GEOPHYSICS, VOL. 42, NO. 4 (JUNE 1977); P. 838–849, 9 FIGS., 4 TABLES

GEOPHYSICAL INVESTIGATIONS OF GROUNDWATER RESOURCES IN THE KALAHARI BASIN

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A regional geoelectrical survey of a semiarid development area of about 4000 km^2, approximately 300 km NNE of Windhoek, has indicated a quadripartite subdivision of the Kalahari sediments of late Cretaceous to Tertiary age, with a variable development due to considerable undulations of the Damara basement. The Karroo formations are apparently less well represented. A two-fold interpretative procedure, in which an initial semiqualitative interpretation involving total longitudinal conductance forms the basis for a subsequent quantitative interpretation, has made it possible to map confidently the major lithological units despite the dearth of reliable stratigraphic control. By relating the geoelectrical data to the groundwater head levels, the degree of penetration and production characteristics of boreholes, and the chemical analyses of water samples, the calcareous sands and sandstones of presumed Middle Kalahari age have been seen to constitute the major aquifer in terms of higher sustained yields of good quality water. Encouraging correlations have been noted between these same production characteristics and the geoelectrically derived thickness, resistivity and transverse resistance of this aquifer. It has therefore been possible to delineate the most promising areas for future groundwater development.

The Dar Zarrouk parameters form the basis of a suggested procedure for optimizing the initial stages of groundwater exploration in similar arid and semiarid regions where there is a general absence of lithostratigraphic information.

INTRODUCTION

The Kalahari Basin extends northward from the Orange River in the Republic of South Africa to include much of the Republic of Botswana and parts of neighboring territories (Figure 1). This region is characterized by a relatively low rainfall and extremely high rates of evaporation and evapotranspiration. There is, therefore, a very strong dependence on groundwater resources. The extensive "Kalahari sandveld" generally precludes conventional hydrogeological investigations, and consequently many water wells have been sited on a wildcat basis. This has generally resulted in a success rate of less than 40 per cent with a correspondingly high financial outlay for each useful production well. In order to improve the efficiency of siting strong abstraction boreholes, geophysical methods have been incorporated into groundwater development programs in these areas to an increasing degree. Electrical resistivity techniques have enjoyed the widest application. These methods have contributed to a much higher percentage of successful water wells (e.g., Jennings, 1969, 1971), and therefore can have an important role in groundwater exploration programs in the Kalahari Basin.

This paper is concerned with a regional geoelectrical survey of an area of about 4000 km^2 located within the Kalahari Basin approximately 300 km north-northeast of Windhoek and 50 km southeast of Grootfontein (Figure 1). The object is to establish a sound scientific basis for the siting of abstraction boreholes in this region. It is hoped that these investigations will contribute to the controlled development of regional groundwater resources in order to meet the anticipated increase in demand.

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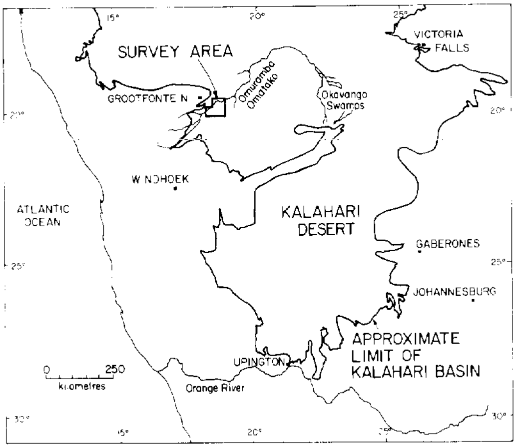

FIG. 1. Location of the survey area.

HYDROGEOLOGY OF THE SURVEY AREA

The survey area is characterized by an extremely erratic annual rainfall of less than 400 mm on average, most of which occurs during the summer months, with an inferred annual potential evapotranspiration for short crops in excess of 2000 mm (Louw and Kruger, 1968). There are no perennial streams but the major river, the Omuramba Omatako, which runs through the northwest of the survey area, can carry substantial floodwaters for short periods during the height of the wet season, when it forms an active part of the endoreic river system associated with the Okavango Swamps (Figure 1).

There is little topographic relief to break the prevalent coarse bush and grasslands, but the widespread surficial dune sands are interrupted by minor occurrences of calcrete, especially along the ephemeral river channels. The area is underlain by extensive Kalahari Beds which are presumed to be mostly of late Cretaceous to Tertiary age. In general, there is thought to be comparatively little direct infiltration of these beds from rainfall, with possible localized exceptions occurring during particularly wet summer seasons in the vicinity of river beds and other places where the vegetation is much less dense. The major source of recharge apparently occurs to the west of the survey area where Karroo sandstones and basalts of the Stormberg series (Triassic to Jurassic) and basement schists and granites of the Damara system (Precambrian) outcrop on the edge of the basin. This is indicated by the distribution of groundwater head levels in which a predominant easterly to southeasterly direction of flow is evident (Figure 2). However, in two localities there are indications of relatively transmissive zones, possibly elongated in the form of channels, whilst a divergence of flow lines in the eastern part of the area suggests a localized zone of low transmissivity. Apart from these indications, conventional information relating to the groundwater potential of this area is scant.

