6	238,0	17,9
10	WN1	586	7,31	73,2	43,9	27,7	1,6	9,2	16,6	215,4	188,8	18,4
11	WN2	591	7,28	76,8	45,4	26,4	1,6	9,1	14,7	232,2	177,4	16,5
12	Annan Shaft	616	8,29	62,6	40,0	49,8	2,5	7,1	34,7	191,5	221,9	5,5
13	No. 2 Shaft	477	7,84	59,2	35,6	14,2	1,1	8,6	11,4	80,1	253,6	13,4
14	WD1	289	7,70	40,3	22,3	2,1	0,7	7,3	1,2	1,6	218,1	2,1
15	VE2	464	7,59	58,5	36,4	16,6	1,2	8,7	12,4	95,6	228,5	14,7
16	WD4	457	7,61	58,3	34,9	15,2	1,3	8,1	10,7	95,8	226,5	13,6
17	WD2	494	7,50	65,8	37,1	17,4	1,3	9,2	12,4	117,5	227,7	14,2
18	WD7	522	7,45	64,9	39,4	25,9	1,7	9,1	14,2	190,9	167,6	16,7
19	WD6	648	7,40	81,1	50,1	29,1	2,0	7,7	19,9	228,9	206,0	30,3
20	WD5	545	7,60	69,5	42,4	12,2	1,2	9,2	17,0	97,3	282,6	22,5
21	WD3	369	7,45	43,7	29,4	9,2	1,4	9,5	18,5	18,0	233,5	15,1
22	VE1	471	7,59	55,5	36,4	15,2	1,2	8,8	11,5	87,8	248,4	14,2
23	BK8	498	7,52	61,7	37,9	20,5	1,7	8,2	18,0	112,3	235,5	10,0
24	BK4	596	7,54	73,4	40,9	35,1	2,1	8,4	13,2	174,2	226,8	11,6
25	BK3	602	7,60	72,2	40,9	35,6	1,6	8,4	32,3	182,8	223,8	12,2
26	BK2	473	7,41	62,6	36,4	14,4	1,2	8,0	23,4	86,9	233,9	13,6
27	BK1	705	7,40	83,1	47,0	52,4	2,0	8,2	43,9	261,1	202,9	12,1
28	BK6	597	7,61	74,4	42,4	32,8	1,5	8,5	32,9	171,4	228,7	12,5
29	BK7	405	7,50	54,1	30,4	9,2	1,2	8,9	8,5	50,5	238,8	12,4
30	TN3	479	7,61	63,7	36,4	9,2	1,2	8,8	12,4	56,2	292,2	7,7
31	BL3	420	7,94	41,2	40,9	3,5	1,3	8,9	5,8	0,0	323,2	4,1

No.	Source	TDS	pH	Ca	Mg	Na	K	Si	Cl	SO_4	HCO_3	NO_3
32	TN2	515	7,52	69,0	34,9	18,8	2,9	8,8	10,7	99,8	270,9	7,9
33	GN1	353	7,62	43,2	30,4	6,2	2,4	8,0	6,4	32,0	227,7	4,7
34	K13	274	7,21	18,2	23,4	16,4	2,9	16,2	5,8	3,4	184,6	18,9
35	BL2	645	7,60	82,4	51,7	11,7	1,3	9,4	24,0	22,8	416,6	33,7
36	RT1	570	7,80	74,0	44,3	4,5	0,7	10,1	14,4	5,3	409,6	17,1
37	W294	588	7,80	72,1	47,3	8,6	1,8	9,2	10,2	31,9	413,3	2,4
38	KL1	635	7,53	78,9	48,1	10,5	10,0	9,2	32,9	44,5	366,3	43,1
39	KL2	525	7,58	69,0	40,9	13,1	1,2	8,8	16,6	64,6	313,6	6,3
40	BL1	508	7,58	64,8	39,4	8,5	1,2	7,8	14,6	13,8	352,9	12,1
41	ML2	491	7,77	59,3	37,9	11,0	2,0	9,2	13,7	5,9	334,8	25,5
42	ML1	697	7,68	80,6	55,2	14,7	3,6	8,8	27,2	22,8	448,4	43,4
43	DT3	482	7,73	64,7	36,4	7,9	1,3	9,2	7,7	20,7	336,9	5,7
44	W261	778	7,60	102,4	63,0	17,8	0,3	6,8	78,0	66,2	400,5	49,2
45	GN2	543	7,58	69,2	39,9	13,5	1,2	9,2	14,2	50,7	352,0	2,6
46	KH1	555	7,69	69,2	44,7	9,4	2,7	9,5	19,7	20,7	369,1	18,5
47	ML5	406	7,67	49,7	31,2	7,2	1,4	8,8	3,6	0,6	310,0	1,5
48	RI1	426	7,90	45,4	32,0	15,3	2,4	10,1	3,5	3,6	322,8	0,3
49	W240	605	7,50	73,1	48,8	10,3	0,8	7,8	9,3	13,3	432,0	16,8
50	ML6	374	7,76	41,2	32,7	5,4	1,8	6,1	3,5	0,0	287,9	0,7
51	ML4	381	7,74	47,5	28,3	4,4	2,9	7,3	2,4	0,0	292,3	2,2
52	KH2	488	7,59	65,9	37,1	3,1	0,8	8,8	2,8	0,0	363,8	14,5
53	ML3	145	6,93	10,8	12,8	5,2	3,4	10,8	2,4	0,0	106,2	4,4
54	ML7	136	7,11	8,4	14,3	5,0	3,5	15,2	1,2	0,0	102,8	0,3
55	TS2	281	7,27	23,8	21,9	13,2	2,5	16,8	15,6	0,0	158,2	45,7
56	DT1	358	7,60	45,5	27,6	5,4	2,0	10,9	3,1	0,0	266,2	10,1
57	SD1	187	7,25	12,1	15,6	9,0	4,0	13,5	2,9	0,0	129,5	13,8
58	DT2	193	7,10	13,8	15,6	9,7	2,5	13,1	2,7	0,0	121,2	27,2
59	ST1	306	7,47	23,8	24,0	17,9	2,9	12,4	5,2	0,0	227,9	4,1

studied area were derived from the following sources: Springs, sampled at Turffontein and Gerhardminnebron. Water from Maloney's Spring is also shown for comparison (Table 9.1 nos. 1-3). Imported effluent waters. These include two components: Effluents from Group I mines with an average annual discharge of $64 \times 10^6 m^3$ (1972-1978), sampled on the eastern boundary (Table 9.1 nos. 4a, 4b, 4). The other component consists of effluents from Group II mines with an annual discharge of $6 \times 10^6 m^3$, sampled at the entrance to Welverdiend Dam (Table 9.1 no. 5). Samples Nos. 6 and 7, Table 9.1, were collected downstream along the river at points S and T respectively. A regular monitoring of effluents from Group I and II mines had been conducted for some time prior to 1978, by the Water Pollution Control Division of the Department of Water Affairs. Results from partial analyses are available and have been plotted in Fig. 9.8 and 9.9. Fig. 9.8 demonstrate the range of the total dissolved solids (TDS) and sulphate ion content involved in effluents from Group I mines. In Fig. 9.9 a linear relation of sulphate to TDS may be observed in effluents from Group II mines. Groundwaters. Some fifty samples from boreholes and mine shafts were collected (Table 9.1) nos. 8-59). Distribution of the sampling points is limited to the available boreholes in the studied area. The sulphate ion content is also shown in Folder 9.1.

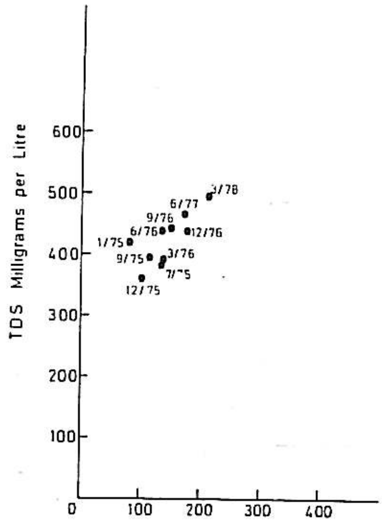


Fig. 9.8

SURFACE WATER SAMPLING POINT J

SALINITY VARIATIONS WITH TIME AND SO_4 vs TDS CORRELATION

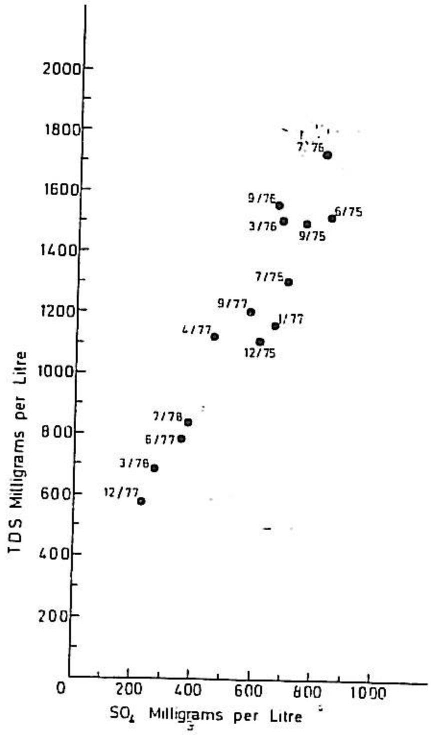


Fig. 9.9

SURFACE WATER SAMPLING POINT Q

SALINITY VARIATIONS WITH TIME AND SO_4 vs TDS CORRELATION

Uncontaminated aquifer water constitutes a bicarbonate solution with calcium and magnesium as major cations, and is characteristically nearly devoid of any sulphate. The almost total lack of sulphate, in these aquifers, is also concluded from results of an investigation conducted in another dolomitic unit, the Schoonspruit Area (Part 11), where no mining activity occurs and which is otherwise analogeous to Turffontein Area. Mineralization of natural water is accomplished in a dynamic system. Higher mineralization of the groundwater is assumed to indicate a longer water-rock interaction time period, which would account for a more extensive leaching process (Schoeller, 1959). Cumulative leaching of bedrock in these formations consequently enriches the groundwater in bicarbonate and calcium and magnesium ions, subject to various constraints.

As previously stated, the majority of the groundwater encountered in the studied area, have, to a minor or major extent, been subject to contamination. Nevertheless, some of the samples do represent original aquifer water. The dominant sources of contamination consist of the mine effluents (Table 9.1 sample Nos. 4a-7). The actual mixing process is rather complicated for several reasons: Firstly, the contaminating sources do not reveal a strict consistency of concentration with time, and occasionally also show various compositions. Secondly, the contaminating sources may come in contact with aquifer waters of various natural concentrations due to mineralization. Thirdly, mixing with $CaSO_4$ -rich solutions (contaminants), introduces the effect of a common ion with $CaCO_3$. In other words, saturation in respect of $CaCO_3$ may be reached at an earlier stage than otherwise.

9.7 Classification of waters

It is possible to classify the waters in the area into groups on a more genetic basis, and to define end members which in various combinations yield the mixed water samples.

Effluents

Were sampled at points H, K, J, Q, S, T (Folder 9.1) and are shown in Table 9.1 nos. 4a-7 and Fig. 9.10. They consist characteristically of sulphatic waters with Ca, Mg and Na as major cations. The two sources of effluents namely points H, K, J and Q differ considerably. Water sampled at points H, K, J is of lower concentration, TDS around 500 mg/l, ion ratios, expressed in reaction values: Ca $\cong$ mg $>$ Na and HCO_3/SO_4 high compared to samples from points Q, S, T. The other source, point Q, reveals high TDS, 1000 mg/l and more. Cation ratios in reaction values are Ca $\cong$ Na $>$ Mg. Significantly low bicarbonate is expressed in the ratio HCO_3/SO_4.

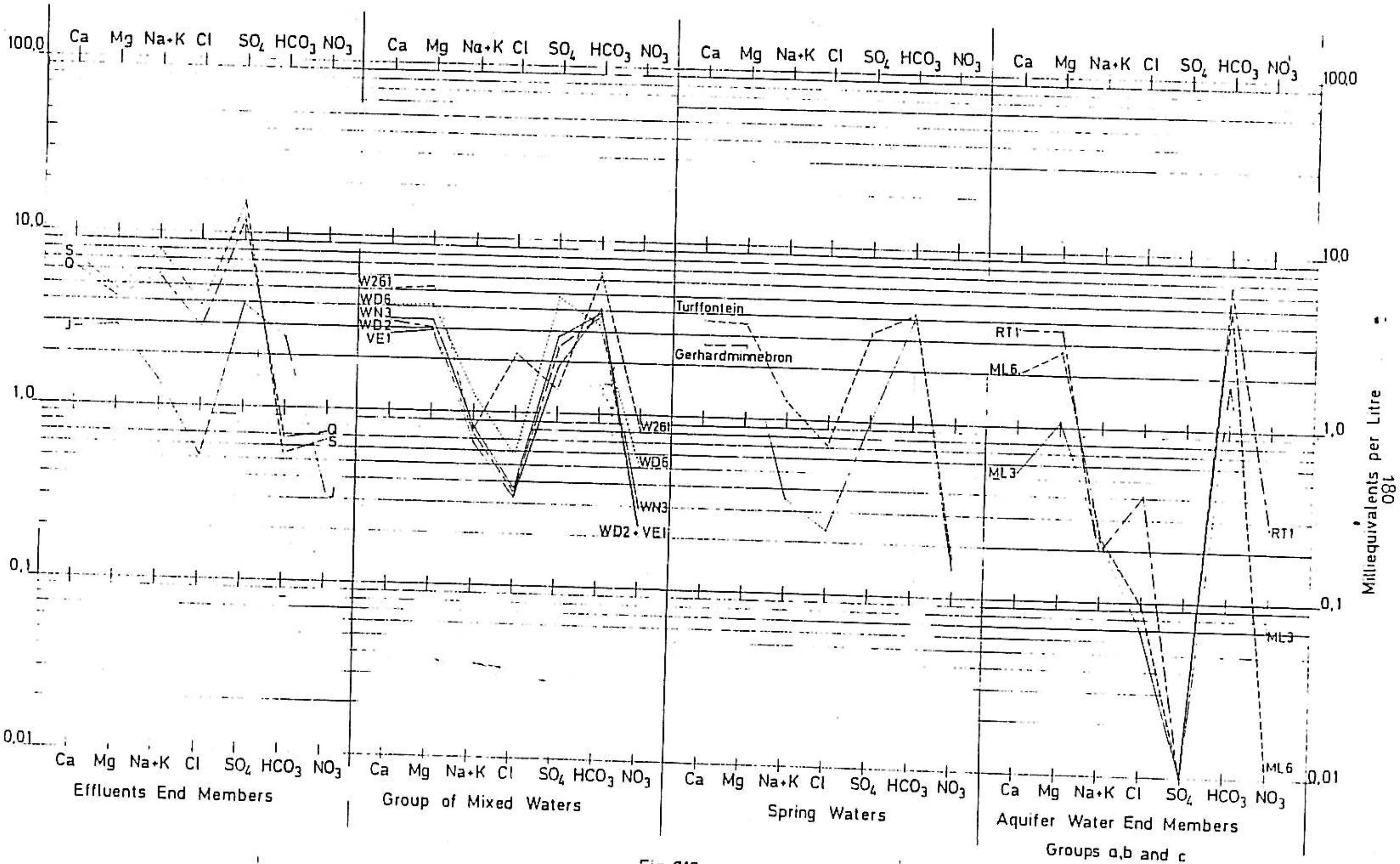


Fig 9.10

CLASSIFICATION OF WATERS IN TURFFONTEIN AREA

ANALYSES REPRESENTED BY LOGARITHMIC PLOTTING OF CONCENTRATION IN MILLIEQUIVALENTS PER LITRE.

