Natural Environment Research Council

British Geological Survey

HYDROGEOLOGY

RESEARCH GROUP

WD/86/012

OLLECTOR WELL PROGRAMME, ZIMBABWE AND MALAWI, 1986-7
BRITISH GEOLOGICAL SURVEY:

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1. Introduction and Summary Review.

This is a joint programme funded by ODA and the Governments of Zimbabwe and Malawi. Previous reports, listed below, have described earlier stages in this programme and notably the construction of the first four collector wells in Zimbabwe.

Wright, et al. 1985 BGS/ODA-Zimbabwe Government Collector Well Project Report

Wright, E P, April 1986 Summary Review of Collector Well Project 1985-86

The present report mainly discusses the results of three completed collector wells in Zimbabwe and some interim data from two collector wells in the final stages of construction in Malawi. Although not included in this discussion, reference should also be made to a further two wells in the final stages of construction in Zimbabwe and the proposal to construct four more in the coming year.

Six appendices in this report provide detailed information on individual sites. Additional sections which follow this review include one (section 2) on geophysical survey techniques and another (section 3) on the geomorphological context of the sites.

1.1 Collector Well Siting

Well sites are selected on the basis of general ground reconnaissance in the vicinity of the source of demand (mainly schools, in one instance a small town). The geophysical techniques employed to date include resistivity profiling and electrical soundings at selected locations. Although high resistivity responses have been shown to be a good indication of shallow bedrock, other results, both of profiles and soundings, have tended to overestimate the thickness of the regolith (disaggregated overburden material which it is feasible to excavate from a well), often significantly so. Electromagnetic traversing with varying coil orientations is giving evidence of potentially more accurate predictions of regolith depths. None of the methods employed have provided significant information on lithological variations within the regolith which could have hydrogeological significance. An identification of a layer of more highly resistive competent rock in the lower levels below the regolith and above the hard bedrock may have significance. It could correspond with the weathered bedrock (saprock) which is included in the weathered sequence but below the disaggregated regolith. The saprock could be penetrated by the radial boreholes and may have high permeability. The regolith above must have adequate saturated thickness but not excessively so and neither must the depth of the base of the regolith be too great, preferably less than 15 metres. With improved excavation methods, probably by greater use of mechanical equipment, this constraint will be of lesser concern.

The subsequent test drilling is designed to confirm the predicted thickness of the regolith, determine the static water level (which may also have been predicted) and to carry out pumping tests. At the present time, a pumping test of 12-20 hours with an abstraction rate about 0.1 litres/sec is considered necessary for the selection of the well site additional to an adequate thickness of saturated regolith. On the assumption of a well depth not exceeding 15 metres, a static water level of less than 5 metres below ground level is preferred. The results of pump testing several test boreholes at each of the Zimbabwe sites has demonstrated a wide range of test responses to pumping. The impression is gaining ground that provided the thickness of the saturated regolith is of the right order, the requirement on adequate yield from the slim borehole may not be too critical. The effect of the radial collectors is sufficiently pronounced to counteract the local conditions encountered in a single hole. It is becoming apparent that the regolith retains structural features which are likely to be steeply dipping, if residual from the altered bedrock, and which may be only rarely encountered in a slim test hole.

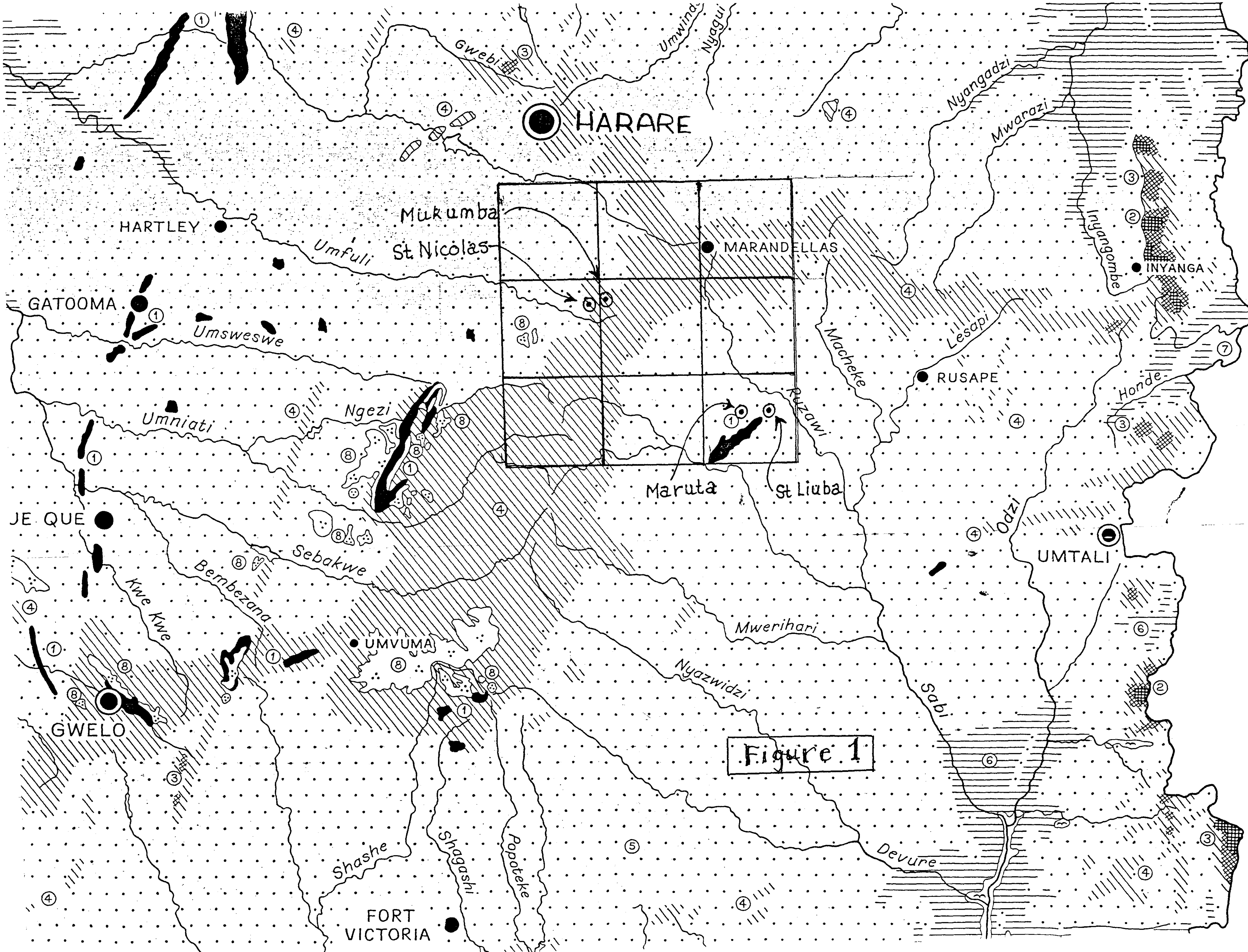
Section 3 discusses the geomorphological context of collector well sites. The understanding of the detailed geomorphological controls is likely to be fundamental in determining the areal potential of collector wells. Key issues are regolith thickness, saturated regolith thickness and the nature of the underlying saprock (weathered bedrock) in addition to hydrological controls, notably recharge. More localised controls to the weathering sequence (regolith + saprock) also include bedrock type. Preliminary indications are that the regolith is relatively thicker over micaceous rocks and with a higher ratio of saprolite to saprock. Basic rocks rich in ferromagnesian minerals will tend to produce less permeable saprolite corresponding to an increased clay content and more homogeneous character.