GEOELECTRICAL TECHNIQUE

Field procedure

The geoelectrical survey comprised some 210 Schlumberger electrical soundings whose center points are located in Figure 3. Several pairs of soundings, mutually oriented at right angles, are represented by a common point of investigation. Because of the extensive vegetation, the soundings had to be carried out along tracks, river beds, and at a few other accessible places such as pans. The maximum current electrode separation (AB) attained varied from 750 m to 7 km, depending on local conditions, with an average value of 3 km. The corresponding maximum depths of investigation are estimated to be between 250 m and 800 m.

Field results

The form of the geoelectrical sounding curves varies considerably throughout the survey area, but all curves are characterized by a final segment of positive gradient which, in many cases, approximates 45 degrees. This indicates a semi-infinite basal unit of relatively high resistivity

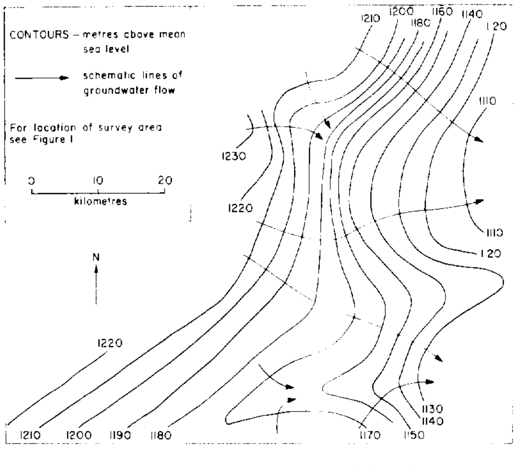

FIG. 2. Groundwater head levels.

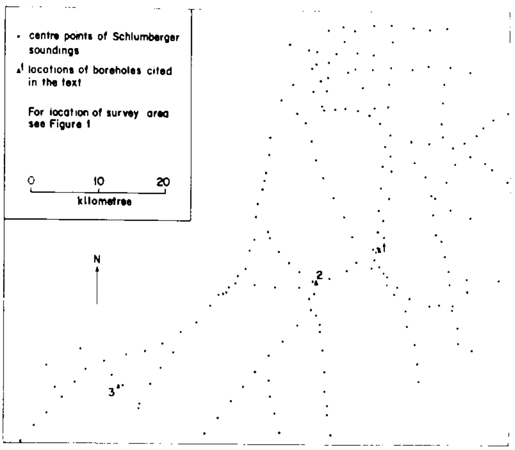

FIG. 3. Distribution of geoelectrical soundings.

Table I. Inferred geoelectrical succession

Geoelectrical unit	Approximate range of resistivity (Ω-m)
Superficial layers	
Surficial dune sand	200–15,000
Calcrete	200–15,000
Kalahari succession	
Upper Kalahari	10–100
Middle Kalahari (upper zone)	60–500
Middle Kalahari (lower zone)	10–70
Lower Kalahari	3–7
Pre-Kalahari	
Karroo	60–200
Weathered Damara	60–200
Damara	>200

which is considered to correspond to the Damara basement. An inspection of all the sounding curves has also allowed the other major geoelectrical units to be recognized. This information is listed in Table 1 together with the approximate range of resistivity associated with each unit. The age classification is based upon conjecture and borehole data gleaned from the more complete strata records. In places, up to seven geoelectrical layers could be recognized in sounding curves of type HKQHA or QHKQH according to the classification of Kalenov (1957). Elsewhere, simple two-layer cases of increasing resistivity, three-layer cases of type A or H, or four-layer curves of type HA were sometimes recorded. The simpler field curves evidently relate to localities where the post-Damara succession is less well represented. Examples of both these groups of curves are given in Figure 4.

Interpretation procedure

A quantitative interpretation of geoelectrical sounding data in the form of horizontally stratified layers of different resistivity is generally not meaningful without some reliable stratigraphic control, or some data relating to the intrinsic resistivities of the various geoelectrical units, at several places within the survey area. This is particularly true as regards deeper layers which are more affected by equivalence and suppression (Kunetz, 1966). Unfortunately, as implied earlier, the majority of borehole records from the survey area are incomplete or unreliable, since they relate to several decades of wildcat drilling. In certain