Aquifer water (Uncontaminated)

Includes waters which developed naturally in the aquifer, underwent mineralization but did not become mixed with effluents. The presence of sulphate is taken as an indication of possible mixture. A small amount of nitrate is constantly present, apparently from both rain water and vegetation origin, yet some excess contents, uncorrelated with effluents contamination could probably be attributed to stock farming and fertilizers. This group can be further sub-divided into three subgroups, a, b and c. The criteria followed is degree of concentration reflected by TDS and HCO_3. The Ca/Mg ratio tends to increase from subgroup a to c. The ranges chosen are however somewhat arbitrary.

Subgroup a

Includes low concentration water, TDS $<$ 300 mg/l, HCO_3 up to 150 mg/l. Such water is found presumably near the upstream boundary of the aquifer. Representative samples of this subgroup ML7 and ML3 (Table 9.1 nos. 54, 53, Folder 9.1 and Fig. 9.10) come from a nearby pre-dolomite aquifer which drains into the studied area. Samples from SD1, DT2 and TS2 (Table 9.1 nos. 57, 58, 55) could also be included, but contain more NO_3.

Subgroup b

Include medium concentration water. TDS are between 300 and 500 mg/l, while HCO_3 concentration is 150-350 mg/l. Representative samples come from boreholes ST1, ML4, ML6, RI1, ML5, BL3 and WD1 (Table 9.1 nos. 59, 51, 50, 48, 47, 31, 14, Folder 9.1 and Fig. 9.10). Samples from boreholes KH2, ML2 and K13 (Table 9.1 nos. 52, 41, 34) are different only in respect of high NO_3 content.

Subgroup c

Is characteristic by being even more concentrated. TDS $>$ 500 mg/l and $HCO_3 > 350$ mg/l. A sample from borehole RT1 (Table 9.1 no. 36, Folder 9.1 and Fig. 9.10), is typical. Samples from boreholes BL2, W294, W240 (Table 9.1 nos. 35, 37, 49) are contaminated variants of this subgroup.

Mixed waters

By far the largest group of samples consists of contaminated mixed water. Various degrees of contamination can be observed and all three subgroups of aquifer water may be involved. Samples from boreholes WN3, WD2, WD6, VE1 and W261 (Table 9.1 nos. 9, 17, 19, 22, 44, Folder 9.1 and Fig. 9.10) were selected for illustration.

Spring waters

Samples from Gerhardminnebron and Turffontein springs (Table 9.1 nos. 2 and 1, Folder 9.1 and Fig. 9.10) would, for all practical purposes, fall under the mixed, contaminated water group. Water emanating at Maloneys Eye, Steenkoppie Compartment (Table 9.1 sample No. 3) may be regarded as uncontaminated genuine aquifer water.

All water samples were investigated for the solubility of calcite and gypsum. A number of samples, representing the mixed-water group, effluents-end-members and spring waters were plotted in Fig. 9.11, after Hem 1970. Fig. 9.11 defines four regions: Unsaturated in regard of both compounds, supersaturated for the same, a gypsum supersaturated zone and a calcite supersaturated zone. Ionic strength was calculated and ion activities were taken into consideration. It appears from Fig. 9.11 that all samples are undersaturated with respect to gypsum. On the other hand the bulk of the mixed water samples are saturated as regards calcite. Samples from boreholes WN1, WD7, WD6 and BK1 (Table 9.1 nos. 10, 18, 19, 27) with relatively high sulphate and low bicarbonate fall in the unsaturated zone. The composition of these waters probably indicates water with a high proportion of effluents compared to aquifer water.

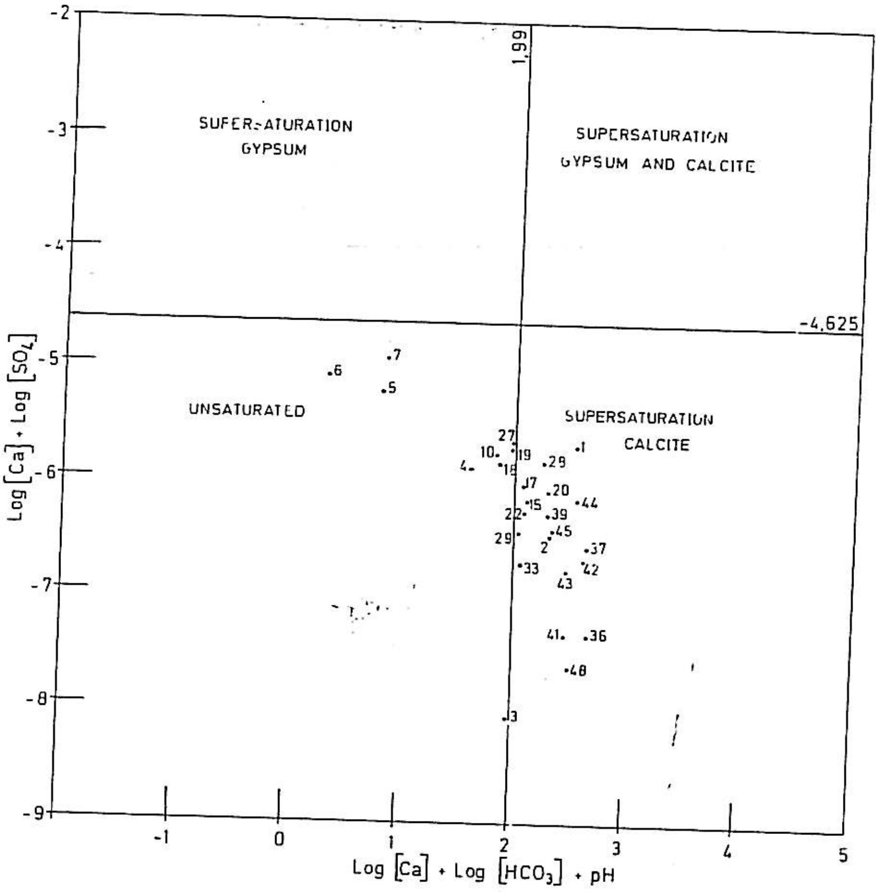


Fig. 9.11

CALCITE AND GYPSUM EQUILIBRIUM SOLUBILITY LIMITS, 25°C AND 1 ATMOSPHERE PRESSURE

Because all investigated waters tend to remain unsaturated with respect to gypsum, it is suggested that SO_4 can be applied as a mean to determine mixing proportions in the various samples.

9.8 Regular chemical monitoring of waters

In order to gain a better understanding regarding the chemistry of surface flows and springs in the area, a monitoring system consisting of 20 sampling points, was established and since January 1980, regular monthly sampling is carried out at these points. Results of the chemical analyses are presented in Table 9.2. Sulphate content only is shown in Table 9.3, and for each sampling date the concentrations of sulphate simultaneously at all stations are tabled. Positions of the sampling points designated C to T and the springs are shown in Folder 9.1. Average values of TDS and SO_4 were calculated for each station (Table 9.2), as well as the relative magnitude, in reaction values of the major cations and anions.

Surface waters with the lowest TDS concentration come from Venterspost Mine at point C, and from West and East Driefontein Mines at points E and G. The average TDS at these points is 435, 470 and 465 mg/l respectively, and the sulphate concentrations are 177, 176 and 178. $Ca \cong Mg > Na$ at all three points and $SO_4 > HCO_3 > Cl$. At point C a few samples occassionally show the relation $HCO_3 > SO_4 > Cl$.

TABLE 9.2: Chemical analyses of surface-water and springs from Turffontein Area in milligrams per litre

Date	TDS	pH	Ca	Mg	Na	K	Si	Cl	SO_4	HCO_3	NO_3
Sampling Point C C2M30											
11/12/79	567	7,8	66,7	37,9	46,7	2,2	7,4	19,2	292,1	91,8	3,1
12/12/80	203	7,2	25,6	18,2	8,7	1,1	5,3	6,4	39,5	98,1	0,3
27/2/80	527	7,9	70,1	41,1	30,4	2,3	0,0	15,7	257,2	107,2	2,7
10/3/80	299	8,0	35,6	26,2	14,8	1,2	7,1	10,7	66,7	136,2	0,8
16/4/80	319	7,7	34,7	28,1	14,3	0,8	7,4	10,4	66,7	155,9	0,8
5/5/80	321	7,5	42,1	26,7	12,8	1,0	7,6	10,7	68,5	150,9	1,1
22/5/80	512	7,7	65,1	35,0	35,4	1,9	7,2	13,4	173,2	177,4	2,9
11/6/80	503	7,6	62,3	35,7	40,0	2,6	7,0	15,4	235,1	100,9	3,9
21/7/80	506	7,3	64,9	38,3	35,5	2,0	7,3	15,9	235,0	104,9	2,5
22/8/80	490	7,9	57,7	36,0	32,2	2,2	7,4	12,9	243,5	94,1	3,8
17/9/80	538	7,3	68,5	40,1	40,1	2,6	7,0	16,0	273,1	86,5	3,6
Average	435								177		

(7) $SO_4 > HCO_3 > Cl$ $Ca > Mg > Na$ (8)

(4) $HCO_3 > SO_4 > Cl$ $Mg > Ca > Na$ (3)

$Ca \cong Mg$

Sampling Point D, 1 m pipe

29/1/80	785	7,3	128,6	40,7	45,2	5,6	5,4	23,3	480,5	52,2	3,7
27/2/80	1129	6,7	207,8	45,0	64,5	7,1	0,0	30,6	755,8	13,6	5,0
10/3/80	812	7,1	127,3	39,5	53,1	3,9	6,1	20,0	503,6	56,0	2,5
16/4/80	851	6,8	144,4	38,4	59,9	5,0	5,4	22,1	515,0	57,0	3,4
5/5/80	823	6,5	123,3	41,4	65,5	3,8	7,1	22,7	490,5	64,6	3,6
22/5/80	772	7,1	120,7	40,8	41,6	3,3	7,1	25,9	441,0	88,3	3,6
11/6/80	800	7,1	137,5	39,1	55,7	4,1	7,1	22,7	458,1	70,7	4,5
21/7/80	830	7,1	142,4	42,0	57,5	4,9	7,4	23,0	463,2	83,2	5,9
22/8/80	797	7,0	130,7	40,5	56,7	4,4	7,3	21,9	452,7	77,3	5,1
17/9/80	790	7,2	128,7	40,1	60,2	4,9	7,3	23,3	435,8	86,6	3,4
Average	839								500		

$SO_4 > HCO_3 > Cl$ $Ca > Mg > Na$

Sampling Point E, Canal from E + W Driefontein Mines

27/2/80	466	7,6	58,0	37,8	32,4	3,1	0,0	19,3	183,6	127,4	4,0
10/3/80	460	8,2	54,1	34,2	36,5	2,4	0,7	16,8	181,0	131,5	2,9
16/4/80	459	7,2	57,8	33,7	34,7	3,0	7,1	18,3	168,4	131,6	4,0
5/5/80	495	7,0	59,5	37,2	35,8	2,7	7,5	19,5	197,6	131,8	2,9
22/5/80	481	7,7	65,1	35,6	30,7	3,1	7,5	20,8	161,6	150,6	6,0
11/6/80	464	7,5	59,7	33,8	33,3	3,0	7,3	17,0	170,4	134,0	5,2
21/7/80	461	7,4	56,7	34,7	31,7	2,8	6,9	18,0	165,5	141,0	3,2
21/8/80	476	7,2	59,2	37,3	40,8	3,7	7,2	19,2	180,4	122,2	6,2
Average	470								176		

Ca ≅ Mg > Na $SO_4 > HCO_3 > Cl$

Sampling Point F Dividing box from Venterspost Mine

29/11/79	721	7,4	127,5	31,8	45,7	4,3	4,6	18,2	411,2	75,5	2,4
18/1/80	735	7,1	118,5	40,9	48,7	4,5	7,3	23,1	407,4	81,3	3,7
12/2/80	849	7,1	145,7	41,7	54,4	4,9	6,0	19,2	493,0	81,2	3,3
27/2/80	1065	6,7	198,9	44,1	60,4	6,8	0,0	29,1	696,9	23,4	4,9
10/3/80	787	7,1	120,3	39,5	50,4	4,0	6,3	19,4	481,1	63,9	2,4
16/4/80	826	6,8	139,7	39,0	59,0	4,9	5,5	22,1	490,6	61,4	3,4
5/5/80	822	7,0	120,2	41,6	63,9	3,7	7,0	22,4	486,7	72,9	3,2
22/5/80	810	7,3	133,5	39,7	55,0	3,5	7,2	14,9	470,3	82,6	3,6
11/6/80	710	7,3	117,6	38,8	48,7	3,6	7,2	20,6	384,2	84,7	4,8
21/7/80	708	7,1	112,4	39,7	47,6	4,1	7,0	21,8	369,2	101,3	4,8
21/8/80	718	7,3	113,8	39,1	47,4	4,3	7,2	20,8	393,3	87,5	4,9
17/9/80	789	7,3	126,4	40,1	58,0	4,8	7,1	23,9	442,3	83,2	3,3
Average	795								461		

Ca > Mg > Na $SO_4 > HCO_3 > Cl$

Sampling Point G Dividing box from E + W Driefontein Mine

29/11/79	432	8,2	51,9	29,0	32,0	2,8	7,1	14,9	180,6	110,1	3,6
18/1/80	488	7,4	59,4	34,1	36,7	3,5	8,4	21,2	196,5	122,5	6,0
29/1/80	444	7,9	50,4	36,8	32,6	2,9	8,0	18,0	177,3	114,0	4,0
12/2/80	443	7,2	52,9	33,0	33,0	2,8	7,9	16,6	165,9	125,8	5,1
27/2/80	466	7,5	57,4	37,8	35,4	3,1	0,0	17,2	183,6	127,4	4,1
10/3/80	462	7,8	54,1	35,8	33,2	2,4	6,8	16,2	178,6	132,5	2,8
16/4/80	471	7,2	59,3	33,6	35,5	3,0	7,0	18,3	181,6	128,2	4,3
5/5/80	498	7,2	59,2	36,4	38,0	2,7	7,6	21,3	194,8	135,1	3,0
22/5/80	463	7,8	63,8	35,4	22,7	2,8	7,3	20,0	154,3	150,6	5,6
11/6/80	445	7,6	56,4	34,2	32,6	2,8	7,4	16,5	153,7	136,1	4,8
21/7/80	462	7,6	57,2	35,0	31,1	3,3	6,8	17,5	164,0	144,1	3,1
22/8/80	482	7,2	59,6	36,4	40,1	3,7	6,9	19,6	181,1	127,9	6,2
17/9/80	493	7,4	60,4	36,1	38,8	3,4	6,7	18,9	200,1	123,9	5,1
Average	465								178		