The geomorphological analysis considers the relative elevations of land surfaces in the context of geomorphological units of varying age. The higher and older surfaces are likely to have thicker regolith. The second group of factors includes relative relief and dambo occurrence. Relative relief will relate to later incision and leaching history and control saturated thicknesses and catenary variations, both thickness and lithology. Dambos in the incised areas will have altered shapes and the facilitated leaching seems likely to result in reduced thickness of the regolith in addition to solution effects altering the lithology. These various factors can control the feasibility of collector well construction and hence potential.

The three collector wells completed in the second phase of construction in Zimbabwe all occur to the south of Harare (Figure 1) and are in the vicinity of rural schools for which they are designed to provide water supply. A fourth site (Maruta) was investigated but rejected following test drilling. The two collector wells in Malawi are in the final stages of completion, awaiting radial drilling. They are located in the vicinity of a small town, Mponela, and are designed for urban supply.

1.2 Large Diameter Well Construction

All the wells completed in the recent series have been of 2 m diameter. With one exception all are of the brick caisson type. The exception is the second well in Malawi which uses concrete segments (three to a ring, 0.5 m thick) emplaced from below. Apart from some initial delay due to faulty design of the segments, the method is now working well and it is hoped will overcome the problems encountered with brick caissons which have resulted in lengthy delays.



HARARE
HARTLEY
GATOOMA
JE QUE
GWELO
UMVUMA
FORT VICTORIA
MARANDELLAS
RUSAPE
INYANGA
UMTALI
Mukumba
St Nicolas
Maruta
St Liuba
Gwebi
Umwind
Nyagui
Nyangadzi
Mwarazi
Inyangombe
Umfuli
Umsweswe
Umniati
Ngezi
Sebakwe
Bembezana
Kwe Kwe
Macheke
Lesapi
Honde
Ruzawi
Odzi
Mwerihari
Nyazwidzi
Sabi
Devure
Shashe
Shagashi
Popoteke
B I Q U E

Figure 1

Problems in caisson construction have resulted from the presence of core stones and sandy material inflows, particularly during periods of heavy rain, and both occurrences are likely to cause skewness, cracking in the caisson or a refusal to sink. An alternative lining by corrugated iron sheet segments is also under consideration and could have advantages in being light and easy to handle. The improved methodology of construction should reduce both time and cost of construction but figures are not yet available to make these comparisons.

1.3 Large Diameter Well Tests

Pump tests requiring both small and deep drawdowns are carried out after the well completion and before radial drilling. The analyses based on 25, 50 and 75% recovery times (Herbert-Kitching, 1981; Herbert-Barker, in preparation) enable transmissivity values to be determined and also the storage coefficient but with a lesser degree of accuracy; comparisons can also be made with the performance of the collector well.

1.4 Radial Drilling

The rig developed for this current series has the facility of being able to drill at any angle between the horizontal and the vertical. In addition to four horizontal holes generally drilled to about 40 m, up to four inclined holes were also drilled at angles from about 5-35^{o} below the horizontal. The evidence to date has not indicated any significant improvement beyond what has been obtained from the horizontal holes. This is probably because the collector wells have been dug to almost the total thickness of the regolith and the horizontal boreholes are probably intersecting the most permeable section near the saprolite-saprock boundary. The situation could be more favourable to angle drilling in thicker regolith sections in which the large diameter well is terminated well above the basal boundary.

1.5 Collector Well Testing

Both short (<1 day) and long term (10-14 days) pumping tests were carried out. The short term tests enable comparisons to be made with the responses of the test on the large diameter well. The main long term test which is preferably carried out towards the end of the dry season, allows calculation of the seasonal transmissivity in addition to predicting a safe yield which can be maintained for a further 180 days without vertical recharge, as an indication of drought potential. Pumping is generally carried out for three 2-hour periods with 3-hourly rests during daylight hours in order to evaluate the manipulation of well storage and to simulate, in as regular a way as possible, a typical well pumping regime, e.g. for irrigation.

1.6 Summary of Results

Table 1 summarises the site conditions at the three completed wells in Zimbabwe. All are on granitic rocks with a similar thickness of regolith, rather surprisingly with a maximum value in the site on the Post African surface which shows higher relief and abundant local outcrops. The feature does demonstrate the variability in weathering depths which are encountered.

Table 2 summarises the pumping tests on the slim boreholes (to the base of the regolith), the large diameter wells and the collector wells. The improvement on the LD wells are in the range 33 to 1150%. The yields are moderate (1 to 1.5 litres/sec) but with pumping drawdowns of between 2 and 3.5 metres.

An important comparison can be made with such boreholes as exist in the same general areas of the collector wells. Unfortunately the numbers are few.

Table 3 summarises the constructional costs of the large diameter wells which represent the major components of the total costs. Fuller details are shown in the Appendices. The substantially higher cost of St Nicholas relates to the lengthy delays caused by sandy inflows below the caisson. The costs of all wells have been inflated by delays due to equipment breakdown. There has been a substantial increase in labour costs in Zimbabwe since the construction of the first series which is reflected in these figures.

1.7 Comparison of Collector Wells with Slim Boreholes

In a previous report, Wright et al., 1985, some broad comparisons were made between the yields of the first four collector wells and mean yields of standard boreholes (section 5.1, op. cit). More comprehensive comparisons are difficult to make but should take account of the following:-

(a) Long term yields (see discussion below).

(b) Failure rates. Insufficient numbers of collector wells have been constructed to make any valid comparisons as yet. However it may be noted that although considerable exploration studies have been carried out at each site, mainly to obtain fuller information for an essentially experimental study in depth, only one site has been actually rejected on the basis of pumping tests in the shallow test boreholes to the collector well depth. The impression being gained is that provided the radials can penetrate the general boundary zone at the base of the regolith (disaggregated weathered overburden), failure to provide a moderate yield is not likely to occur even though the large diameter well may prove to give almost negligible yields on test. This feature probably reflects the great influence of the transitional regolith-saprock zone (poor yields of the LD well if very thin) and of residual fracture systems which are mainly of steep dip and perhaps only rarely encountered in the large diameter well (or slim test hole). Failure rates in slim boreholes may always have the constraint imposed by the variability of fracture systems which need to possess a sufficient density to provide success. At present, failure rate is about 30% overall.