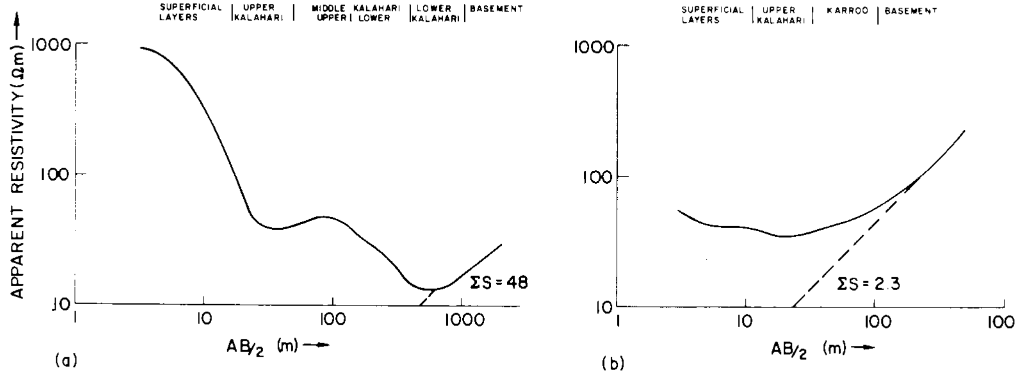

FIG. 4. Specimen sounding curves : (a) Kalahari succession fully represented; total longitudinal conductance = 48 siemens. (b) Kalahari succession partially represented; total longitudinal conductance = 2.3 siemens.

cases there is no information at all. This dearth of reliable borehole information necessitated an alternative approach to the geoelectrical interpretation of sounding curves from this area. This was based on the so-called Dar Zarrouk parameters (Maillet, 1947), whose practical application has recently been outlined by Zohdy et al (1974).

Transverse (unit) resistance T and longitudinal (unit) conductance S are defined for a given geoelectrical layer as:

$$T = h\rho \qquad S = h/\rho,$$

where h and ρ are, respectively, the thickness and resistivity of that layer. The transverse resistance can be determined from a sounding curve for strata which are resistive relative to both the immediate overburden and the underlying layer (Kunetz, 1966). For beds which are resistive only relative to the underlying stratum, the transverse resistance can at best only be estimated. The longitudinal conductance can be evaluated for beds which are conductive relative to the underlying unit. This is achieved through a determination of the total longitudinal conductance of all strata lying above that relatively resistive unit (Keller and Frischknecht, 1966; Orellana and Mooney, 1966). These considerations form the basis for the adopted bipartite interpretation procedure.

The range of resistivities associated with the Lower Kalahari is apparently very much less than those which relate to the underlying Karroo bedrock and Damara basement and to the other constituents of the Tertiary and post-Tertiary succession (Table 1). This means that the total longitudinal conductance of the post-Damara succession will approximate that of the Lower Kalahari itself. Since the degree of development of the Lower Kalahari can be expected to be greater in the deeper areas of the basin, the distribution of total longitudinal conductance will serve as a semiqualitative indication of basement structure. This makes it possible to recognize how given soundings are positioned relative to the basement geology. This, in turn, facilitates the correlation of sounding data during group interpretation. In particular, where a line of soundings has been carried out across the strike, the quantitative interpretation of these data can be much more definite if reference is made to this supporting information during the actual process of interpretation, since the transition from curves of type HKQH to type HA due to an increasing basement elevation can be more reliably analyzed.

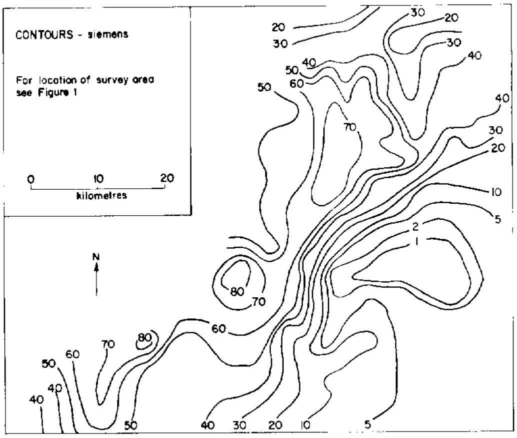

FIG. 5. Distribution of the total longitudinal conductance of the post-Damara succession.

The construction of a regional map of total longitudinal conductance, therefore, was regarded as an essential preliminary to any quantitative interpretation of the sounding data. As further control, soundings were carried out at those few boreholes where the available stratigraphic records suggested that the basement had been penetrated. It is believed that an approach of this kind greatly reduces the effects of geoelectrical equivalence and suppression upon the interpretation of sounding data from areas where there is a dearth of surface outcrop and borehole control.

Each sounding curve was initially interpreted semiqualitatively through the determination of appropriate values of the Dar Zarrouk parameters. This information was then used, together with the data of Table 1, and supplemented by curve-matching of two- and three-layer masters in conjunction with auxiliary charts (Orellana and Mooney, 1966; Rijkswaterstaat, The Netherlands, 1969), in order to obtain a horizontally stratified geoelectrical model. The resulting quantitative interpretation was checked by computing a theoretical sounding curve from the postulated geoelectrical model (Mooney et al, 1966), and comparing this with the corresponding field curve. The model was subsequently modified within the limits imposed by the Dar Zarrouk parameters in order to improve the agreement. Although the final interpretation cannot be regarded as a unique solution, subsequent investigations in adjacent areas where there is better stratigraphic control have shown broadly similar ranges and distributions of geoelectrical parameters.