Ca ≅ Mg > Na $SO_4 > HCO_3 > Cl$

Sampling Point H Dividing box mixed

29/11/79	616	7,7	99,3	31,3	40,5	3,7	5,7	16,6	334,5	81,4	2,5
18/1/80	665	7,2	99,1	39,6	45,0	4,3	7,7	23,2	346,9	94,3	5,1
29/1/80	669	7,7	101,8	37,2	40,4	4,6	6,6	21,7	373,4	79,5	4,0
12/2/80	663	6,9	100,0	38,2	46,0	4,1	6,8	18,6	361,8	85,6	2,2
27/2/80	879	7,0	156,8	43,4	53,3	5,6	0,0	26,3	535,4	53,5	4,6
10/3/80	666	7,2	91,9	36,8	43,6	3,1	6,4	18,2	374,7	89,0	2,7
16/4/80	645	7,0	97,1	36,2	47,2	3,8	6,3	19,7	337,0	93,8	3,9
5/5/80	669	6,7	92,7	39,4	49,6	3,2	7,0	20,2	357,4	96,3	3,2
22/5/80	597	7,5	92,8	37,7	41,9	3,0	7,2	18,0	278,5	112,7	4,9
11/6/80	597	7,4	93,2	37,1	43,3	3,4	7,2	18,5	282,8	106,2	4,8
21/7/80	582	7,2	87,5	37,3	41,5	3,6	7,0	20,2	260,9	119,3	4,2
21/8/80	612	7,1	92,9	38,3	46,7	4,6	7,1	21,9	285,9	110,1	5,5
17/9/80	599	6,9	83,0	37,4	46,4	4,2	6,8	21,1	285,4	111,2	3,6
Average	651								340		

Ca > Mg > Na $SO_4 > HCO_3 > Cl$

Sampling Point J C2M57

29/11/79	631	7,7	99,9	31,3	46,7	3,9	5,7	18,6	341,3	80,9	2,9
18/1/80	655	7,1	98,8	39,0	45,0	4,3	7,5	22,3	339,6	94,2	4,2
29/1/80	660	7,8	101,8	38,8	40,4	4,6	6,5	21,2	361,4	81,6	3,7
12/2/80	641	7,0	100,3	37,4	43,6	4,0	6,8	18,3	336,9	90,0	3,8
27/2/80	822	7,0	142,3	40,1	50,7	5,3	0,0	24,7	490,7	63,5	4,3
10/3/80	631	7,5	88,7	36,5	42,3	3,1	6,5	18,2	339,0	94,0	2,6
16/4/80	659	7,1	99,7	36,7	49,6	3,9	6,5	20,9	343,6	94,3	3,8
5/5/80	603	7,2	82,4	37,9	45,5	2,9	7,3	18,5	290,3	114,8	3,0
22/5/80	552	7,4	85,6	36,4	38,3	3,2	7,2	16,7	241,1	118,8	5,0
11/6/80	609	7,4	94,1	35,6	43,2	3,5	7,3	20,7	293,7	105,2	5,2
21/7/80	560	7,3	79,3	37,0	36,8	3,3	7,0	19,1	244,3	129,2	3,5
22/8/80	594	7,0	88,5	38,3	47,3	4,2	7,1	20,8	271,3	110,3	5,7
17/9/80	589	7,3	79,5	37,8	46,4	4,1	6,9	21,3	279,8	108,2	4,8
Average	631								321		

Ca > Mg > Na $SO_4 > HCO_3 > Cl$

Sampling Point K C2M32

29/11/79	630	7,7	102,2	32,2	45,0	3,9	6,2	18,0	336,7	83,0	2,8
18/1/80	656	7,2	100,7	39,1	44,7	4,1	7,3	22,6	339,0	94,2	4,0
29/1/80	667	7,8	101,2	38,9	41,2	4,6	6,5	21,3	370,4	79,4	3,7
12/2/80	695	7,0	102,6	38,8	45,1	3,7	6,8	17,2	397,5	78,8	4,1
27/2/80	856	7,0	149,6	42,9	52,0	5,5	0,0	24,2	519,4	58,0	4,7
10/3/80	634	7,3	86,9	36,5	42,9	3,0	6,4	17,6	348,9	88,7	2,6
16/4/80	667	7,0	102,5	38,7	52,3	4,3	6,2	20,2	347,4	91,3	3,6
5/5/80	611	7,2	82,4	38,2	46,4	3,0	7,3	19,3	300,9	110,0	3,1
22/5/80	563	7,6	89,5	36,1	38,9	3,0	7,2	16,6	251,7	115,8	4,5
11/6/80	608	7,4	91,5	35,9	43,2	3,5	7,3	19,1	298,0	104,1	5,0
21/7/80	580	7,3	83,7	37,7	38,8	3,4	7,1	20,2	258,9	126,8	3,5
22/8/80	608	7,1	93,7	38,6	48,0	4,6	7,1	21,2	281,6	107,3	5,6
17/9/80	596	7,3	82,2	37,1	47,2	3,8	7,0	20,6	286,1	108,0	4,4
Average	644								334		

Ca > Mg > Na $SO_4 > HCO_3 > Cl$

Sampling Point L C2M44

27/2/80	511	7,4	62,9	40,4	40,6	2,6	0,0	16,7	238,5	104,6	4,2
10/3/80	386	8,0	43,1	30,7	26,2	2,1	6,5	13,5	128,4	133,8	1,6
16/4/80	435	7,2	55,6	33,1	29,4	2,4	7,1	16,2	148,7	139,1	3,4
5/5/80	470	7,7	59,7	36,4	37,7	3,1	7,5	17,6	170,2	135,1	3,0
22/5/80	496	7,3	69,5	36,1	36,6	2,9	7,2	15,7	202,3	119,9	5,6
11/6/80	516	7,2	65,2	35,6	45,8	2,8	7,1	17,1	240,7	95,4	6,3
22/7/80	526	7,3	66,8	37,7	36,2	2,0	6,9	15,9	240,1	117,4	2,9
21/8/80	496	7,1	62,0	36,7	42,7	3,2	7,0	17,3	200,1	121,1	5,9
17/9/80	533	7,1	67,0	38,8	40,8	2,7	6,6	17,5	255,7	97,8	5,9
Average	485								203		

Ca > Mg > Na (7) $SO_4 > HCO_3 > Cl$

Mg > Ca > Na (2)

Sampling Point M, inflow to Nature Reserve

18/1/80	635	7,3	95,3	36,9	43,5	4,0	7,5	22,8	324,9	95,2	4,5
29/1/80	687	7,7	105,5	38,1	40,8	4,9	6,3	22,7	388,4	76,0	4,0
12/2/80	642	7,0	100,4	38,5	40,1	4,0	6,8	19,0	336,6	92,1	4,0
27/2/80	793	7,2	137,5	42,7	45,2	5,1	0,0	27,8	462,8	67,9	4,3
10/3/80	630	7,6	87,7	37,2	39,6	2,9	6,5	18,1	343,9	91,9	2,3
16/4/80	644	7,0	99,4	36,9	45,8	3,3	6,2	18,5	331,9	98,5	3,4
5/5/80	597	7,3	83,9	38,0	44,1	2,9	7,2	18,8	288,9	110,9	2,5
22/5/80	601	7,4	83,9	37,6	40,1	3,1	7,1	38,3	276,4	110,0	4,4
11/6/80	610	7,3	91,5	36,1	46,7	3,8	7,2	20,0	294,2	105,2	5,1
22/7/80	565	7,2	82,3	37,0	37,5	3,2	6,8	19,1	248,3	127,3	3,1
22/8/80	588	7,0	89,8	38,0	45,3	4,2	6,9	20,1	267,3	110,9	5,9
17/9/80	606	6,9	86,1	37,7	47,2	4,2	6,6	20,9	288,4	110,9	3,8
Average	633								321		

Ca > Mg > Na $SO_4 > HCO_3 > Cl$

Sampling Point N Outflow from Nature Reserve

18/1/80	572	7,5	73,4	39,5	45,0	4,0	6,7	21,9	344,5	35,4	1,5
29/1/80	667	8,8	90,5	40,5	47,9	5,1	5,7	25,3	421,2	28,4	2,4
12/2/80	678	7,2	98,1	36,9	44,8	4,6	6,0	17,2	429,7	38,8	1,5
27/2/80	695	7,3	109,7	40,6	47,6	4,9	0,0	25,9	430,7	33,0	2,4
10/3/80	665	7,2	88,6	37,5	46,2	4,2	5,3	20,8	416,3	44,6	1,9
16/4/80	665	6,8	101,5	37,3	47,2	3,8	5,6	20,2	385,2	62,2	2,3
5/5/80	596	7,1	76,3	37,4	47,0	3,7	6,1	20,0	320,0	82,9	2,3
22/5/80	621	7,3	90,3	37,1	45,6	3,6	4,7	25,1	331,2	80,9	2,4
11/6/80	518	7,4	74,6	36,0	42,0	3,5	5,3	30,4	214,6	108,8	3,0
22/7/80	542	7,1	75,8	38,0	43,5	4,2	4,9	20,7	273,0	78,3	3,2
22/8/80	539	6,9	71,7	38,6	46,0	4,1	5,3	20,5	265,0	85,3	2,1
17/9/80	545	7,2	68,2	39,1	43,6	4,2	5,0	20,3	263,4	100,4	1,1
	609								341		

Ca > Mg > Na $SO_4 > HCO_3 > Cl$

Sampling Point O Tarred Road Inflow to Welverdiend Dam

18/1/80	584	7,0	78,5	39,8	44,7	4,1	6,1	24,0	350,5	35,3	1,0
29/1/80	648	7,7	87,2	39,1	46,5	5,1	5,2	24,5	409,3	29,5	2,0
12/2/80	639	7,3	93,1	37,4	44,2	4,3	5,8	14,4	391,3	47,7	1,0
10/3/80	672	7,5	93,9	38,1	45,5	4,1	4,6	21,3	422,1	41,5	1,2
16/4/80	626	6,7	89,8	36,5	44,9	3,7	4,9	19,7	359,4	65,3	1,6
5/5/80	593	7,1	77,3	38,0	47,0	3,5	5,4	20,0	320,4	78,8	2,1
22/5/80	639	7,0	90,4	40,2	50,5	3,6	4,2	20,3	345,0	82,0	2,7
11/6/80	529	7,4	73,3	36,0	42,0	3,4	3,9	19,5	264,8	83,6	2,4
22/7/80	545	6,9	74,9	38,3	42,8	4,6	4,3	21,3	272,7	82,8	3,5
22/8/80	539	6,8	71,7	38,9	46,0	4,1	4,2	21,5	265,4	85,2	2,2
17/9/80	551	6,9	65,4	36,3	45,0	4,8	2,9	21,4	283,1	92,1	0,1
Average	597								335		

Ca > Mg > Na $SO_4 > HCO_3 > Cl$

Sampling Point P Railway Brdg. Inflow to Welverdiend Dam

27/2/80	985	6,8	131,5	42,5	122,2	8,9	0,0	157,8	460,0	57,5	4,6
10/3/80	657	8,3	89,3	37,5	44,8	3,9	4,6	21,2	412,8	41,5	1,2
16/4/80	632	6,7	92,7	36,5	45,5	3,7	4,7	19,7	360,0	67,5	1,7
5/5/80	592	7,3	77,3	38,6	47,0	3,6	5,3	21,3	320,8	75,7	2,0
22/5/80	605	7,6	78,9	39,7	49,9	3,5	3,9	20,9	341,2	64,5	2,8
11/6/80	516	7,8	71,2	36,6	44,8	3,7	3,7	20,5	231,4	100,2	3,7
22/7/80	546	7,0	76,1	38,0	43,5	4,3	2,9	21,3	276,3	79,7	3,5
22/8/80	547	8,6	68,7	35,8	43,5	4,1	0,0	22,7	285,7	84,8	1,4
17/9/80	519	7,1	60,4	35,3	45,0	4,1	1,1	21,2	282,0	68,0	1,7
	622								330		

Ca > Mg > Na $SO_4 > HCO_3 > Cl$

Sampling Point Q C2M60 Inflow to Welverdiend Dam, Group II mines

18/1/80	1325	6,2	152,8	62,0	166,0	13,9	11,4	123,1	763,8	17,3	14,2
29/1/80	1013	7,4	123,5	34,9	129,1	15,2	8,3	121,7	498,2	73,6	8,1
12/2/80	1213	6,6	163,6	39,3	161,2	17,4	9,0	112,2	646,8	53,3	9,7
27/2/80	991	6,7	124,3	42,1	132,8	10,8	0,0	102,9	521,6	46,4	9,7
10/3/80	855	6,7	106,8	28,1	114,6	13,5	7,8	93,3	420,7	59,3	10,9
16/4/80	924	6,5	116,9	30,7	133,4	14,4	7,4	100,0	447,7	63,5	10,4
5/5/80	1075	6,3	113,5	34,4	168,4	14,3	7,9	132,3	504,1	85,8	14,3
22/5/80	1044	6,5	140,8	43,5	134,3	13,1	9,0	107,3	541,8	38,4	15,6
11/6/80	2030	6,4	273,6	92,9	325,6	15,8	7,3	839,4	429,9	29,7	15,3
22/7/80	1162	6,7	165,1	32,1	168,2	16,3	5,8	127,2	554,9	74,0	17,9
22/8/80	1238	6,6	150,1	44,1	184,0	15,8	6,2	251,8	517,4	52,0	16,8
17/9/80	1368	5,3	154,1	55,9	168,2	13,8	9,4	119,5	835,4	0,3	11,2
Average	1187								557		

Ca > Na > Mg (9) $SO_4 > Cl > HCO_3$

Na > Ca > Mg (3)