(c) Comparisons of costs for equivalent yields. At the present time the experimental wells are 2-3 times more costly to construct than a standard borehole but without considering the yields. The bulk of the costs relate to construction. There is every reason to suppose that costs can be reduced by improved methods of construction and more particularly so in a large scale development programme where more advanced technological methods could be considered. Combinations of self-help with high technology (for construction below the water table) might also be a consideration for the future.

(d) Maintenance and sociological aspects. In some areas, particularly where geology constrains the sites of boreholes to considerable distances from the demand location, collector wells could prove more convenient. The advantages of a single pump to a larger yielding well as compared with several boreholes each with a pump to provide the equivalent yield will relate to capital pump costs but more importantly to maintenance. Collector wells are more vulnerable to pollution but with a moderate thickness of a clayey saprolite in the unsaturated zone (a common feature), pollution may not be a problem provided the well sides and surrounds have an adequate sanitary seal. For distributions to tanks and standpipes, the larger yield of collector wells have obvious advantages and for small urban supplies, chlorination would be in order.

1.7.1 The most important comparison is with long term yields. A discussion is given below on the boreholes in the vicinity of the four collector wells studied in the present series.

(1) St Nicholas School. Three boreholes were constructed in January to March 1985. Two of these boreholes were capped and one is fitted with a Bush pump. The reasons for the lack of use of even the one fitted with a pump is unclear but may relate to the distance from the school (approximately 1km). The collector well by comparison is very close to the school and therefore conveniently sited.

Brief notes on the borehole tests are given below which include a test on completion and tests carried out more recently in order to make comparisons with the collector well.

S3896 (southernmost)	January-March 1985	11-12 November 1986
0-16 m soft rock	9 hour test	6½ hour test
16-60 m hard rock	0.53 litres/sec	0.475 litres/sec
	(no drawdown data)	D/d: 23 m
S3895 (central)	9 hour test	5 hour test
0-42 m soft rock	0.30 litres/sec	0.28 litres/sec
42-61 m hard rock	(overflowing)	D/d: 41 m
S3894 (northernmost)	9 hour test	11½ hour test
0-22 m moderately hard rock	0.44 litres/sec	0.4 litres/sec
22-43 m hard rock	SWL: c. 6 m bgl	D/d: 19 m
43-56 m soft rock		

The drawdown data of the most successful borehole (S3896) has been analysed using semi log plots. The calculated transmissivity is 0.72 m^2/day and storativity (S) of ca. 0.1 which is very high. For a pumping rate of 0.5 l/sec the drawdown would reach the bottom of the borehole in about 7 days. For the longer term yield it could be assumed that drawdown could only be tolerated to the base of the regolith at 16 m when S would drastically reduce and drawdown increase rapidly. The correlated discharge (Q) for 180 days with these parameters would be 0.06 l/sec as compared with 1.5 l/sec for 6 hours or 0.38 l/sec for the collector well with equivalent drawdowns of 16 m and 5 m respectively. The longer term yield is 6-7 times higher for the collector well or taking drawdown into account (yield per metre of drawdown) there is a 15 times improvement.

(2) Makumba. No boreholes in the near vicinity. Nearest is 10 km away.

(3) St Liobas. A borehole was drilled to 45 m in the close vicinity of the school which was reported to yield 1 l/sec on test. Shortly after completion the pump was removed and has never been replaced (several years ago). No reason has been given and the borehole is now disused and because it was not capped has now been filled up with rubble. We suspect that the water levels may have dropped seasonally so that the yield fell completely below a handpump performance.

(4) Maruta. A borehole near the school was drilled to 45 m but the yield on test (0.08 l/sec) was too low to fit a handpump. In the event no collector well was constructed because of low yields in the slim test hole but as noted earlier, this might not now be considered a sufficient reason for site rejection.

2. **General Discussion on Geophysical Surveys.**

Geophysical surveys were undertaken on a regular basis as part of the site selection procedure for locating collector wells in the first pilot project undertaken in Zimbabwe. The main priority of the geophysics was to outline areas where the depth to bedrock was sufficient to permit construction to the planned deth of about 12-15 m, thus ensuring adequate storage capacity. Information on the other critical factors, such as the rest water levels, formation permeabilities and the presence of lateral variations which would indicate preferred orientations for drilling the radials, was obviously required if possible.

Most of this work was done by staff of the local Water Department using reconnaissance Schlumberger resistivity profiling techniques with detailed follow-up in more promising areas. The results illustrated that while high resistivities are a good indication of unsuitable ground conditions - usually showing shallow bedrock - it is very difficult to interpret the data quantitiatively in terms that correspond with the experience of subsequent test drilling and well construction (see Wright and Others, 1985). This is attributed in part to the degree of ambiguity inherent in the resistivity method but it is also a function of the highly variable nature of the regolith on a local scale; as resistivity values are based on sampling a relatively large volume of ground in comparison with the effective depth of investigation, their resolution is limited. Another difficulty arises in relating the electrical properties of the regolith and weathered bedrock to their mechanical strength. Chemical processes, essentially related to the formation of clay minerals, tend to determine the bulk resistivity of the material though its porosity will also have an influence. Conductive paths can be formed through a rock matrix at an early stage by alteration at the surface of its constituent mineral grains and this means that layer resistivities can suggest promising zones which turn out in practice to be too hard for well construction. Drilling results can also prove misleading in this respect but in some cases the resistivity interpretations consistently predicted regolith below levels at which boreholes encountered hard rock.

A limited amount of supervised geophysical fieldwork was undertaken in Zimbabwe at three of the sites chosen for the second series of collector wells, namely near the schools of Mukumba, St Nicholas and St Lioba. Once again it was necessary to rely on electrical methods using resistivity soundings and electromagnetic traversing with an EM34-3 in an attempt to find sites suitable for testing by exploratory drilling. All of the localities were in marginal areas where borehole success rates in the past had been poor, and bedrock outcrops were common. In these circumstances the aim was to find any sites where there was some possibilities of success, accepting that the risk factor would be high. The work done and the results obtained have been described elsewhere (Carruthers, 1985).

3. Geomorphological Context of the Collector Well Sites

3.1 Location

The area within which the collector wells are situated is shown in Figure 1, which is a portion of Lister's map of erosion surfaces in Zimbabwe. It lies to the south-east of Harare (formerly Salisbury), straddling the main interfluve between north westerly drainage to the Zambezi river and south easterly drainage which flows more directly to the ocean via the Sabi river.

The monotonously flat surface of the interfluve has been assigned by Lister to the African Surface (diagonal stripe on Figure 1) with almost imperceptable finger-like penetration of the Post African Surface towards the interfluve (Lister, pers. comm.). In the north east and south west, the area shown as stippled on Figure 1 has been assigned essentially to the Post African Surface.