PRELIMINARY GEOELECTRICAL INTERPRETATION

The distribution of the total longitudinal conductance of the post-Damara succession is shown in Figure 5. Low values of this parameter indicate where the Kalahari succession is relatively thin and where, in the absence of pronounced variations in surface topography or the thickness of the superficial layers, the basement elevation must be relatively high. It can be seen that there is a sizable area within which the total longitudinal conductance is less than 5 S. Obviously, this area must be accorded the lowest priority as regards groundwater exploration.

On the other hand, there are three places where the total longitudinal conductance exceeds 70 S. Here the thickness of the sedimentary sequence can be expected to attain a local maximum. More specifically, since the higher values of total longitudinal conductance are thought to be due to an increased conductance of the Lower Kalahari unit, these maxima should be regarded as indicative only of a comparatively good development of this particular stratum. Therefore, although Figure 5 can be used to define zones of poor groundwater potential, it should not be used to select target areas for groundwater development, since the latter can only be properly defined after considering all the sedimentary strata.

The use of a preliminary geoelectrical interpretation involving the Dar Zarrouk parameters as a basis for defining target areas of good groundwater potential has not been attempted here. This would involve the construction of maps showing the variation in T or S for a given geoelectrical unit across the survey area. However, it can be seen from Figure 2 that the groundwater head level can fall by more than 50 m over a horizontal distance of 10 km. From the geological information that is available, it can be construed that certain water-bearing strata which are fully saturated in the west of the survey area would lie wholly above the water table in the east. Therefore, the distribution of the relevant Dar Zarrouk parameter would have little meaning as an indicator of groundwater potential. It will be seen later that, in areas where the aquiferous strata remain fully saturated, the semiqualitative approach to the delineation of target zones does have a potentially useful application.

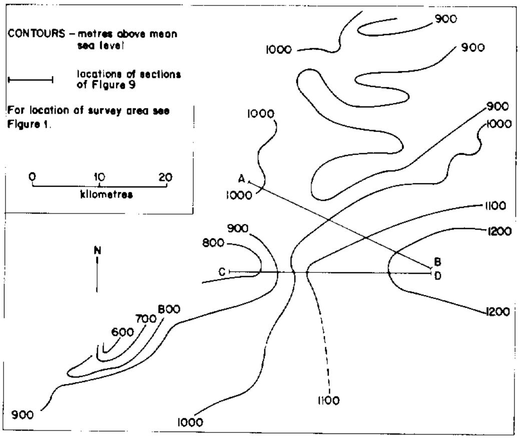

FIG. 6. Variations in inferred elevation of the basement.

QUANTITATIVE GEOELECTRICAL INTERPRETATION

In the absence of good control information, the quantitative interpretation of the sounding data has been carried out by referring to the preliminary interpretation of the previous section, and to the limited useful borehole information that is available. At no stage has it been possible to take account of the effects of anisotropy. Particular difficulty was encountered in interpreting those segments of the sounding curves which relate to the lower zone of the Middle Kalahari, and to the Lower Kalahari.

The lower Middle Kalahari is often suppressed due to its intermediate resistivity relative to the adjacent strata. However, since it has been recognized in places throughout the survey area, this layer has been included in the majority of interpreted models except where there was an obvious indication to the contrary.

The resistivity of the Lower Kalahari has been interpreted as around 3 Ω-m over most of the area. This has generally resulted in interpretations which are consistent both with the shape of the corresponding minima of the majority of sounding curves and with data from the few calibration boreholes.

In certain localities, particularly in the north of the survey area, both the lower Middle Kalahari and the Lower Kalahari are relatively thin, and can be represented as an apparently single unit in what appears as an H-type segment of a sounding curve. Here an attempt has been made to resolve these two layers despite the general lack of calibration data. Suppose, for example, that a total longitudinal conductance of 10 S can be assigned to the lower Middle Kalahari and Lower Kalahari at a place where their combined thickness is thought to be about 100 m, where the minimum apparent resistivity in the sounding curve is 35 Ω-m, but where data from nearby soundings suggest formation resistivities of 30 and 3 Ω-m, respectively. Then the initial quantitative interpretation of these two layers follows from solving the simple equation,

$$10 = \frac{h}{30} + \frac{100 - h}{3},$$

where h is the thickness of the lower Middle Kalahari. Fortunately the process of computer-checking each interpretation did afford some control on this approach. The justification for this action, and for the other conforming procedures mentioned above, is that the resulting final geophysical interpretation is geologically more acceptable than it would be otherwise.

The inferred elevation of the basement, obtained in accordance with the above procedures, is depicted in Figure 6. The area of shallow basement which was indicated in Figure 5 is clearly demarcated. There is generally an encouraging similarity between the contour distributions of Figures 5 and 6. Although these are by no means identical, this does confirm the usefulness of the total longitudinal conductance as a broad indicator of structural variations associated with a highly resistive basement (Breusse and Astier, 1961).

Isopachytes of the major subdivisions of the Kalahari succession are not presented here since, as stated earlier, data of this kind can be of strictly limited value in groundwater exploration where there is a high regional gradient of groundwater head levels.