Sampling Point R C2M69 Outflow from Welverdiend Dam

11/12/79	1035	6,7	147,1	41,1	113,5	12,7	6,6	89,4	586,4	27,8	9,9
18/1/80	1052	6,1	136,2	39,6	127,3	15,2	8,3	113,7	566,9	32,8	12,2
29/1/80	543	6,8	117,3	36,5	98,1	14,1	6,5	77,0	148,8	39,0	5,7
12/2/80	1011	6,4	140,7	39,6	121,2	12,7	8,1	91,2	558,6	30,0	9,1
27/2/80	745	7,2	117,0	39,7	48,0	4,6	0,0	53,4	435,4	45,2	1,7
10/3/80	796	6,4	93,5	32,3	98,8	11,2	6,6	75,8	432,2	36,3	9,2
16/4/80	825	6,6	105,9	38,7	93,4	7,1	5,4	98,9	409,1	61,6	4,6
5/5/80	830	6,5	86,9	32,9	125,1	8,6	5,9	72,7	418,2	71,5	8,1
22/5/80	839	6,5	115,7	41,2	91,1	8,4	6,6	78,1	438,4	50,1	9,7
11/6/80	925	6,8	122,8	45,5	127,8	7,7	5,0	203,8	344,0	61,2	6,9
22/7/80	1031	6,7	134,4	41,0	143,0	12,2	5,1	145,5	471,3	67,0	11,6
22/8/80	987	6,6	121,1	37,2	134,4	13,7	6,3	124,5	482,3	51,1	16,5
17/9/80	1437	5,5	158,6	56,6	188,5	14,0	8,9	241,6	762,8	0,0	5,9
Average	927									466	

Ca > Na > Mg SO_4 $Cl > HCO_3$

Gerhardminnebron Spring

6/69	395	8,1	55,0	25,0	8,0	-	-	11,0	3,0	293,0	0,0
11/69	354	8,4	44,0	29,0	20,0	-	-	11,0	10,0	240,0	0,0
5/71	261	8,0	42,0	23,0	25,0	-	-	14,0	29,0	244,0	0,0
7/71	256	8,1	48,0	33,0	4,0	-	-	18	24,0	258,0	0,0
10/71	243	8,4	40,5	27,7	10,3	-	-	5,7	33,2	250,2	-
6/77	394	7,7	50,9	31,5	7,2	1,0	6,7	12,5	38,5	244,1	8,0
1/79	403	7,8	52,6	31,0	7,8	0,5	7,7	8,0	49,1	237,7	8,7
18/1/79	369	7,5	53,3	33,0	8,2	0,8	9,3	10,9	52,3	198,3	3,0
29/1/80	368	7,7	51,5	31,8	7,9	0,8	9,3	9,3	51,3	203,9	2,2
12/2/80	365	7,6	53,8	33,5	7,5	0,9	9,2	18,3	40,8	198,9	1,9
10/3/80	359	7,7	52,1	32,0	8,1	0,9	7,9	8,2	50,7	196,9	2,1
16/4/80	366	7,6	55,2	31,9	7,7	0,7	8,0	7,1	49,2	203,9	2,2
5/5/80	363	7,5	53,5	32,1	8,2	0,9	8,3	8,1	49,1	199,8	2,5
22/5/80	373	7,5	55,8	28,1	8,1	1,2	8,1	8,4	59,5	201,7	2,2
11/6/80	351	7,7	49,3	30,7	8,3	1,0	8,4	7,0	48,3	195,8	2,5
22/7/80	364	7,8	54,4	33,0	8,0	0,9	7,9	7,9	47,1	202,6	2,2
22/8/80	365	7,9	52,1	31,7	7,6	0,9	7,7	8,5	52,4	202,1	2,3
18/9/80	364	7,7	55,0	33,2	10,1	0,9	7,8	7,8	51,8	195,2	1,7
Average	364								50,2		

Ca ≅ Mg > Na $HCO_3 > SO_4 > Cl$

Turffontein Spring

6/69	585	7,8	67,0	50,0	21,0	-	-	53	115,0	275,0	4,0
11/69	594	8,3	68,0	50,0	31,0	-	-	99,0	87,0	259,0	0,0
5/71	416	8,3	55,0	39,0	24,0	-	-	36,0	134,0	250,0	0,0
7/71	397	8,0	64,0	40,0	22,0	-	-	36,0	98,0	256,0	9,0
10/71	417	8,1	57,2	36,5	43,3	-	-	23,7	123,2	266,7	-
6/77	583	7,7	72,0	40,3	36,2	1,5	6,7	33,3	147,1	240,9	11,6
1/79	605	7,7	73,4	42,7	30,1	1,1	8,4	25,6	156,9	256,6	10,1
18/1/80	529	7,5	71,1	42,1	26,3	1,2	9,6	22,7	148,9	202,0	5,1
29/1/80	532	7,4	69,3	43,9	25,9	1,3	9,5	24,4	147,5	207,6	2,4
12/2/80	520	7,6	72,8	41,1	26,7	1,4	9,6	23,7	138,9	201,4	3,9
10/3/80	526	7,5	70,1	41,1	26,7	1,3	8,4	22,2	154,4	199,6	2,2
16/4/80	527	7,5	72,7	40,8	27,0	1,1	8,2	21,1	148,7	204,8	2,3
5/5/80	525	7,4	70,3	41,1	27,5	1,5	8,7	24,3	145,6	204,5	2,6
22/5/80	527	7,4	75,4	37,1	26,3	1,2	8,4	21,1	149,6	205,3	2,4
11/6/80	507	7,7	64,4	39,2	27,6	1,4	8,6	22,0	144,2	196,6	2,7
22/7/80	514	7,8	73,2	42,7	26,2	1,3	8,4	22,4	133,7	203,8	2,5
22/8/80	526	7,9	70,4	40,7	26,9	1,4	8,1	22,7	150,3	203,2	2,3
17/9/80	523	7,6	71,7	42,4	27,3	1,2	8,2	22,9	151,6	196,2	1,8
Average	523								146,6		

$Ca \cong Mg > Na$ $\quad$ $HCO_3 \cong SO_4 > Cl$

TABLE 9.3: Sulphate concentration of surface-water and springs from Turffontein Area, in milligrams per litre

Date	Turffontein Eye	Gerhardminnebron Eye	Welverdiend Dam				Nature Reserve					Dividing Box					
			C2M69	C2M60	Railway	Road			C2M44	C2M32	C2M57	Mixed	W + E	Dri. Venterspost		1 m pipe	C2M30
			R	Q	P	O	N	M	L	K	J	H	G	F	E	D	C
6/69	115,0	3,0															
8/69		154(?)															
11/69	87,0	10,0															
5/71	134,0	29,0															
7/71	98,0	24,0															
10/71	123,2	33,2															
6/77	147,1	38,5															
1/79	156,9	49,1															
1/79	156,8	48,8															
29/11/79				569,1		337,0				336,7	341,3	334,5	180,6	411,2			
11/12/79			586,4														292,1
18/1/80	148,9	52,3	566,9	763,8		350,5	344,5	324,9		339,0	339,6	340,8	196,5	407,4			
29/1/80	147,5	51,3	148,8	498,2		409,3	421,2	388,4		370,4	361,4	373,4	177,3			480,5	
12/2/80	138,9	40,8	558,6	646,8		391,3	429,7	336,6		397,5	336,9	361,8	165,9	493,0			39,5
27/2/80			435,4	521,6	460,0		430,7	462,8	283,5	519,4	490,7	535,4	183,6	696,9	183,6	755,8	257,2
4/3/80	154,2	49,9															
10/3/80	154,4	50,7	432,2	420,7	412,8	422,1	416,3	343,9	128,4	348,9	339,0	374,7	178,6	481,1	181,0	503,6	66,7
16/4/80	148,7	49,2	409,1	447,7	360,0	359,4	385,2	331,9	148,7	347,4	343,6	337,0	181,6	490,6	168,4	515,0	66,7
5/5/80	145,6	49,1	418,2	504,1	320,8	320,4	320,0	288,9	170,2	300,9	290,3	357,4	194,8	486,7	197,6	490,5	68,4
11/6/80	144,2	48,3	344,0	429,9	231,4	264,8	214,6	294,2	240,7	298,0	293,7	282,8	153,7	384,2	170,4	458,1	235,1
21/7/80	133,7	47,1	471,3	554,9	276,3	272,7	273,0	248,3	240,1	258,9	244,3	260,9	164,0	369,2	165,5	463,2	235,0
22/8/80	150,3	52,4	482,3	517,4	285,7	265,4	265,0	267,3	200,1	281,6	271,3	285,9	181,1	393,3	180,4	452,7	243,5
17/9/80	151,6	51,8	762,8	835,4	282,0	283,1	263,4	288,4	255,7	286,1	279,8	285,4	200,1	442,3		435,8	273,1

Higher salinity is observed at point D, the end of the 1 m pipe where TDS = 839 mg/l, SO_4 = 500 mg/l, Ca > Mg > Na and $SO_4 > HCO_3 > Cl$.

At the outlet from the dividing box at point H, TDS = 651 mg/l, SO_4 = 340 mg/l, Ca > Mg > Na and $SO_4 > HCO_3 > Cl$.

Water entering the eastern boundary of Turffontein Area is monitored at three points J, K and L. At sampling point J (C2M57), TDS = 631 mg/l, SO_4 = 321 mg/l, Ca > Mg > Na, $SO_4 > HCO_3 > Cl$. At sampling point K, TDS = 644 mg/l, SO_4 = 334 mg/l, Ca > Mg > Na and $SO_4 > HCO_3 > Cl$. At sampling point L, water with low TDS concentration come from Venterspost: TDS = 485 mg/l, SO_4 = 203 mg/l, Ca ≅ Mg > Na, $SO_4 > HCO_3 > Cl$.

Water monitored from the eastern boundary down to Welverdiend Dam at points M, N, O, P does not show any marked difference or increase in TDS concentration. Sampling point M at the inflow to the Carletonville Nature Reserve TDS = 633 mg/l, SO_4 = 321 mg/l, Ca > Mg > Na, $SO_4 > HCO_3 > Cl$. At sampling point N, outflow of the same water TDS = 609 mg/l, SO_4 = 341 mg/l, Ca > Mg > Na, $SO_4 > HCO_3 > Cl$. At sampling point O, TDS = 597 mg/l, SO_4 = 335 mg/l, Ca > Mg > Na, $SO_4 > HCO_3 > Cl$. At sampling point P, the inlet to Welverdiend Dam, TDS = 622 mg/l, SO_4 = 330 mg/l, Ca > Mg > Na, $SO_4 > HCO_3 > Cl$.

Much more concentrated water is encountered where Group II mines water is being monitored, before the entrance to Welverdiend Dam, at sampling point Q. Here TDS = 1187 mg/l, SO_4 = 557 mg/l and there is a significant ion ratio combination with $Ca \cong Na > Mg$ and $SO_4 > Cl > HCO_3$.

Water sampled at the outlet of Welverdiend Dam, point R, is a mixture of point Q water and points P, O, N water. This reflects itself in the TDS = 927 mg/l, and SO_4 = 446 mg/l, while the ion ratios are $Ca > Na > Mg$ and $SO_4 > Cl > HCO_3$.

As already mentioned before, groundwaters in this area have been affected by contamination, and this may be noticed when analyses from the two springs are inspected. At Gerhardminnebron TDS = 364 mg/l, SO_4 = 50,2 mg/l, $Ca \cong Mg > Na$, $HCO_3 > SO_4 > Cl$. At Turffontein TDS = 523 mg/l, SO_4 = 147 mg/l, $Ca \cong Mg \quad Na$, $HCO_3 \cong SO_4 > Cl$.

From the above-described chemistry of the water it may be concluded that the salinity of the effluents from Group I mines has increased substantiously compared to previous data (Fig. 9.8). Although regular monitoring covers a short period of less than one year, it is assumed that the increase of salinity has started earlier, namely, with the interception of Donaldson Dam water which began in September 1977. Thus the relative amounts of effluents delivered by the 1 m pipe have an important impact on the total salinity of water spread over the Turffontein Area.

Likewise, water temporarily stored in Welverdiend Dam, and the outflow from this dam become rather concentrated due to the influx of Group II mine effluents.

9.9 Suggested model of groundwater contamination

The aquifer in the studied area may be conceived as a reservoir into which near-constant amounts of contaminating effluents are recharged. Only part of the added salinity drains from the system in the course of each successive discharge event. The remaining salinity tends to accumulate and increase the concentration in the aquifer body. A model is thus postulated, to explain the observed data, and which may, after establishment of a proper monitoring system, be employed to:

(a) calculate the total storage in the aquifer, and

(b) Predict salinity development in the aquifer.

In the model, the aquifer will be viewed as a single compartment in which the contaminant has a uniform concentration which is detected in the outflow at springs. Any contaminant added to the aquifer will thus be assumed to mix instantly with the existing water.

At some initial time t_o it will be assumed that the aquifer has a storage V_o, and that the concentration of contaminant in the aquifer is C_o. At a later time t, it is supposed that the storage in the aquifer is V(t), and the concentration of the contaminant is C(t). Then the storage of the aquifer will be governed by the following balance equation:

Rate of change of volume in aquifer = inflow - outflow, i.e.

$$\frac{dV}{dt} = Q_I(t) - Q_o(t) \qquad (1)$$

where $Q_I(t)$ denotes the recharge of the aquifer at time t and $Q_o(t)$ the spring flow at time t. Similarly, the concentration in the aquifer will be governed by a mass balance equation:

Rate of change of mass in aquifer
= Mass flowing in - Mass flowing out, or,

$$\frac{d}{dt}(cV) = C_I(t)\, Q_I(t) - C(t)\, Q_o(t), \qquad (2)$$

where $C_I(t)$ denotes the concentration of the contaminant in the recharge water. It is assumed here that the concentration C_I is averaged over all the recharges taking place to the aquifer. Note that the concentration C(t) of the outflow is assumed to be identical to that of the aquifer. Fig. 9.12 gives a schematic outline of the suggested model.

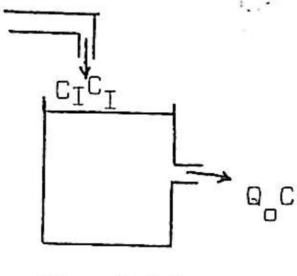


Fig. 9.12

Subject to the initial condition $V(t_o) = V_o$, equation (1) is solved as

$$V(t) = V_o + \int_{to}^{t} \left\{ Q_I(s) - Q_o(s) \right\} ds \qquad (3)$$

Equation (2) is solvable, only if $V(t) > 0$ for all $t > to$, that is to say only if the storage of the aquifer is never equal to zero, i.e. the aquifer is dry. In this case one derives, subject to the initial condition $C(t_o) = C_o$:

$$C(t) = C_o \exp - \left\{ \int_{to}^{t} \frac{Q_I(s)}{V(s)} ds \right\} + \int_{to}^{t} \frac{C_I(s)\, Q_I(s)}{V(s)} \exp \left\{ - \int_{s}^{t} \frac{Q_I(r)}{V(r)} dr \right\} ds \qquad (4)$$

Equations (3) and (4), in the above model, describe the storage and concentration of contaminant in the aquifer at any time t.

To give some physical meaning to equations (3) and (4), note that

$V(t) = V_o$ for all $t > to$

if, and only if

$Q_I(t) = Q_o(t)$ for all $t > to$

In other words, the storage in the aquifer is only constant if, and only if, the outflow matches the recharge at all times.