3.2 Relief

The relief is shown in Figure 2. The highest part of the African Surface on the interfluve in this area is around Marandellas, at about 1640 m. To the south west, the African Surface along the watershed lowers gradually to about 1450 m. The north westerly slope away from the watershed is gradual but on the south east side, the more aggressive incision by the rivers flowing more directly to the ocean (as indicated by the deeper penetration of the contours along them) results in more abrupt changes in slope and generally steeper slopes towards the main incising streams, particularly in Sengezi, Nyamidzi and upper Sabi in the south east.

Incision by these latter streams has left several groups of hills standing as outliers of the African Surface. The largest of these, the Wedza Block (assigned by Lister to the sub-Karoo Surface) has a conspicuous bench at 1640 m, an altitude comparable with the interfluve surface around Marandellas. The bench of the block lies some 240 m above the very flat spur running south east from Wedza Township, through Maruta school, the only one of the four prospective collector sites which was not developed. This south easterly trending spur is one of several flat-topped spurs also running in a southeasterly direction from the main shed. Their flatness would suggest that they are extensions of the main surface on the watershed (not represented on Lister's map). If they are, then the altitude gap between the Wedza Block and the nearby Maruta spur indicates that the ca. 1400 m surface of the spur represents a younger land surface component than the surface at ca. 1600 m, that is, the African Surface is not monocyclic, but composed of chronologically separate components and this in turn implies profiles with different characteristics and hydrological properties.

It appears, therefore, that prior to major Post African incision, there was an erosional situation in which the south easterly flank of the main shed was gently modified, very much like the present north westerly flank.

3.3 Relative Relief

The local relative relief (difference between highest and lowest points) was analysed at the 1 sq km unit level.

Relative relief was classified thus:

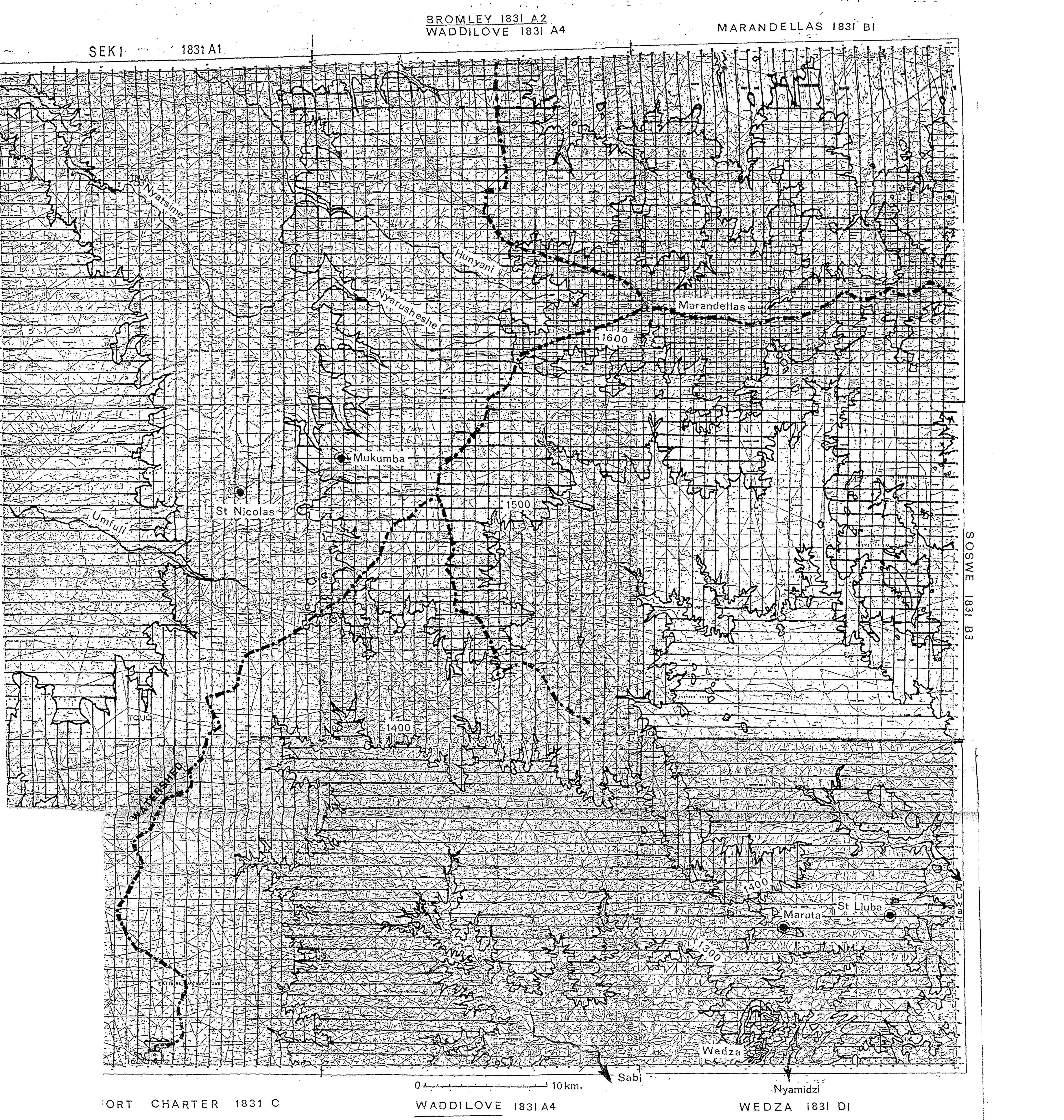

BROMLEY 1831 A2
WADDILOVE 1831 A4
MARANDELLAS 1831 B1
SEKI 1831 A1
SOSWE 1831 B3
ORT CHARTER 1831 C
WADDILOVE 1831 A4
CHOKODZA 1831 C2
WEDZA 1831 D1
Nyatsime
Hunyani
Nyarusheshe
Marandellas
1600
Mukumba
St Nicolas
Umfuli
1500
1400
WATERSHED
1400
Maruta
St Liuba
1300
Ruwazi
Wedza
Sabi
Nyamidzi
0 10 km.

FIGURE 2

1. less than 20 m/km square
2. 20-40 m/km square
3. 60-80 m/km square
4. 100-180 m/km square
5. over 200 m/km square

This approximates to slopes thus:

1. less than 1 degree
2. 1-3 degrees
3. 3-5 degrees
4. 5-10 degrees
5. over 10 degrees

The original multicoloured map is housed at BGS Wallingford. Figure 3, compiled from this, shows three categories only, i.e.