By comparing the geoelectrical models with the more definite borehole records, it has been possible to deduce broadly the lithology and limits of thickness of the various geoelectrical units of Table 1. It should be noted, however, that the latter are strongly affected by equivalence.

The superficial formations consist predominantly of sand. Calcrete occurs mainly on the surface, but in exceptional cases it can extend to depths greater than 50 m. The Upper Kalahari unit which persistently overlies the Middle Kalahari is generally less than 25 m thick, although in certain localities over 50 m have been indicated. This is essentially arenaceous but the associated range of resistivity implies a significant clay content in places. This unit may correspond to the ochreous sands of late Tertiary age which have been suggested by Cahen and Lepersonne (1952) as the uppermost series in a tripartite lithological subdivision of the Kalahari beds. The Middle Kalahari deposits, which comprise an upper resistive zone and a lower relatively conductive zone, can attain a thickness of over 400 m. The upper zone consists of a calcareous sand or sandstone with a predominance of limestone in places. The lower zone apparently consists of a reddish fine- to medium-grained calcareous sandstone. The Middle Kalahari units almost certainly correspond to the calcareous beds of the Urinanib Plateau (Mabbutt, 1955) which extends from south of Windhoek to the Upington area. The thickness of the very conductive Lower Kalahari can exceed 300 m where this unit is particularly well developed. It would appear to comprise substantially a reddish or brown calcareous clayey sand which probably corresponds to the Kalahari marls reported in northern Cape Province (Du Toit, 1954) and southern Botswana (Boocock and Van Straten, 1962). However, in places, it has been described as a coarse-grained sand or gravel.

The quadripartite subdivision of the Kalahari succession in terms of electrical resistivities is, for present purposes, considered to correspond to a tripartite lithological subdivision, with the upper and lower geoelectrical units of the Middle Kalahari being grouped together.

The Middle and Lower Kalahari units can be absent in areas of shallow basement. The underlying formations have been identified with Karroo lavas and sediments in some places, and with schists and granites of the Damara system in others. The geophysical evidence for the occurrence of Karroo strata in this area is somewhat tentative, and it is possible that these are only of limited extent. The Damara succession can be recognized in sounding curves throughout the survey area as a semi-infinite unit of high resistivity.

INTEGRATION OF GEOELECTRICAL AND HYDROLOGICAL DATA

The meaningful delineation of aquiferous strata requires that the formations of interest lie wholly or largely below the water table. Since the groundwater head levels (Figure 2) vary by up to 120 m within the survey area, which can be equivalent to the thicknesses of the major geoelectrical units, it is imperative that the quantitative geoelectrical interpretation be considered relative to the posi-

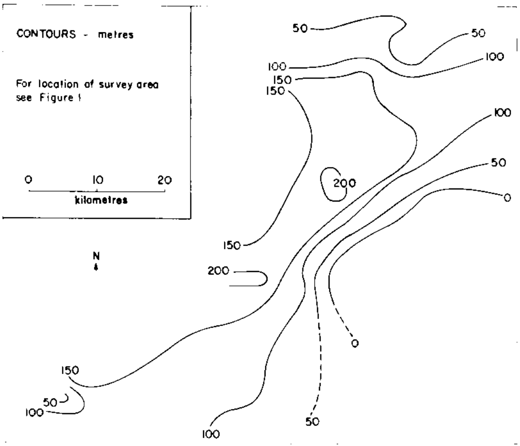

FIG. 7. Inferred isopleths of saturated thickness of the Lower Kalahari.

tion of the water table. The surface resistivity method is generally not a good detector of the water table in consolidated sediments, especially where these are argillaceous or well bedded. This has been confirmed during the present survey. The interrelationship of geoelectrical and hydrological data is, therefore, initially investigated by comparing the geoelectrical interpretation with the contour distribution of Figure 2.

Contour distributions

It will be recalled that the data of Figure 2 suggested two relatively transmissive zones within the post-Damara succession. By comparing Figures 2 and 6, it can be seen that the more northerly zone corresponds to an inferred channel within the basement. It is believed that this particular feature of the groundwater head levels is due to a relatively transmissive in-fill of Lower Kalahari sediments. At the more southerly place the situation is less clear, but is expected to clarify as data from adjacent areas are incorporated into the study. The divergence of the groundwater flow lines in the east of the survey area corresponds to the area of shallow basement. This indicates that the secondary permeability of the Damara System is generally not sufficiently high for this to be considered an important aquifer.

The inferred saturated thickness of the Lower Kalahari subdivision is depicted in Figure 7. This varies from over 200 m in two localities to zero where the basement is shallow. In the latter case the unit is not present. Otherwise, it is sufficiently deep relative to the water table to be virtually fully saturated.

The inferred saturated thickness of the Middle Kalahari subdivision is shown in Figure 8. This varies from over 300 m at one locality to zero in the southeast of the survey area where the basement becomes shallower and the water table deepens.