Consider now the special case where at all times the inflow is equal to the outflow and constant, i.e. $Q_I(t) = Q_o(t) = Q$ for all t and therefore $V(t) = V_o$ for all t. Suppose further that the initial concentration $C_o = 0$, and contaminant is added at a constant rate $C_I(t) = C_i$ for all times t. As explained above, this appears to be roughly the case in the investigated springs. In this case (4) reduces to

$$c(t) = C_i \left[1 - \exp\left\{ \frac{Q\,(t_o - t)}{V_o} \right\} \right] \text{ for all } t > t_o \qquad (5)$$

The concentration in the above situation is given in Fig. 9.13. Note that at all times the concentration in the aquifer is increasing and tending to, but never actually reaching, the concentration of the source.

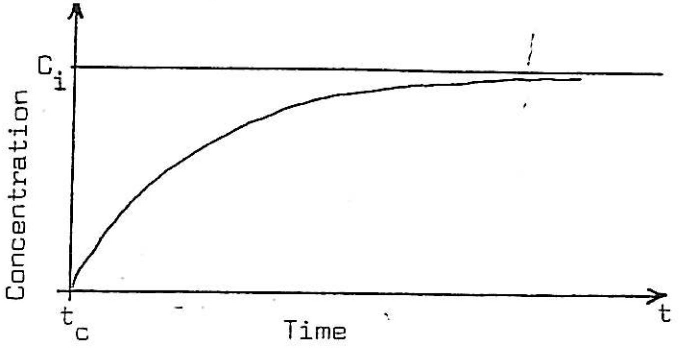


Fig. 9.13

The preceeding simplification allows one to obtain a value of the storage V_o of the aquifer. Supposing the concentration $C(t)$ of the contaminant in the spring has been measured together with the outflow of the spring Q. Then, plotting t versus $C_i - C(t)$ on a logarithmic scale, one derives from (5).

$$t = \frac{t_o - V_o}{Q} \log_e 10 - \log_{10} C_i - C(t) \quad \text{See Fig. 9.14}$$

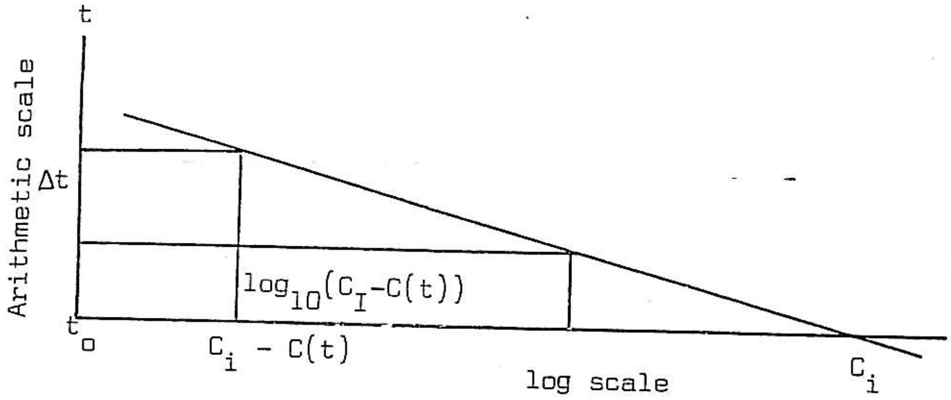


Fig. 9.14

Thus from the slope of this line one can derive the storage of the aquifer

$$V_o = - Q \log_{10} e \quad \frac{\Delta t}{\Delta \log_{10} \quad (C \quad - C(t)}$$

and the time at which contamination began by the intercept where $C(t) = 0$ (or $C \quad - C(t) = C_i$).

It is most regretful that continuous monitoring of effluents and spring waters did not accompany the spreading of water over the Turffontein Area during the period prior to 1979. In the absence of the necessary data, a certain measure of uncertainity remains concerning the interpretation of the mechanism of the aquifer.

Several older water analyses stored in the data bank of the Department of Water Affairs are presented in Table 9.2 and 9.3, and the sulphate content versus time at Gerhardminnebron Spring is shown in Fig. 9.15. Two different curves denoting an increase in salinity may be observed in Fig. 9.15. During the first period, 6/1969-10/1971, the sulphate content rose from 3 to 33 mg/l, while during the second period, 6/1977-1/1979, the sulphate increased from 38 to 49 mg/l. Apparently some decrease in salinity might have taken place as well between these two periods, namely during the interval 1973-1976, for which no measurements are at hand.

In Fig. 9.16, the storage in the aquifer has been calculated according to the above suggested model. The two periods 1965-1971 and 1977-1979, were treated independently. The storage values arrived at are 33,5 x $10^6 m^3$ and 29,4 x $10^6 m^3$ respectively. These calculations refer only to that part of the aquifer which is involved in the mixing process.

The salinity at the outflow is assumed to have stabilized around 50 mg/l sulphate concentration. Equilibrium has therefore probably been reached, and the outflow concentration may reflect the mixture ratio of uncontaminated recharge water to recharge from effluent sources. The concentration of the percolating effluents is expected to be somewhat higher than 180 mg/l SO_4 (Group I mine effluents before the construction of the 1 m pipe), due to the fact that some water of Group II effluents

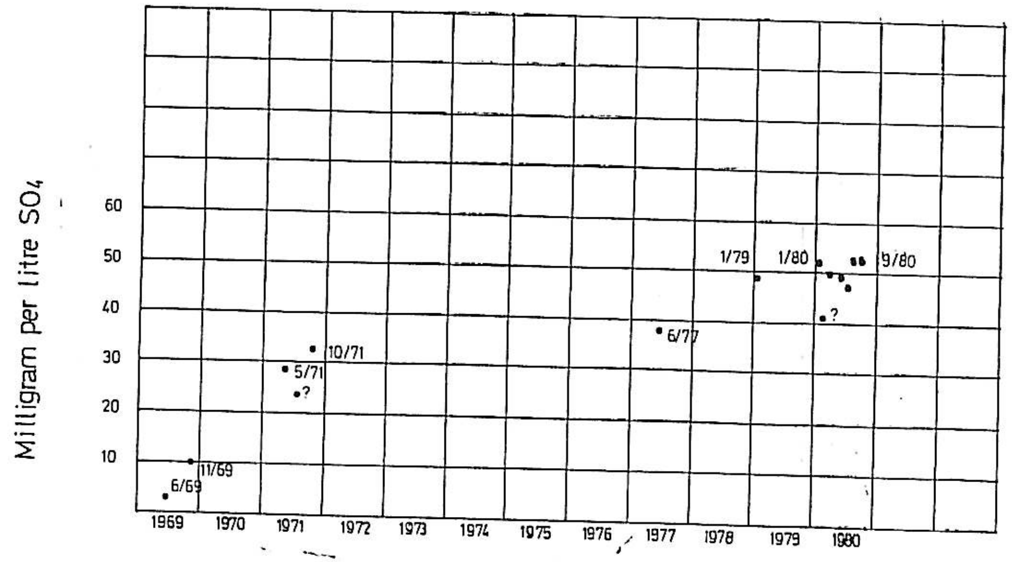
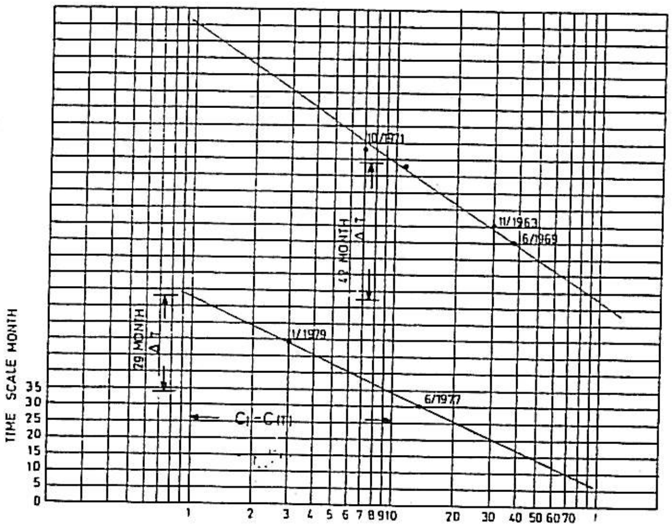


Fig. 9.15

Concentration of sulphate in water
from Gerhardminnebron Spring

Calculation of storage water involved in mixing at Gerhardminnebron, Spring



$$V_O = Q \times LOG_{10} E \; \frac{\Delta T}{\Delta LOG_{10}(C_I - C_{(T)})}$$

PERIOD 1977/1979

DATE	$C_{(T)}$	$C_I - C_{(T)}$
6/1977	38 5	13 5
1/1979	49	3

$V_O = 2{,}36 \times 10^6 M^3 \times 0{,}43 \times \frac{29}{1}$

$V_O = 29{,}4 \times 10^6 M^3$

WHERE $C_I = 52$ MG/L

$Q = 2{,}36 \times 10^6 M^3$/MONTH

PERIOD 1969/1971

DATE	$C_{(T)}$	$C_I - C_{(T)}$
6/1969	3	37
11/1969	10	30
5/1971	29	11
10/1971	33	7

$V_O = 1{,}86 \times 10^6 M^3 \times 0{,}43 \times \frac{42}{1}$

$V_O = 33{,}5 \times 10^6 M^3$

WHERE $C_I = 40$ MG/L

$Q = 1{,}86 \times 10^6 M^3$/MONTH

Fig. 9.16

also finds its way to Gerhardminnebron Spring. If, for the sake of argument the average concentration of the effluents is taken as 200 mg/l SO_4, this would mean that some 25% of the total recharge comes from this source, equal to about 7 x $10^6 m^3$/year.

Data from Turffontein Spring (Tables 9.2 and 9.3) do not allow any calculation of storage. On the other hand, as it appears that the salinity is more or less constant, one would like to find the relative proportion between uncontaminated recharge water and effluents. The difficulty lies with the fact that it is not clear what average salinity contributes to Turffontein Spring system. The average concentration of the contaminant should be between 180 mg/l sulphate as encountered in effluents from Group I mines, and 557 mg/l, which is the concentration of effluents from Group II mines. Salinity of 180 mg/l cannot be accepted, as this would mean that all the water at Turffontein Spring consists of effluents. On the other hand, if the more concentrated effluents are the sole contributors, it would indicate that 27% of the springwater consists of effluents. Because of the relative quantities involved, it is obvious that the sulphate concentration must be considerably lower than 557 mg/l. It may thus be concluded that the relative proportion of the effluents is much higher than 23%, a minimum of 33% may not be far-fetched if one compares the sulphate salinity of sampling point R (466 mg/l), with 147 mg/l, the salinity at the spring.

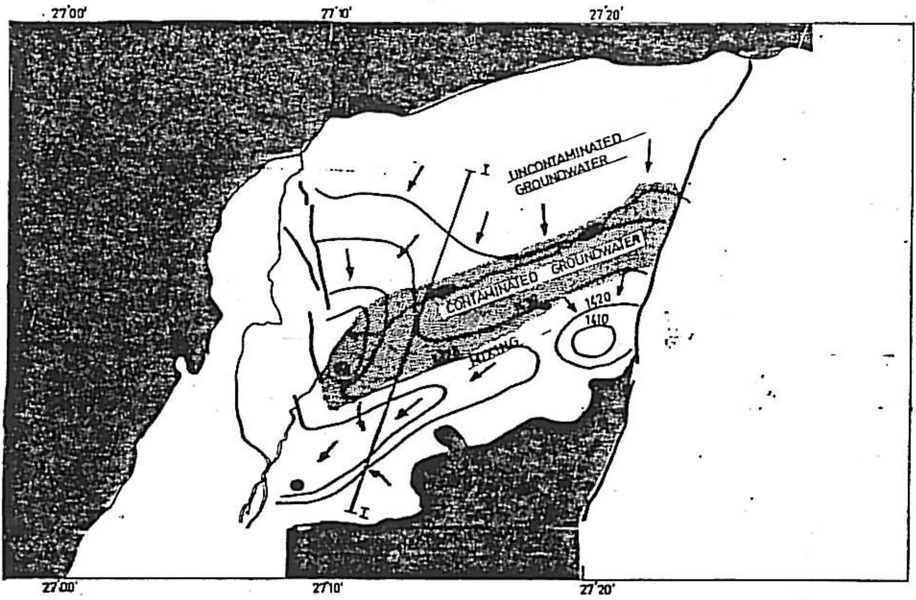
9.10 Discussion

The increase in salinity at Gerhardminnebron Spring which in each case later seem to stabilize, could in all cases be attributed to a phase of increased input salinity. It has already been noted that since the end of 1977, the input effluents of Group I mines have become more concentrated (sampling points J, K, L, M, N, O, P), a fact which could account for the later phase observed in Fig. 9.15. The tracing of a similar change in input during 1969-1971 is however more complicated. During the first part of the dewatering episode at West Driefontein Mine, vigorous pumping was carried out to overcome the underground flooding, and enormous volumes of highly contaminated water were diverted into the river (W.L. Cousens, personal communication). No figures are available concerning quantity and quality. Except for this event, the composition of the effluents prior to 1977 was very much the same as what is presently observed at sampling point G. In both episodes described, it is doubtfull whether the pulse of excessively contaminated water could, in actual fact, reach the spring at such a high rate of progress.

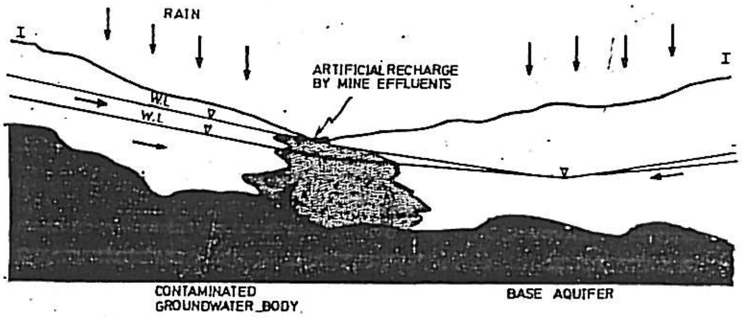
An additional simultaneously operating factor to explain the observed facts would be a changing head of groundwater upstream. It emerges from Fig. 9.5, 9.6, 9.7 and 10.5 that the discharge at the springs reacts nearly instantaneously to changes of groundwater levels. One is therefore inclined to relate the increase in salinity at the outlet with a change of head upstream.

An extensive body of contaminated groundwaters underlies the river zone as is demonstrated by the sulphate content of boreholes sampled in this sector (Folder 9.1). This body of contaminated water has been accumulating constantly through the percolation of effluents. Due to the rise of groundwater levels, a steeper gradient is created and consequently bigger amounts of groundwater flow towards the spring. Quantitatively, most of the groundwater supplying the spring system comes from the direction of the river, and because this body of water is contaminated, a rise of salinity in the spring, from a steady threshold concentration, may be related to the increase of the hydraulic gradient. Fig. 9.17 outlines this concept schematically. Uncontaminated groundwater, north of the river, pushes the contaminated body towards the spring. The aquifer is confined in places only and replenishment into the aquifer takes place all over the outcrops, so that the contaminated water body thus becomes diluted while moving downstream towards the outlet. Dilution is further achieved through mixing with groundwater from the southern sector of the area.