1. less than 20 m = less than 1 degree (dotted)
2. 20-40 m = 1-3 degrees (diagonal cross)
3. over 60 m = over 3 degrees (black)

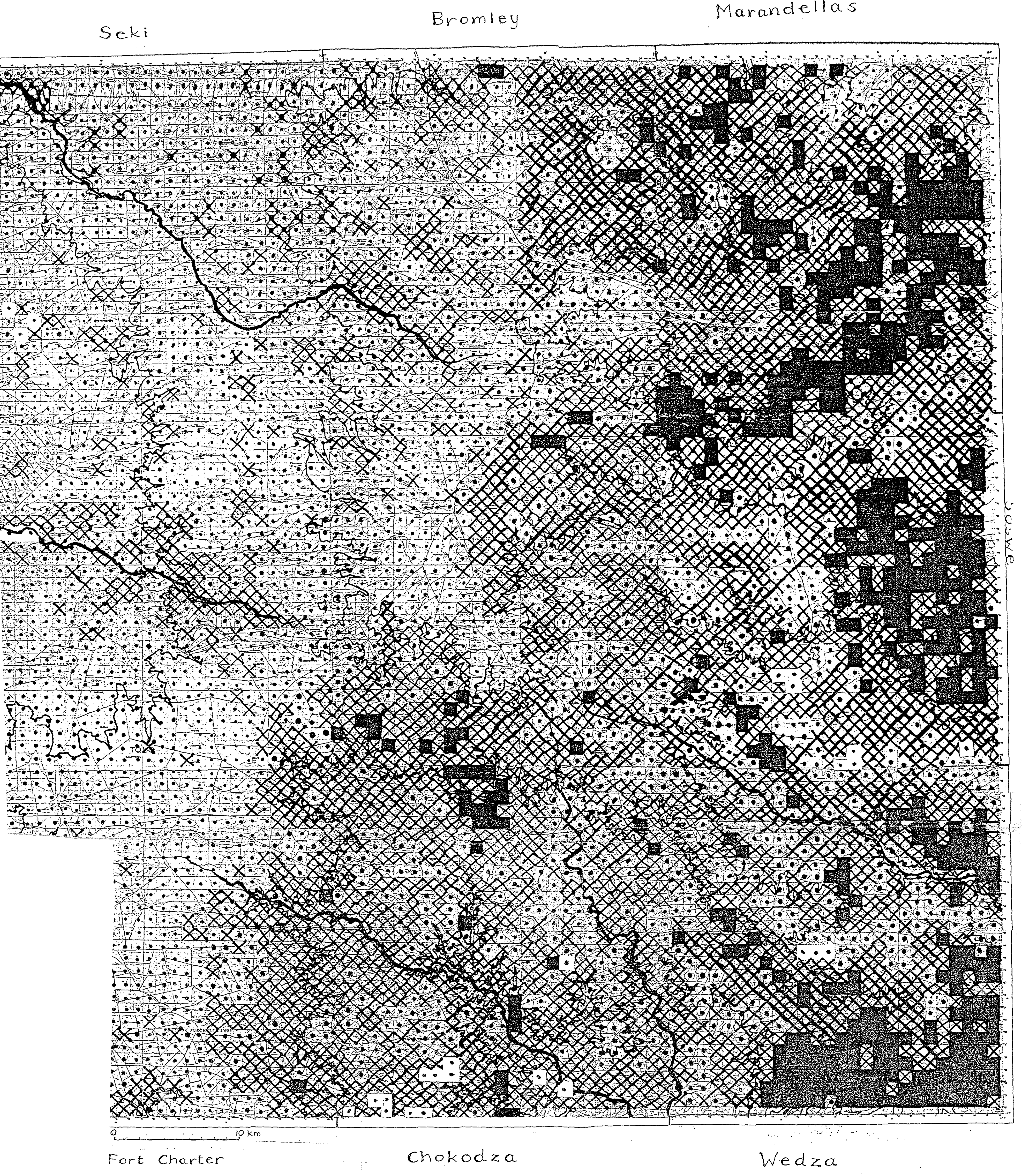
This analysis shows:

1. The watershed surface is characterised by low relative relief (less than 20 m/km square), i.e. slopes of less than 1 degree.

2. The north westerly flank of the main interfluve (assigned by Lister to Post African) has equally low relative relief and slopes, but is 'invaded' by belts of slightly higher relative relief (20-40 m) and steeper slopes (up to 3 degrees) along parts of the main rivers. Had the gently sloping north westerly flank represented the African Surface, progressively invaded by the Post African, then we would expect to find the development of the higher relative relief to be progressively more pronouned in a downstream direction along the rivers. However, this seems not to be the case. On the Bromley sheet, for example, zones of incision occur roughly between 1500 and 1550 m along the courses of the Hunyani R. (1510-1560) and the Nyarusheshe R. (1480-1540). At lower altitudes, slopes along their courses are again in the lowest category, increasing again, in the case of the Nyatsime R. at about 1380 m. On the Mahusekwa sheet, the Umfuli R. is also informative in this respect; there is a pronounced zone of higher relief closely associated with the river at about 1400 m, while further downstream the areas of higher relative relief are further from the valley itself, which comprises the upper part of a third, lower surface.

   This suggests that the interfluve and north westerly flanks comprise three surfaces as shown in Figure 4. Lister's boundary between African and Post African Surfaces appears to coincide with the ca. 1500 m break, but this is relatively minor in comparison with the 1400 m break, which suggests that the boundary should be placed there and the African Surface subdivided into two components, with a break at ca. 1500 m.

3. On the south easterly flank of the divide, the relative relief map clearly shows the extent to which the watershed surface or surfaces have been invaded by subsequent surface development, which penetrates almost to the divide itself.