The comparatively thin Upper Kalahari generally lies above the water table, although there are localized indications of a saturated thickness in excess of 50 m in the west of the survey area. It is not regarded as an important aquifer for the purposes of the present study.

The implications of Figures 6–8 can be better appreciated by reference to selected sections across the survey area (Figure 9), the locations of which are given in Figure 6.

Along the section AB, the Lower Kalahari apparently wedges out to the west of borehole 1 (Figure 3) with the Middle Kalahari terminating to the east of this same borehole. Both these formations are apparently saturated to some extent close to their respective points of termination. However, borehole 1 was recorded as dry. Furthermore, the lithological description relating to this site was not consistent with other strata records, but indicated thin weathered basalts overlying red-to-purple fine-grained sandstone toward the base of the geoelectrical unit which had been interpreted solely as Middle Kalahari. These are believed to represent the Karroo volcanics and Cave sandstone which comprise the upper groups

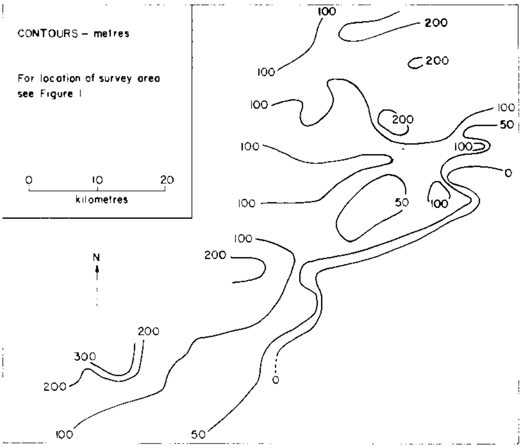

FIG. 8. Inferred isopleths of saturated thickness of the Middle Kalahari.

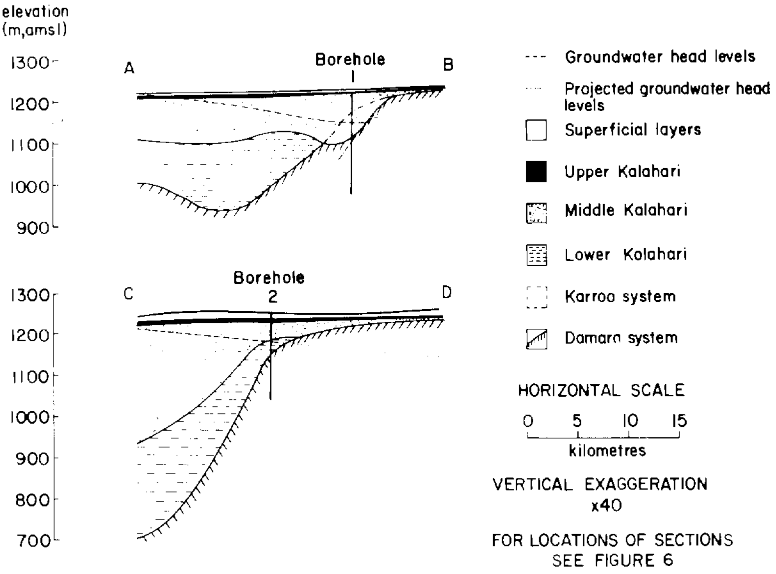

FIG. 9. Selected geoelectrical sections.

of the Stormberg series and which, in this locality, rest unconformably on Damara basement.

The Cave sandstone could not be distinguished geoelectrically from Middle Kalahari which, in any case, is probably derived from the former. Therefore it is to be expected that there will be places, in areas of shallow basement where the Lower Kalahari is absent, at which the geoelectrical subdivision termed the Middle Kalahari also includes the much less permeable Karroo sandstones. Fortunately this is not a serious problem, since the areas of shallow basement are known to be of low priority as regards groundwater resources. The Karroo sandstones are of intermediate resistivity relative to the Lower Kalahari and Damara basement. It is therefore expected that these formations will not manifest themselves in a sounding curve where there is a thick overburden of Lower Kalahari. Because of this geoelectrical equivalence and suppression, it has not been possible to map the Karroo formations within the survey area. In the particular case of section AB, their presence can be inferred from the kink in the interpreted basement surface, as indicated in Figure 9.

The geoelectrical section CD shows that the saturated thickness of the Middle Kalahari approaches zero before that of the Lower Kalahari from west to east. However, the production characteristics of borehole 2 (Figure 3) were far higher than those expected from the limited saturated sedimentary section which was penetrated. It is believed that these waters are largely derived from a fracture zone within the basement. This means that the basement rocks can serve as a useful aquifer, although the contrasting yield of borehole 1, which was apparently similarly positioned relative to the shallow basement feature, suggests that groundwater storage within the Damara varies erratically.

Borehole production characteristics

In this area, these generally comprise test yields obtained shortly after the wildcat drilling of water wells. Since these figures do not relate to intrinsic aquifer properties, borehole data have been analyzed in groups where possible, and average values obtained for similar hydrogeological conditions.