The above explanations may present serious limitations concerning the application of the suggested model. It seems that the basic condition which requires recharge discharge constant for a series of time periods may not strictly be the case.



MAP SHOWING INFERRED GROUNDWATER FLOW PATTERN AND THE AREAL EXTENSION OF THE CONTAMINATED GROUNDWATER BODY



SCHEMATIC GEOHYDROLOGIC CROSS SECTION EXPLAINING THE INCREASE OF SALINITY AT GERHARDMINNEBRON SPRING AS A RESULT OF A STEEPER GROUNDWATER GRADIENT

Fig. 9.17

9.11 Conclusions

Effluents from gold mines were shown to recharge artificially the aquifer, and at the same time cause contamination of the groundwater. Some proof is available that the rate of artificial recharge is related to the flow volumes of the effluents (section 9.5).

The sulphate content in groundwater and springs has been used as a reliable parameter to indicate quantitavely the ranges of contamination. It emerges from this study that Gerhardminnebron and Turffontein areas seem to represent two separate spring systems, yet each system is being contaminated by two sources of effluents. The contaminating sources from Group I and Group II mines differ in concentration and also in composition. It is also noted that the concentration of effluents from Group I mines increased since 9/1977 due to additional quantities of more concentrated waters from Donaldson Dam. An increase of inflow salinity C_I to the aquifer may thus be anticipated.

Judging by the proportion of effluents to uncontaminated aquifer water, assumingly in equilibrium in the spring systems, it is evident that percolation through the central sector along the Wonderfontein River is very high. The total recharge in this sector is expected to be even higher if natural rain and run-off recharge is added. Similar conditions were noticed in Venterspost and Bank Compartments (see parts 7 and 8).

One of the consequences due to quality deterioration of the water in areas under investigation can already be traced at Boskop Dam. Table 9.4 includes the results of water analyses from Boskop Dam stored at the Data Bank of the Department of Water Affairs. Boskop Dam serves as a collector of water of the Mooi River, and all surface and spring water leaving Turffontein Area. In spite of the irregular occassional nature of sampling at Boskop Dam during the last decade, two periods 1971-1972 and 1978-1979, during which a distinct higher salinity prevailed, can be noticed. These periods may be correlated with the outflows from Turffontein Area as monitored at Gauging Station C2M69 (Fig. 9.1). Obviously the routine flow of contaminated water into Boskop Dam would have an impact on the quality of the water stored in the dam, a factor to be considered in water planning of this area.

TABLE 9.4: Chemical analyses of water from Boskop Dam in milligrams per litre

Date	Depth/m	TDS	pH	Ca	Mg	Na	K	Si	Cl	SO_4	HCO_3	NO_3
28.6.68	0,0	448	8,2	44,0	37,0	18,0	-	-	14,0	24,0	311,0	0,0
28.6.68	7,5	448	8,1	44,0	37,0	18,0	-	-	14,0	24,0	311,0	0,0
17.9.68	7,0	472	7,3	44,0	39,0	23,0	-	-	14,0	35,0	317,0	0,0
17.9.68	0,0	420	7,8	44,0	39,0	18,0	-	-	14,0	0,0	305,0	0,0
6.11.68	5,0	424	8,0	38,0	35,0	21,0	-	-	14,0	29,0	287,0	0,0
6.11.68	0,0	437	8,3	38,0	37,0	23,0	-	-	14,0	38,0	287,0	0,0
6.3.69	3,5	359	8,4	32,0	41,0	0,0	-	-	18,0	0,0	268,0	0,0
6.3.69	0,0	358	8,2	32,0	40,0	1,0	-	-	14,0	9,0	262,0	0,0
6.3.69	6,0	390	8,4	30,0	42,0	9,0	-	-	14,0	27,0	268,0	0,0
8.7.69	14,0	410	8,4	42,0	38,0	9,0	-	-	18,0	29,0	274,0	0,0
8.7.69	7,0	385	8,4	39,0	37,0	6,0	-	-	16,0	19,0	268,0	0,0
8.7.69	0,0	414	8,2	40,0	37,0	14,0	-	-	14,0	34,0	275,0	0,0
15.1.70	5,0	346	8,4	36,0	35,0	2,0	-	-	11,0	25,0	237,0	0,0
15.1.70	0,0	376	8,3	32,0	35,0	16,0	-	-	18,0	38,0	237,0	0,0
15.1.70	10,0	358	8,4	34,0	33,0	12,0	-	-	18,0	24,0	237,0	0,0
26.1.70	6,0	433	8,5	40,0	37,0	23,0	-	-	21,0	62,0	250,0	0,0
26.1.70	0,0	422	8,1	38,0	37,0	23,0	-	-	28,0	58,0	238,0	0,0
26.1.70	12,0	419	7,8	40,0	37,0	4,0	-	-	27,0	67,0	244,0	0,0
12.1.72	11,0	360	8,2	33,0	34,0	16,0	-	-	13,2	54,0	210,0	0,0
12.1.72	0,0	345	8,2	28,0	34,0	16,0	-	-	13,1	55,0	199,2	0,0
12.1.72	5,5	345	8,3	29,0	34,0	15,0	-	-	13,2	52,0	202,0	0,0
8.3.75	0,0	330	8,6	27,6	34,0	9,7	1,2	-	3,1	33,8	220,1	0,1
8.3.75	8,0	268	9,1	14,6	32,7	9,7	1,5	-	2,9	31,6	175,3	0,1
8.3.75	13,0	285	8,9	19,5	30,8	9,2	1,6	-	3,3	30,2	190,1	0,0
12.2.76	0,0	365	7,9	39,3	32,1	10,6	1,4	-	4,0	33,1	244,0	0,0
12.2.76	5,5	365	7,8	39,1	32,0	10,6	1,3	-	4,1	32,6	245,0	0,0
12.2.76	11,0	368	7,9	39,3	32,6	10,9	1,3	-	4,0	33,3	246,0	0,0
29.3.77	21,0	45	6,5	3,0	2,0	2,0	2,0	3,1	2,0	14,0	19,0	0,1
4.4.77	0,0	377	7,8	36,4	30,3	15,9	2,2	4,9	6,7	26,5	258,5	0,3
4.4.77	5,0	383	7,7	37,7	31,7	15,7	2,2	4,9	6,7	27,1	261,3	0,3
4.4.77	12,0	406	7,7	42,0	33,0	15,5	2,1	5,7	6,1	28,8	277,4	0,6
7.11.77	0,0	404	7,7	38,0	35,6	9,6	1,8	5,2	10,1	34,0	272,9	1,1
13.12.77	0,0	378	7,6	36,0	33,9	12,5	0,6	5,6	10,7	38,9	244,4	0,7
9.1.78	0,0	298	7,3	27,8	25,7	9,9	0,1	6,9	6,7	28,0	199,0	0,0
14.6.78	0,0	455	7,9	57,9	33,9	14,9	1,8	6,3	9,6	71,8	262,5	2,2
8.8.78	0,0	480	7,8	60,1	35,6	16,3	1,7	4,9	12,2	90,2	259,7	3,7
12.9.78	0,0	508	7,8	63,9	38,4	16,9	2,1	4,6	12,1	90,7	280,0	3,5
23.10.78	0,0	478	7,9	55,8	36,8	17,1	2,0	5,4	14,3	93,3	255,9	2,2
27.11.78	0,0	477	7,8	57,7	38,4	16,5	1,4	5,3	11,4	86,7	264,0	0,8
3.1.79	0,0	341	7,8	39,2	31,0	4,7	1,1	6,8	3,8	2,2	258,9	0,2
10.5.79	0,0	432	8,1	49,1	37,4	15,4	1,3	6,0	12,6	65,4	248,7	1,7
19.6.79	0,0	446	7,9	50,2	39,2	16,1	1,3	6,4	13,7	73,7	249,5	2,3

10. AN ANALYSIS OF SPRINGS

10.1 Available data

Reference is made in this work to some of the more important springs of the studied area, the locations of which are shown in Fig. 2.1. Details concerning yields and observation periods are given in Table 10.1.

TABLE 10.1: Annual discharge of springs in the studies area

Spring	Annual discharge $10^6 m^3$		Observation period
	Minimum	Maximum	
Bank C2M30	12,5	22,0	1957 - 1968
Turffontein C2M13	7,8	15,5	1912 - 1978
Gerhardminnebron C2M11	21,0	29,0	1906 - 1978
Maloney A2M10	11,0	22,0	1907 - 1978
Schoonspruit C2M64	26,0	63,3	1966 - 1978

Sub-surface drainage area is not included in Table 10.1 because in most cases it is still vaguely defined. Montly discharge figures for each spring are plotted on hydrographs, Fig. 10.1, Fig. 10.2 and Folder 10.1. Discharge amounts were corrected to represent thirty-days months. Also shown in Fig. 2.1 are former springs which stopped flowing in consequence of over-pumpage or dewatering of dolomitic groundwater flooding underground workings of gold mines. Two of the spring systems, Gerhardminnebron and Turffontein have recently been contaminated by sulphatic mine effluents (see part 9).

10.2 The annual recharge pattern

For most of the investigated springs no annual recession curve, coinciding with the dry winter season can be traced. This characteristic feature stands out in striking contrast to descriptions of springs in karstic carbonate terrains from various parts of the world. The occurence of a typical recession curve due to the alternation of distinct wet and dry seasons often enabled researchers to develop applicable formulas to calculate the storage of the aquifer involved with spring systems e.g. Mero (1958), Mero (1963) and Torbarov (1976).

As previously discussed, (see Part 4), the investigated aquifer consists of ancient remaining karst systems and a "weathered zone" of mainly fluvio-glacial deposites. Clays are abundant and the aquifer is often locally confined or semi-confined. This set-up differs considerably from classical active karst aquifers.

10.3 The mechanism of replenishment

The lack of a recession curve may only partly be explained by the prolonged rainfall season and the lack of a short peak rainfall period. To counter-affect the natural depletion of the aquifer during the dry seasons, some recharge mechanism must be operating all through the year. Part of the natural recharge into the aquifer takes place immediately following precipitation, this is demonstrated in Fig. 5.8 where automatically-recorded water levels were plotted versus daily rainfall. Comparison of daily rainfalls with the daily discharge at two springs reveals a phase difference of four to six months. This phenomenon could be followed due to the introduction lately, of automatic recording. The lag can be traced only during the winter as base flow during summer time cannot be effectively separated from run-off. In Fig. 10.3 a four month phase difference between a rainy episode and an increase of the discharge at Turffontein Spring can be observed. A rainy episode consists of a sequence of rain days. In Fig. 10.4 the same phase difference amounts to six months. A phase shift of six months is suggested when monthly discharge at Bank Spring is compared with the monthly rainfall data in Fig. 10.1.

It is thus concluded that the natural replenishment in the dolomitic aquifer involves, schematically, a two-phase system: A relatively immediate phase, and a later delayed one. Every rain episode would affect the aquifer storage twice, first when direct recharge takes place and again after several months, on the arrival of the delayed recharge phase. In late summer the direct and delayed recharge phases are expected to coincide. A complete no-recharge period hardly exists, a fact which would account for the lack of an annual recession curve.