Seki
Bromley
Marandellas
0
10 km
Fort Charter
Chokodza
Wedza

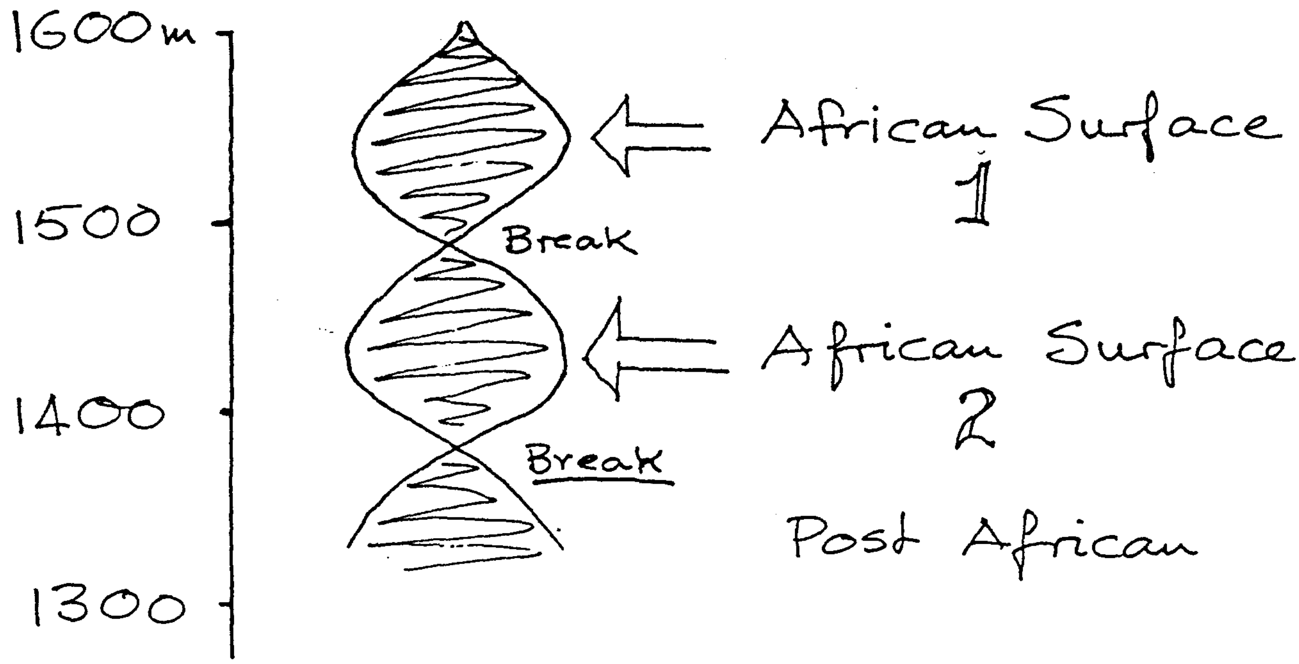

1600m
1500
1400
1300
Break
Break
African Surface 1
African Surface 2
Post African

Figure 4

4. Low relief landscape components survive as long narrow strips along the crests of the south easterly tending ridges. Nevertheless, there are conspicuous breaks where these flat-topped ridges back onto the main divide. This indicates that, as on the north westerly flank, there are two components to the flat African Surface, in the south east, the younger component being represented on the flat ridges.

3.4 Dambos

Figure 5 shows a map of the dambos within this area. The map was compiled from A. Bullock's air photo mapping of dambos directly onto the topographic maps, and it shows, in conjunction with Figure 3, the following features:

1. The largest areas of dambo are associated with low relative relief.

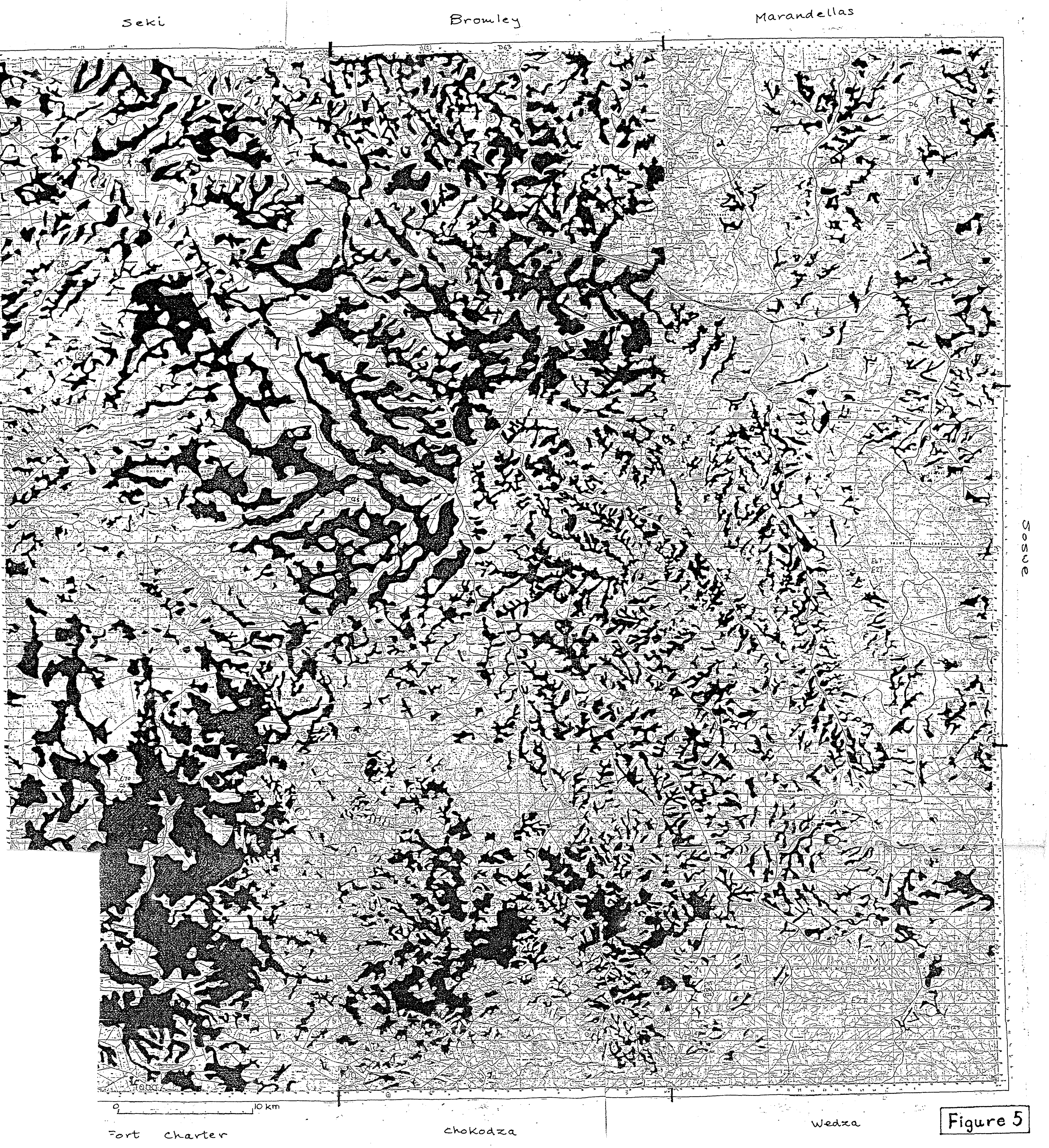
2. The north westerly flanks of the watershed have much larger dambos than the more aggressively incised south eastern flanks, and there is a conspicuous area with few dambos, which coincides with the invasion of the Umfuli River, earlier assigned to the African/Post African boundary.

3. On the south easterly side of the watershed, dambos survive as numerous relatively small features in strips along the tops of the south easterly trending spurs.