The contour distributions of Figures 2 and 6 indicate those areas where the Damara basement lies above the water table. Eight boreholes located in these areas show an average test yield of 0.1 m^3/hour. This lends quantitative support to the earlier comments regarding the generally poor groundwater resources of these formations.

A comparison of Figures 7 and 8 permits the delineation of those areas where the Middle Kalahari lies entirely above the water table, where the Lower Kalahari is present in a saturated state, and which are considered to be sufficiently distant from the nearest zone of saturated Middle Kalahari to prevent the ingress of waters from this subdivision into the zones of influence of pumped wells. The average test yield of six boreholes located within these areas was 1.5 m^3/hour.

A further study of Figure 8 leads to the recognition of those areas where the saturated thickness of the Middle Kalahari is comparatively great. The average test yield of the 13 boreholes which terminate within this unit, and whose degree of partial penetration is believed to be sufficiently low to prevent a serious up-coming of water from the lower Kalahari during test pumping, has been calculated as 3.0 m^3/hour.

There are, therefore, strong indications that the Middle Kalahari constitutes the most productive aquifer within the survey area. In fact, it is the only geoelectrical subdivision which supports borehole production characteristics that are generally in excess of the regional average test yield of 2.3 m^3/hour. The production characteristics associated with the Lower Kalahari are significantly weaker. Groundwater storage within the Damara basement is apparently restricted to localized fracture zones.

Groundwater quality

An analysis of water-quality variations within the Kalahari succession is meaningless if no account is taken of changes in the saturated thickness of these strata. For this reason, the investigation has been restricted to the properties of groundwaters sampled both during pumping and as dip specimens from those two groups of boreholes which penetrate saturated Kalahari strata as defined in the previous subsection.

The groundwaters of the Middle Kalahari show a range of total dissolved solids of 400–2600 ppm with an average value of about 900 ppm. These are believed to be relatively recent recharge waters derived largely from the edge of the basin, although in some localities they are significantly augmented by the infiltration of rainwaters.

In contrast, the groundwaters of the Lower Kalahari have a total dissolved solids content which generally exceeds 3000 ppm with values of up to 30,000 ppm being recorded in some places. It is not certain whether these waters, too, were derived from the edge of the basin, with the greater concentrations arising from a lower permeability of the Lower Kalahari and a correspondingly greater period of potential dissolution. Alternatively, they may comprise fossil waters which were originally subjected to extremely high evaporation in conditions similar to those found in pans and vleis.

Table 2. Relationship of saturated formation thickness to borehole test yield for the Middle Kalahari.

Range of saturated thickness (m)	Average borehole test yield (m^3/hour)
50–100	1.1
100–200	3.3
>200	5.6

It is clear that the groundwaters of the Middle Kalahari are of vastly superior chemical quality to those of the Lower Kalahari. Boreholes which penetrate both of these units can be expected to show an intermediate water quality depending partly on the relative degrees of penetration. Unfortunately, there are not sufficient data available for the depiction of lateral variations in water quality in either of these subdivisions.

Delineation of areas for future groundwater development

The conclusions of the previous two subsections indicate that the Middle Kalahari constitutes the major aquifer in terms of higher sustained yields of good quality water. In the absence of information relating to storage, the selection of target areas for future groundwater development has been concerned only with the delineation of zones where the Middle Kalahari has a high transmissivity. Since transmissivity is the product of aquifer thickness and hydraulic conductivity, this ideally involves the location of areas where both the inferred saturated thickness and the permeability of this subdivision are relatively high.

Localized zones of high aquifer thickness can be inferred from Figure 8. The range of variations in saturated thickness extends far beyond the limits of equivalence, and therefore this chart forms an excellent basis for the selection of target areas. Table 2 gives a semiqualitative indication of the relationship between the saturated thickness of the Middle Kalahari and the test yield of boreholes which penetrate this subdivision. Inferred saturated thicknesses of less than 50 m have not been considered since these sometimes relate to areas of shallow basement where the Lower Kalahari is absent and, therefore, might include a significant representation of Karroo strata.

Table 3. Relationship of normalized formation resistivity to borehole test yield for saturated Middle Kalahari.

Range of normalized resistivity (Ω-m)	Average borehole test yield (m^3/hour)
0–50	1.8
50–100	7.1
>100	7.5

Permeability has been seen to be related to geoelectrical parameters in several arenaceous aquifers where there is a predominant intergranular component of groundwater flow (Worthington, 1976). This requires that values of formation resistivity be initially adjusted in order to take account of, inter alia, variations in groundwater quality. Unfortunately there are not, as yet, sufficient water quality data to effect these corrections throughout those areas where the Middle Kalahari is largely saturated. Nevertheless, those limited data that are available have been used to compile Table 3, in which values of formation resistivity, determined from soundings at sampled boreholes, have been normalized to a groundwater resisitivity of 10 Ω-m using Archie's law (Archie, 1942). This table indicates that the formation resistivity of the Middle Kalahari generally increases with the test yield of boreholes. It is interesting to note that a similar increase in resistivity with borehole yield has been reported for a calcareous formation elsewhere (Vincenz, 1968). However, in neither case has any correction been made for the possible effects of matrix conduction.