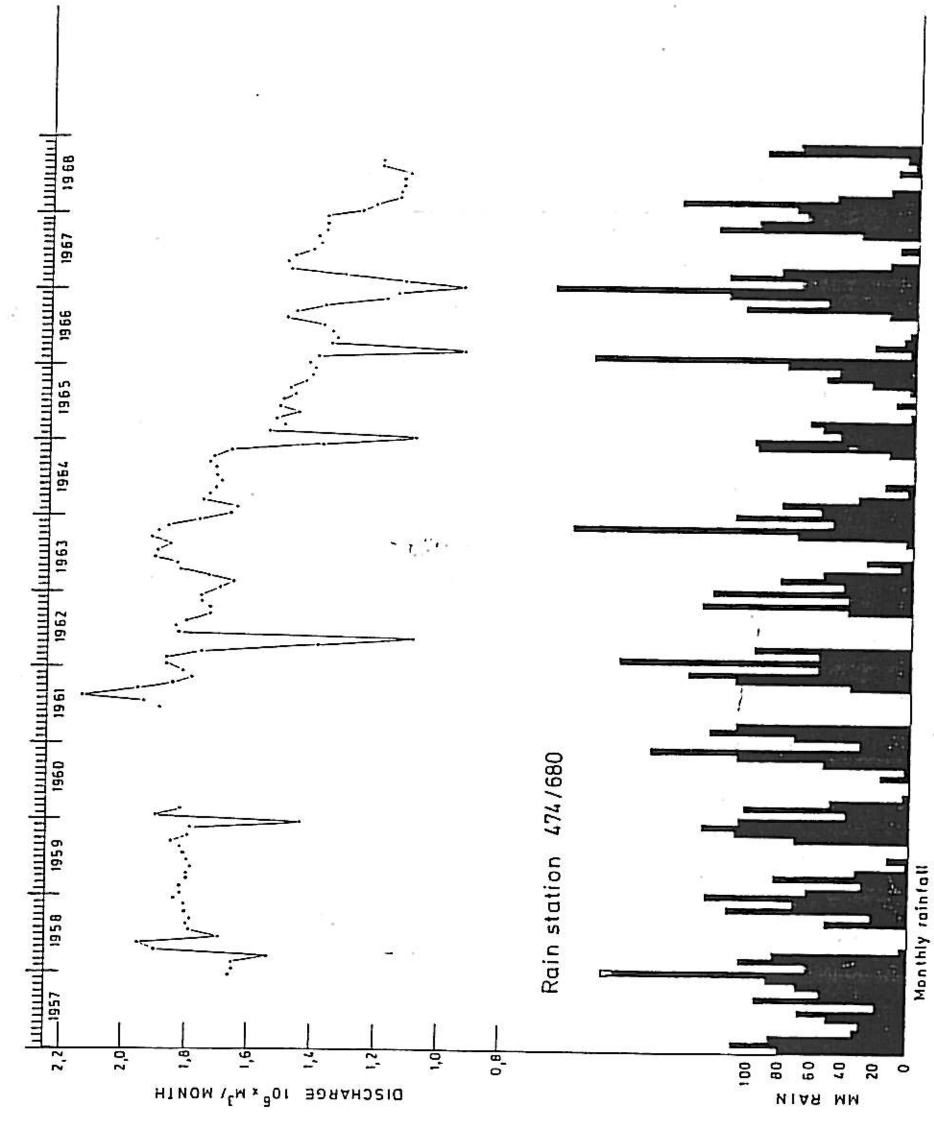


Fig. 10.1

Monthly discharge at Bank Spring C2m30 corrected to 30 day months

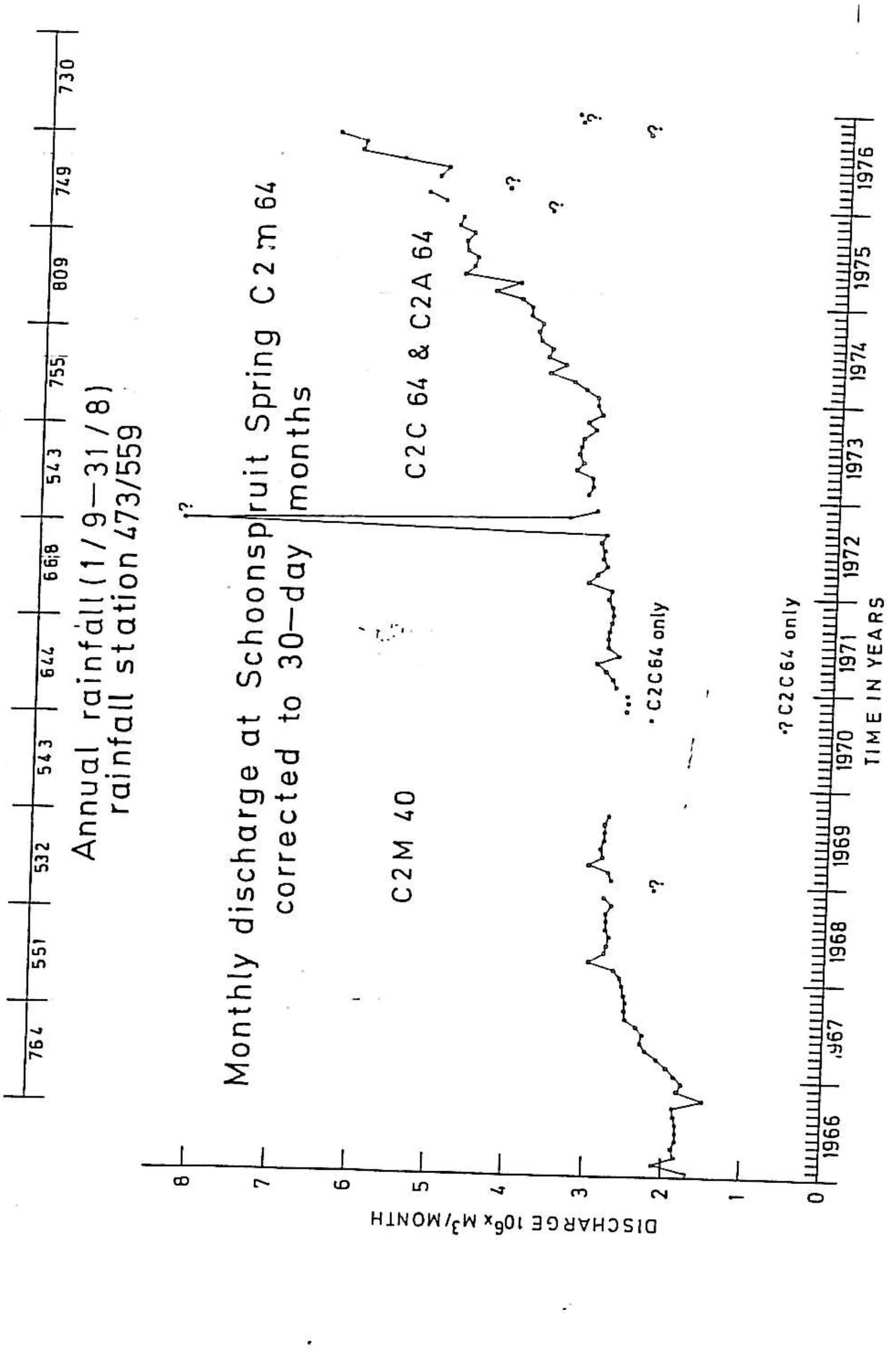

Annual rainfall (1/9—31/8)
rainfall station 473/559
764
551
532
543
644
66;8
543
755
809
749
730
Monthly discharge at Schoonspruit Spring C 2 m 64
corrected to 30—day months
C2M 40
C2C 64 & C2A 64
C2C64 only
?C2C64 only
?
8
7
6
5
4
3
2
1
0
DISCHARGE 10⁶ x M³/MONTH
1966
1967
1968
1969
1970
1971
1972
1973
1974
1975
1976
TIME IN YEARS

Fig.10.2

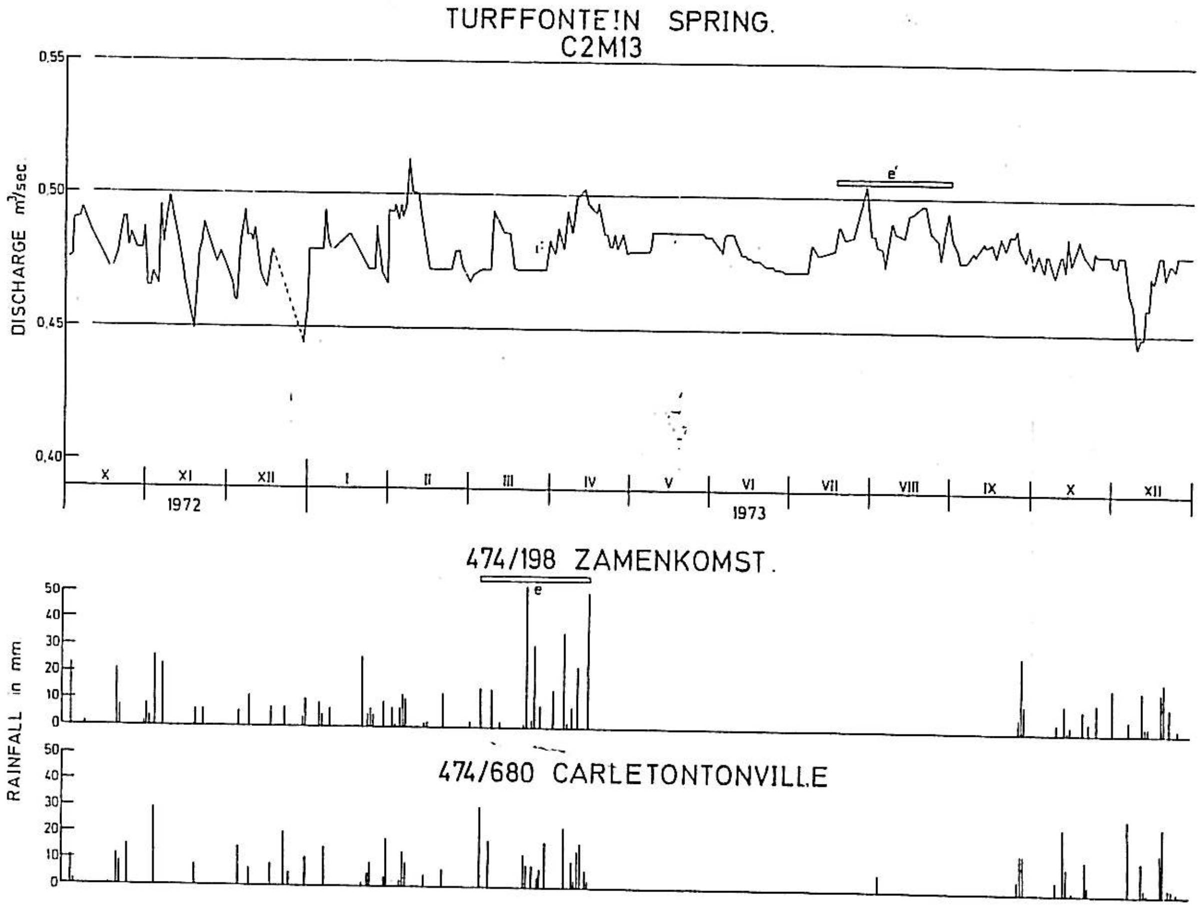


Fig. 10.3

Daily discharge against daily rainfall.
A four month phase difference observed between a rainy episode and its manifestation in the discharge

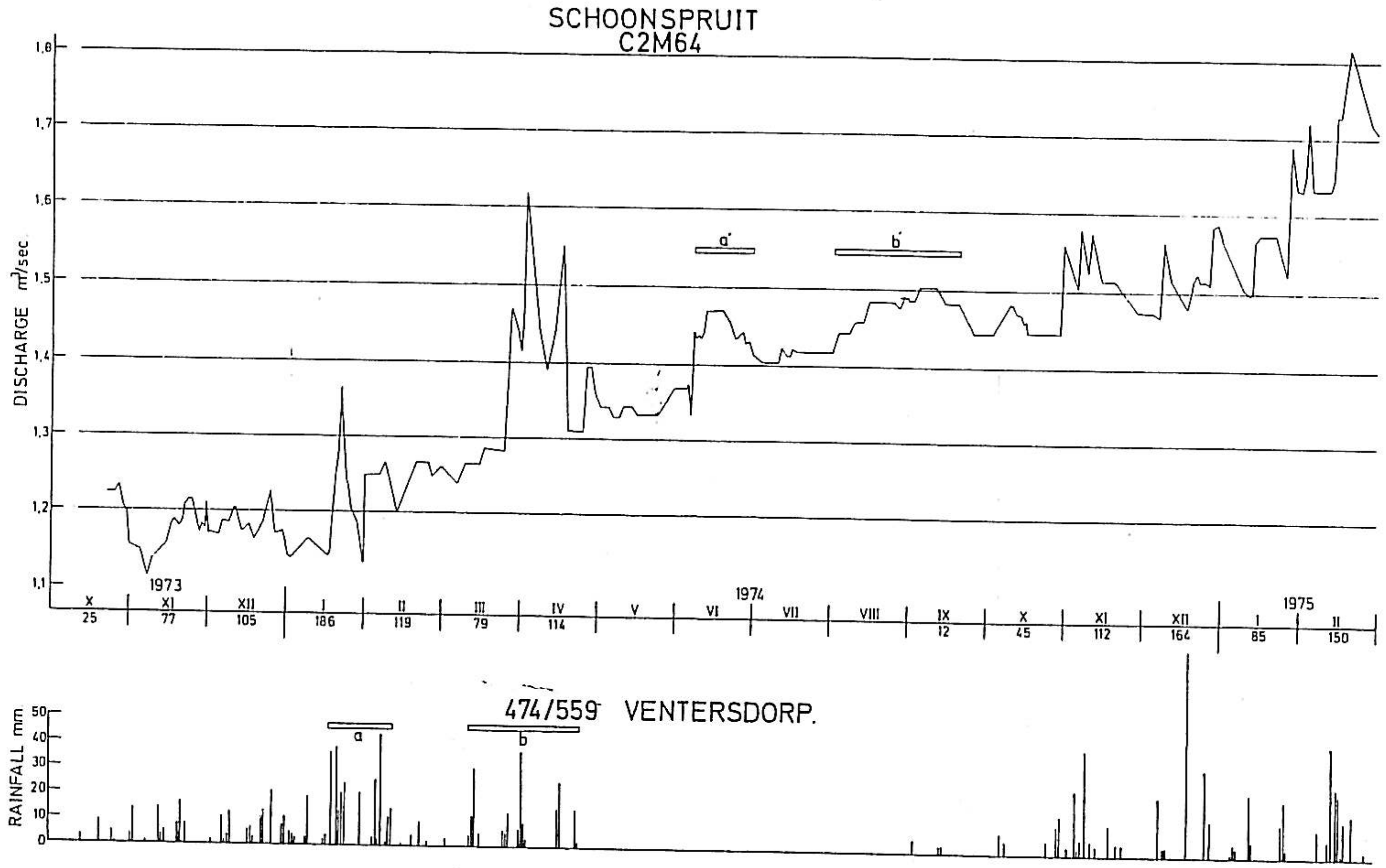


Fig.10.4

Daily discharge against daily rainfall.
A six month phase difference observed between a rainy episode and its manifestation in the discharge.

As a working hypothesis immediate recharge may be conceived as intake via fissures and fractured fault zones, while the delayed recharge consists of rainwater slowly precolating through soil and rock of lower permeability.

The time lag assumingly depends amongst other factors on the thickness of the vertical rock section between ground surface and the groundwater level. The ratio between the areal extension of a thick unsaturated zone and a shallow unsaturated zone in any given compartment would affect the shape of the discharge hydrograph which is practically a reflection of the total amount of recharge vs time.

There appears to be a rapid response of spring flow to changes of water levels in the aquifer as noticed in Fig. 10.5 where the discharge at Turffontein Spring is shown against a water-level hydrograph of a borehole (SW1) upstream. Retarded vertical percolation probably accounts for most of the time lag.

It is noteworthy that in areas where artificial recharge of effluents has lately become quantitatively significant, e.g. at Turffontein Spring, the present records of discharge differ markedly from previous records i.e. immediate recharge conveys the impression of a recession during the dry season (Folder 10.1).

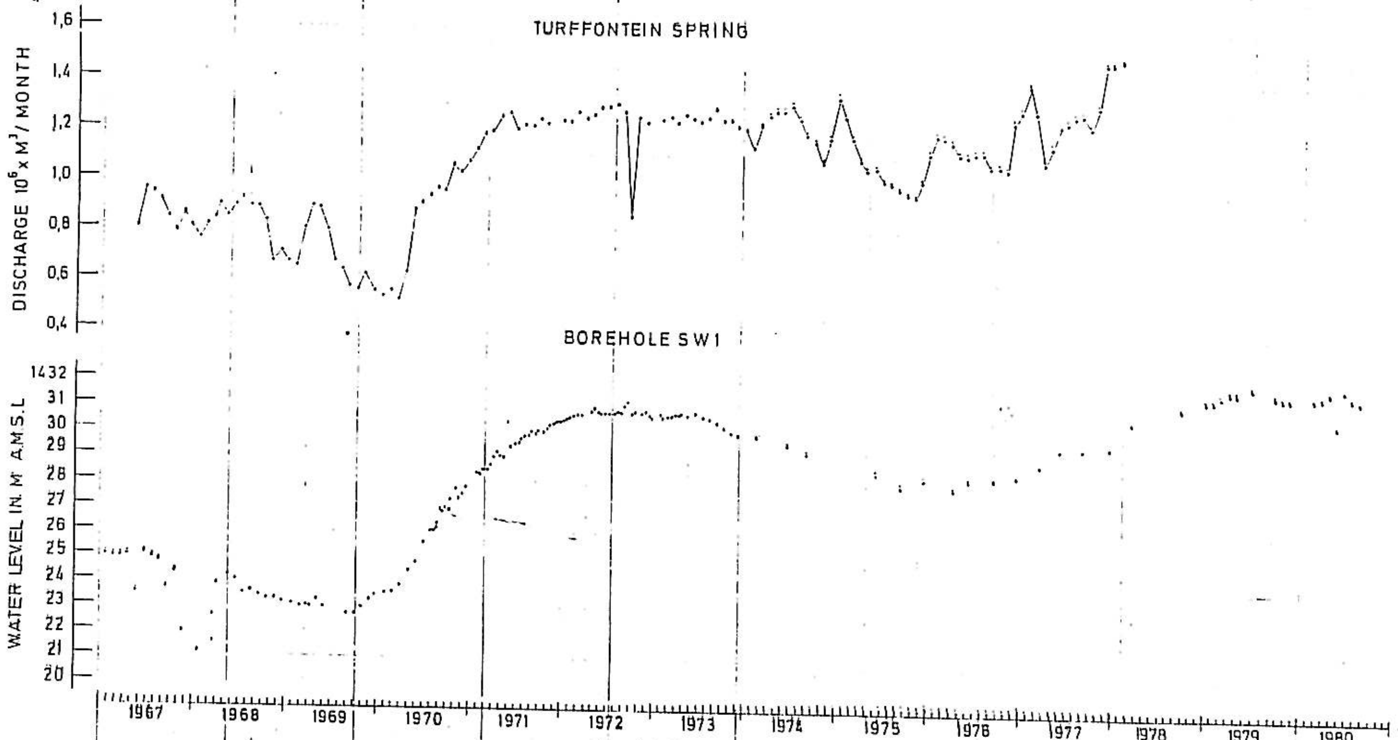


Fig.10.5
Monthly discharge at Turffontein Spring
vs. groundwater levels in borehole SW 1.