4. There is a conspicuous break in dambo occurrence between 1350 and 1400 m, a belt running roughly northwards between the Fort Charter and Chokodza sheets. This coincides admirably with Lister's boundary between African and Post African surfaces in this locality (Figure 1). However, the extensive Post African dambos on the Chokodza sheet are at a lower altitude (ca. 1300+ m) than the ridge-top dambos (ca. 1400 m) further to the north. This altitude gap itself suggests that the 1300+ m surface on the Chokodza sheet is younger than that represented on the ridge tops, in an area also generally assigned to Post African by Lister. Further support for the view that the 1300+ m dambo area is a younger surface than the 1400 m ridge tops derives from the susceptibility of the two areas to invasion by younger cycles of erosion; the most rapid encroachment is clearly in the south, so there is no reason why a surface in the south should survive while the same surface in the north is broken up into narrow ridge tops. Hence, it would seem that it is the valleys between the ridges in the north that are equivalent to the 1300+ m surface at Chokodza.

5. The progressive reduction in dambo area associated with increased relative relief resulting from incision, allows the dambos to be placed in a chronological sequence of evolution (destructive). Much as in Malawi, extensive dambos with 'dry islands' and 'wet focal points' yield place to a reticulated pattern, which in turn develops into a more integrated, fluviatile-like pattern when the links across the developing interfluves drain out. The integrated patterns become progressively 'pinched out' downstream, where slopes steepen and stream development facilitates evacuation of water.

6. The dambos at the 'integrated pattern' stage of evolution are, in particular, often distinctly linear, with abrupt dog-leg changes in direction, strongly suggesting lithological, probably fracture control in their configuration.



Seki
Bromley
Marandellas
Sosue
0
10 km
Fort Charter
Chokodza
Wedza

Figure 5

7. Since the area of the dambo has decreased with incision, the present non-dambo areas are divisible into two classes of profile: (a) areas which have always been freely draining regolith and (b) areas of former dambo, now drained out (palaeodambo). As these have had different leaching histories, the profiles may be expected to differ significantly and the distinction between freely draining regolith profiles and palaeodambo profiles may be important to the siting of collector wells.

3.5 The Hydrological Implications of the Geomorphological Analaysis

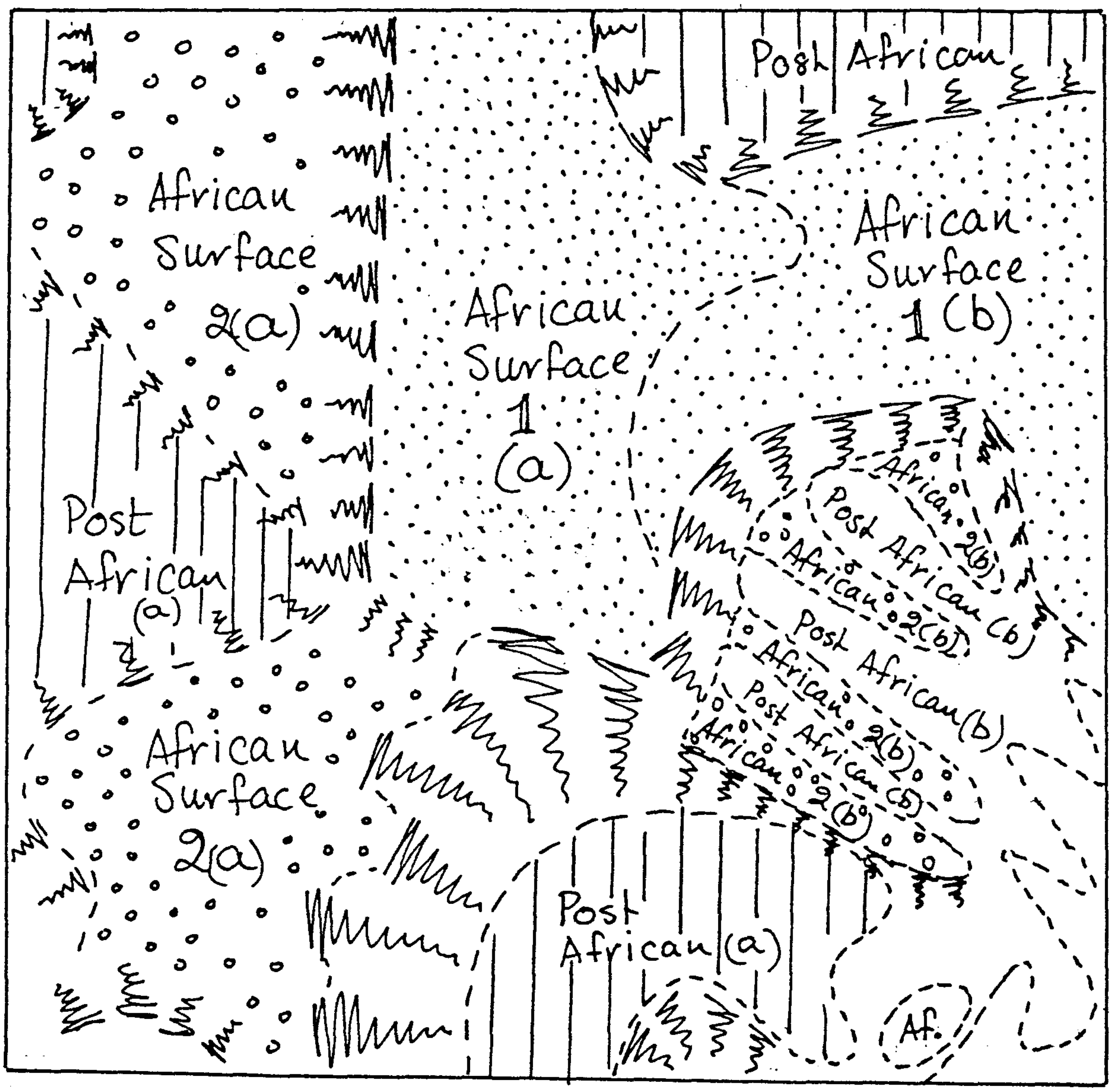
1. It is already well known that, intra-regionally, erosion surfaces of different ages have different "characteristic" profiles - different depths of weathering, different saturated zones, etc. This provides a first step in determining the hydrological potential, particularly for the collector wells, but also for boreholes where an overlying, saturated weathering profile provides a reservoir of water which feeds to fractures at deeper levels.

2. Given the generalisation that the depth of weathering on the African Surface is about 10-15 m on average, ranging from over 30 m to nothing, it is immediately apparent that the subdivision of the African Surface into two components, in this case separated by some 100 m, carries with it the clear implication that profile characteristics on these two components may differ significantly, and if 'age of surface' is to become a more useful, more precise, guide to hydrological potential, it is necessary to carry geomorphological analysis to a more detailed level than that provided by Lister's overview, which was not directed at hydrogeological application, but at contributing to a global view of denudational chronology.