It appears that higher borehole yields will be obtained where both the saturated thickness and the resistivity of the Middle Kalahari are comparatively great. Since both these parameters can be affected by geoelectrical equivalence, the total transverse resistance of the Middle Kalahari might constitute an even better indicator of aquifer productivity, especially in view of the dearth of reliable stratigraphic control. A correlation of transverse resistance with borehole test yield has been restricted to data from sampled boreholes at which electrical soundings have been carried out. As a preliminary, values of transverse resistance were normalized to a groundwater resistivity of 10 Ω-m using simple equations (Worthington, 1975, p. 356). Table 4 indicates that the normalized transverse resistance of the Middle Kalahari increases with the test yield of boreholes. This confirms that lateral variations of total transverse resistance within those sections of the Middle Kalahari which are largely saturated would furnish a good indication of areas of promising groundwater potential, although if corrections for water quality are not made the results could be misleading. Again, no account could be taken of the possible effects of matrix conduction.

Production characteristics from recent drilling

An intended supply borehole has recently been sited where the total transverse resistance of the Middle Kalahari is around 9000 Ω-m^2 and where the inferred saturated thickness of this subdivision is approximately 180 m. This is borehole 3 of Figure 3. It can be seen from Tables 2 and 4 that production characteristics far in excess of the regional average of 2.3 m^3/hour could be expected. In fact, the borehole test yield at this site was 6.7 m^3/hour.

OPTIMUM GEOPHYSICAL PROCEDURES FOR GROUNDWATER EXPLORATION

The considerations of the previous sections can be used as a basis for postulating an optimum strategy for hydrogeophysical exploration in areas such as this part of the Kalahari Basin where there is virtually a total dependence on groundwater from sedimentary strata, where there is a dearth of reliable stratigraphic control, and where a predominant conductive unit occurs toward the base of the sedimentary sequence.

Since sedimentary basins frequently occur within a highly resistive basement, a semiqualitative evaluation of the regional structure can be obtained rapidly through variations in the total longitudinal conductance of the sedimentary sequence, a parameter which can be determined directly from sounding data. This information will afford some control on the subsequent quantitative interpretation of the sounding curves. It also defines those areas where the sedimentary sequence is thin, and where there might be expected to be a poor groundwater development potential.

Table 4. Relationship of normalized transverse resistance to borehole test yield for saturated Middle Kalahari.

Range of normalized transverse resistance (Ω-m^2)	Average borehole test yield (m^3/hour)
<4000	3.1
4000–8000	4.9
>8000	7.1

The target areas for initial groundwater development can often be identified through variations in one or other of the Dar Zarrouk parameters associated with the most promising aquiferous unit, provided that this unit remains largely saturated within the area of interest and that there are no pronounced changes in either water quality or matrix conduction. Boreholes sited in initially selected areas should furnish higher production characteristics than might otherwise have been expected, provide meaningful stratigraphic control for the quantitative interpretation of the sounding data, and yield some information relating to variations in groundwater quality.

A strategy of this nature would optimize the need for control information, the water requirements of the area in question, and the financial outlay involved, during the early stages of groundwater development programs within similar arid or semiarid zones. More intensive groundwater development can then follow on the basis of the quantitative geophysical interpretation. A complementary strategy has already been proposed for the application of geophysical techniques during intensive groundwater studies of arenaceous aquifers where there is reliable borehole control (Worthington and Griffiths, 1975).

CONCLUSIONS

A geoelectrical interpretation procedure based on the Dar Zarrouk parameters has permitted the delineation of the major lithostratigraphic units within a sizable survey area over highly resistive basement, despite the general absence of calibration data from both surface outcrop and borehole records. The recognition of the relatively thin Karroo strata has been impeded by equivalence and suppression. The data suggest a quadripartite geoelectrical subdivision of the Kalahari succession, with the calcareous sands and sandstones of presumed Middle Kalahari age constituting the most promising aquifer in terms of both productivity and groundwater quality.

The production characteristics of boreholes sited within the Middle Kalahari show encouraging correlations with surface-measured geoelectrical parameters. This means that the surface resistivity method constitutes a potentially sound basis for the delineation of priority areas for future groundwater development. Furthermore, in view of the general correlation of the Kalahari beds over large sections of the basin (Cahen and Lepersonne, 1952), this conclusion may have a much more general validity. In this respect it is particularly interesting to note that, in those parts of the Kalahari of Botswana where geophysical surveys have indicated a substantial saturated thickness of the Kalahari beds, borehole yields may be five times greater than those relating to areas where older formations constitute the major aquifers (Jennings, 1969).

Procedures have been suggested for the optimum use of geoelectrical techniques during the early stages of groundwater exploration in similar arid and semiarid areas where there is no control information. It is contended that the implementation of these procedures could greatly benefit underdeveloped regions where there is virtually a total dependence on groundwater.

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