10.4 Long-term rainfall-recharge relation

The relationship between annual natural recharge and rainfall has been studied. The study concentrated on Maloney's spring where many years continuous records of discharge are available.

Maloney's Spring is the only known outlet of groundwater from the Steenkoppie Compartment. The Compartment extends over an area of approximately 170 km^2. The spring elevation is + 1 490 m and the depth to water level is between 40 m and 80 m. In most of the Compartment the thickness of the aquifer above spring elevation is between 1 m and 15 m. Abstraction quantities used to be small compared to the potential but have increased recently to an estimated amount of 4.8 x $10^6 m^3$ per year. No mining is being practiced in this compartment and the aquifer is uncontaminated. No observation wells are available in this compartment.

Rainfall figures were calculated as the arithmetical mean of number of stations (6 to 10) in the studies area, (Table 10.2). Rainfall means were compared with annual discharges from Maloney's Spring. Annual recharge was taken as the sum total of the outflow between two successive minima i.e. 1 March to 28 February, and this is referred to as a hydrological year. The corresponding meteorological year is 1 September to 31 August, six month previous. By selecting the hydrological year in this way emphasis is laid on the delayed recharge, while the immediate recharge at the beginning of each wet season is included in the previous hydrological year's total. The annual discharge at the spring and mean rainfalls are listed in Table 10.3. The plotting of these variables did not show any comprehensive interdependance.

TABLE 10.2: Annual amounts of rainfall in the studied area, in mm

Rain Season	Station No.														
1/9 - 31/8	474/ 242	474/ 255	474/ 198	474/ 502	474/ 679	474/ 680	474/ 751	474/ 781	474/ 790	475/ 19	475/ 121	475/ 338	475/ 370	mean	475/ 456
1907/8	499	686	-	629*	-	-	-	611	624	540	564	-	462	576	631
1908/9	795	941	-	762	-	-	-	1 071	823	794	945	-	1 012	892	1 727
1909/10	441	668	-	-	-	-	-	560	591	567	648	-	638	587	720
1910/11	600	747	-	-	-	-	-	830	597	713	815	-	687	712	864
1911/12	532	595	-	-	-	-	-	566	439	566	528	-	509	533	568
1912/13	398	715	-	-	-	-	-	-	507	637	675	-	566	583	589
1913/14	358	467	456*	391	-	-	-	407	509	565	423	-	426	444	488
1914/15	788	724	819	947	-	-	-	603	714	661	955	-	1 109	813	959
1915/16	494	558	384	600	661	-	-	524	557	510	532	-	569	538	-
1916/17	-	514	564	638	608	-	-	-	500*	528	543	-	742	591	967
1917/18	-	700	742	883	-	-	-	-	867*	877	925	-	1 057	864	1 236
1918/19	-	346	498	703*	-	-	-	659	558	506	673	-	699	598	657
1919/20	424	418	510	479	642	-	-	394	454	543	396	-	605	486	600
1920/21	532	563	529	642	726	-	-	728	626	556	701	-	666	626	742
1921/22	690	425	527	597	662	-	-	538	555	475	462	-	740	567	682
1922/23	498	445	513	683	611	-	-	687	692	567	730	-	715	614	889
1923/24	431*	300	433	549	271	-	-	624	503	593	471	-	434	464	556
1924/25	-	775	947	929	674	-	-	882	674	872	867	-	970	843	1 176
1925/26	-	397	611	589	473	-	-	574	441	548	581	-	633	538	639
1926/27	-	512	482	594	579	-	-	519	476	518	798	-	653	569	620
1927/28	-	598	724	718	594	-	-	560	456	626*	582	-	676	613	782
1928/29	-	458	638	767	617	-	-	745	561	677*	774	-	655	651	855
1929/30	-	532	647	852	790	-	-	-	695	742	748	-	730	717	888
1930/31	534	400	387	647	454	-	-	-	404	486	637	-	680	514	679
1931/32	415	412	395	451	472	-	-	475	437	501	564	-	549	467	596
1932/33	362	376	427	499	-	-	-	-	416	589	697	-	472	479	544
1933/34	753	550	689	735	-	-	-	-	620	776	646	-	759	691	820
1934/35	484	490	748	652	-	-	559	510	533	602	591	-	661	583	677
1935/36	-	629	675	633	-	-	723	521	590	586	586	-	727	630	770

Rain Season 1/9 - 31/8	Station No. 474/ 242	474/ 255	474/ 198	474/ 502	474/ 679	474/ 680	474/ 751	474/ 781	474/ 790	475/ 19	475/ 121	475/ 338	475/ 370	mean	475/ 456
1936/37	-	547	637	598	-	-	647	-	672	599	698	-	722	640	1 634(?)
1937/38	-	453	511	801	-	-	649	-	557	568	546	-	699	594	747
1938/39	-	838	849	899	-	-	-	-	791	788	892	-	772	832	926
1939/40	-	732	728	550	-	-	805	-	581	577	716	-	757	680	770
1940/41	-	598	584	547	-	-	-	-	590	561	756	-	816	636	764
1941/42	-	294	587	522	-	-	807	-	612	678	654	-	888	630	898
1942/43	-	697	730	633	-	-	-	-	796	600	834	-	1 070	765	1 276
1943/44	-	764	947	816	-	-	1 140	-	1 020	1 028	1 008	-	1 068	973	1 208
1944/45	-	474	605	529	-	-	703	-	514	471	629	-	755	585	874
1945/46	-	555	601	583	-	-	574	-	323	-	534	-	569	534	635
1946/47	-	630	652	635	-	-	545	-	686	-	618	-	731	642	663
1947/48	-	579	783	661	-	-	741	-	620	411	685	-	792	659	773
1948/49	-	608	524	585	-	-	564	-	-	456	472	-	585	542	629
1949/50	-	644	946	828	-	-	833	-	-	577	795	-	868	784	950
1950/51	-	514	504	605	-	-	622	-	473	577	647	-	797	592	739
1951/52	-	539	535	512	-	-	640	-	542	406	562	-	690	553	630
1952/53	-	590	691	588	-	-	596	-	747	-	-	-	834	674	793
1953/54	-	460	519	456	-	-	541	-	553	-	-	-	693	537	602
1954/55	-	711	850	666	-	-	1 000	-	-	-	-	-	1 014	848	1 125
1955/56	-	608	585	533	-	-	715	-	-	-	-	611	-	610	685
1956/57	-	834	882	729	-	-	738	-	-	-	-	640	-	764	957
1957/58	-	583	719	496	-	-	801	-	-	-	-	645	-	648	906
1958/59	-	610	720	484	-	-	692	-	-	-	-	558	-	612	909
1959/60	-	551	641	643	-	-	499	-	-	-	-	607	-	588	717
1960/61	-	535	681	678	-	-	775	-	-	-	-	815	-	696	-
1961/62	-	458	495	607*	-	673	617	-	-	-	-	586	-	565	420*
1962/63	-	517	701	335*	-	557	536	-	-	-	-	527	-	567	687
1963/64	-	438	522	568*	-	657	509	-	-	-	-	599	-	545	656
1964/65	-	618	534	417	-	527	527	-	-	-	-	-	-	524	538
1965/66	-	635	521	565	-	461	509	-	-	-	-	379	-	511	556
1966/67	-	800	883	711	-	830	1 211	-	-	-	-	1 063	-	916	1 108

Rain Season	Station No.														
1/9 - 31/8	474/ 242	474/ 255	474/ 198	474/ 502	474/ 679	474/ 680	474/ 751	474/ 781	474/ 790	475/ 19	475/ 121	475/ 338	475/ 370	mean	475/ 456
1967/68	-	520	486	505	-	649	520	-	-	-	-	525	-	534	636
1968/69	-	498	519	397	-	505	628	-	-	-	-	601	-	524	652
1969/70	-	501	432	509	-	560	560	-	-	-	-	697	-	543	748
1970/71	-	799	825	658	-	720	816	-	-	-	-	986	-	800	969
1971/72	-	563	555	503	-	536	812	-	-	-	-	557	-	587	833
1972/73	-	410	561	461	-	494	536	-	-	-	-	951	-	568	638
1973/74	-	644	865	586	-	799	812	-	-	-	-	512	-	703	712
1974/75	-	601	733	573	-	640	775	-	-	-	-	799	-	686	837
1975/76	-	713	914	736	-	826	1 003	-	-	-	-	809	-	833	923
1976/77	-	598	711	597	-	847	750	-	-	-	-	670	-	695	839
1977/78	-	856	918	630	-	909	1 019	-	-	-	-	896	-	878	1 277

*Include period of no record

Even a superficial investigation of Maloney's Spring discharge indicates however a strong correlation between exceptionally high annual rainfall and corresponding high discharges, for example 1908/9, 1914/15, 1917/18, 1943/44, 1970/71. In fact, the magnitude of annual spring discharges, immediately following high rainfall events, are more controlled by the high rainfall event than by subsequent lower rainfall events. Several successive high annual rainfalls tend to show an accumulative effect on the discharge, for instance 1974/75 - 1975/76. This "memory" is confirmed by the results of an auto-correlation function (correlogram). Using the annual spring discharges, a strongly auto-regressive process is revealed with a significant dependance over a period of 3 to 4 years (see Fig. 10.6). Correspondingly annual rainfalls reveal a random process.

Some success has been achieved by employing a stepwise multiple linear regression technique (I.B.M. statistical programme based on curve fitting), to study the correlation between annual rainfall and annual spring discharges. Using this technique, the best linear fit to the input data is described by the equation:

$$Q = 1{,}2828 \times Q_{-1} - 0{,}4083 \times Q_{-2} + 0{,}0054 \times R - 1{,}2521$$

where

Q = The predicted annual discharge in $10^6 m^3$

Q_{-1} = Annual discharge of the antecedent year in $10^6 m^3$

Q_{-2} = Annual discharge of the second antecedent year in $10^6 m^3$

R = Rainfall in mm for the corresponding year as Q

$-1{,}2521$ = constant term.

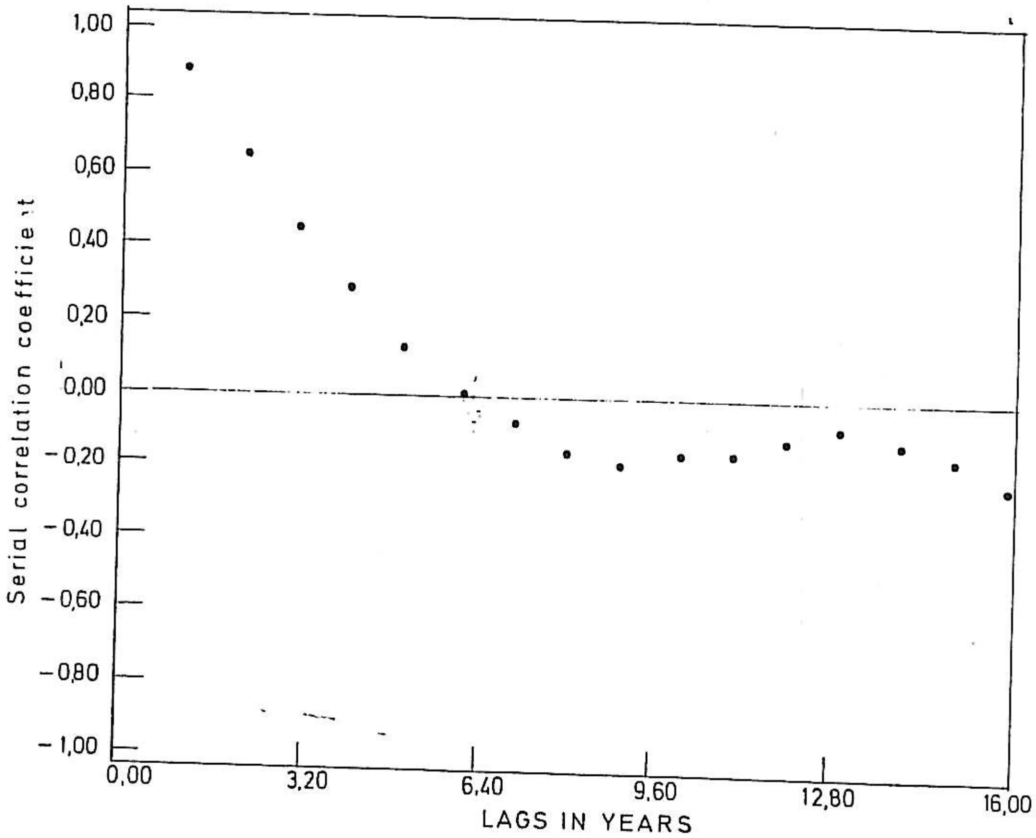


Fig. 10.6

The use of annual spring discharges in the above correlogram reveals a strongly autoregressive process with a significant dependence over a period of 3 to 4 years

Annual discharge can be predicted provided the discharge of two antecedent years and the corresponding annual rainfall are available. Predicted and measured discharges correlate at levels in excess of 85% (Table 10.3).

At this stage it was felt that a mathematical model could possibly be applied at Steenkoppie Compartment to enable an assessment of the aquifer storage i.e. the volume of water stored between the groundwater level surface and a plane at the elevation of the spring.

Research workers from the Operations Research and Statistics Division at the NRIMS of the CSIR were approached and asked to construct such a model which would involve the available data i.e monthly average rainfalls and monthly spring outflows. The results and a proposed model have been described by Markham et al, 1980.

In this model outlfow from the aquifer is compared to the discharge through a pipe at the bottom of a storage tank, the configuration of which is constant at all heights above the outlet. This suggests that the rate of discharge is proportional to the volume of water stored in the aquifer. As previously mentioned, there were no piezometers operating in Steenkoppie Compartment.

The model consists of three components, the discharge-storage relationship, the water balance equation and the rainfall replenishment mechanism.