3. Terrain analysis can place a particular site fairly precisely within the pattern of surfaces, but quite clearly, to assign a site to a particular age of surface is again, only the first step. For example, an outlier of the African Surface, standing as a residual, elevated above extensive areas of younger land surface would be expected to have a much reduced saturated zone, in comparison with profiles in the heart of a large area of surviving African Surface. Also, the relative relief on the basal surface of weathering would be increased by the facilitated leaching through the elevated profile. Although this kind of contrast is so self-evident as to be hardly worth a mention, it is perhaps less evident, but equally important to recognise that, for similar reasons, sites on a particular surface to the east of the divide, for example on one of the long narrow flat-topped ridges, need bear little similarity to sites on exactly the same age of surface to the west of the divide, where incision is much less. In effect, the leaching history of a site may be more important than the age of the surface. The age of the surface only provides a common starting place as far as profile development is concerned and the present nature of the profiles depends on what has happened following incision of the surface.

   On the bases of (a) age of surface and (b) differences in post-incision history, the area can be divided into broad regions with differing hydrological potential - in so far as geomorphology affects the potential, as opposed to lithology which, when superimposed on the geomorphic classes, provides a further breakdown of hydrological potential. A rough representation of hydrological potential, as indicated by the geomorphological history of this area is shown in Figure 6.

Figure 6



African Surface 1
1(a) = Low relief
1(b) = Highly dissected + residuals standing above

African Surface 2
2(a) = Low relief
2 (b) = Flat ridge tops

Post African Surface
(a) = Low relief
(b) = Valley form

A more precise map of hydrological potential could be provided using:

1. Inter-contour distances analysis
2. Altitudinal plot of the pinch-out points of dambos

The combination of these would allow the more precise mapping of boundaries between surfaces. The present terrain analysis has extended only to the point where the four collector well sites can be placed in their geomorphic context.

3.6 The Location of the Collector Well Sites within the General Geomorphological Context

The locations of the four sites are strongly contrasted. Mukumba, at about 1520 m, and St Nicholas, at about 1480 m, occur on the gently sloping north west flank of the main divide. Mukumba appears to be located at the lower limit of the altitude range of the higher of the two African Surface components (ca. 1500-1600+ m), while St Nicholas is in the break zone between this and the lower component (ca. 1375-1450 m). Maruta and St Lioba are both on the more strongly dissected south east flank. The former, at 1400 m, is perched atop and near the end of an extended spur or ridge, running south eastwards from the main divide, evidently at the lower limit of the younger and lower component of the African Surface. The latter, St Lioba, at 1340 m, is set well into the break below the Maruta Surface, that is, in the break above the Post African Surface. Their relative positions are summarised in Figure 6a.

4. Modelling.

A two dimensional model of a collector well system has been constructed which reproduces the standard Hantush-Papadopulos analytical results and which has been used to carry out sensitivity analysis in relation to various critical parameters. These include storage, specific yield, permeability, discharge rates and variable durations, well diameter, collector lengths, etc. The radial collectors are approximated on the model as a disc with radial symmetry. What appears to be particularly important is the relationship to transmissivity. For high transmissivity values of the order of 100 m^2/day with an aquifer thickness of 7 m, a 2 m well with collectors performs little better than a 3 m well without collectors. For a transmissivity of 5 m^2/day, which is fairly typical of the basement regolith aquifer in Zimbabwe, a marked contrast in recovery response is apparent. These differences are demonstrated in Figures 7 and 8.

The model has also been used with data from actual well tests. In some instances where relatively homogeneous conditions were apparent, the model drawdown responses corresponded closely with the observed values. In several other instances this is clearly not so, with the actual collector well showing a marked 'improvement' on the theoretical. This could be expressed as a higher regional transmissivity but the effect could relate to the collectors being located in a basal layer of higher permeability or due to their having encountered fissure systems. The layered system can be investigated by modelling methods but the fissure effects will be more difficult to isolate.

The long term yields of collector of dug wells will depend on how quickly water levels recover after pumping. The recovery behaviour can be better understood by a study of the behaviour of dug wells as described by Papadopulos and Cooper, 1967. Figure 8 describes the change in dimensionless drawdown, $s/(Q/4\pi T)$, with dimensionless time, $4Tt/r_w^2S$. The type of drawdown curve changes with a factor, α, r_w^2S/r_c^2, in which suffixes c and w refer to casing and well respectively.

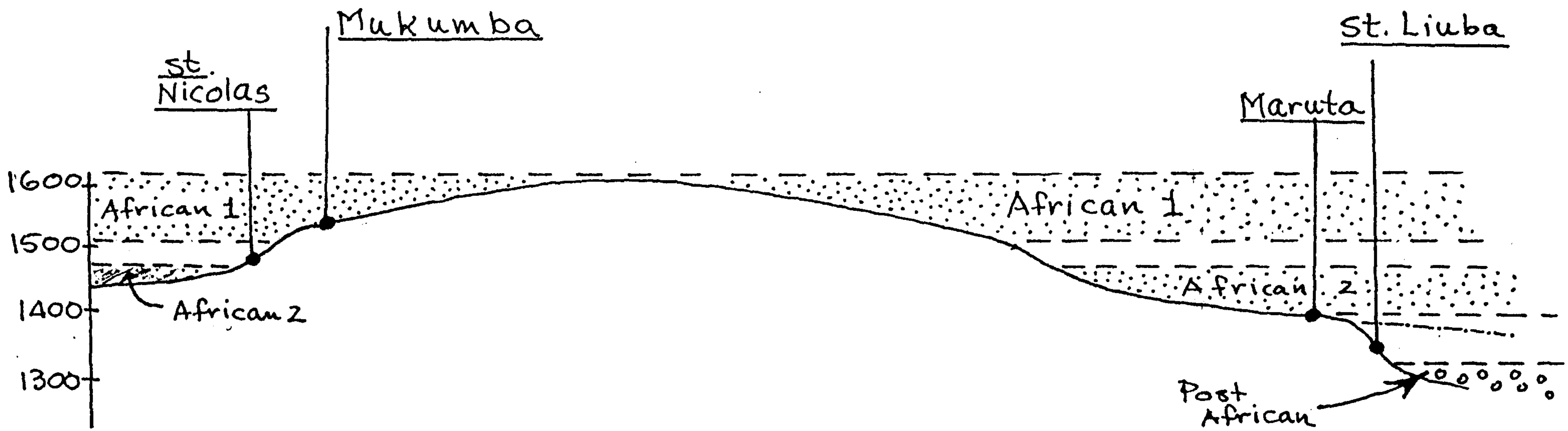

Mukumba
St. Liuba
St. Nicolas
Maruta
1600
1500
1400
1300
African 1
African 1
African 2
African 2
Post African

Figure 6a

Figure 7. Modelled response of large diameter well in aquifer of transmissivity of 5 m^2/day and other units as shown. Three periods of pumping with intervals and final recovery period.

2x Well Radius : 3 m S_u = 0·1 S_c = 0·001 T_H = 5 NO ADITS

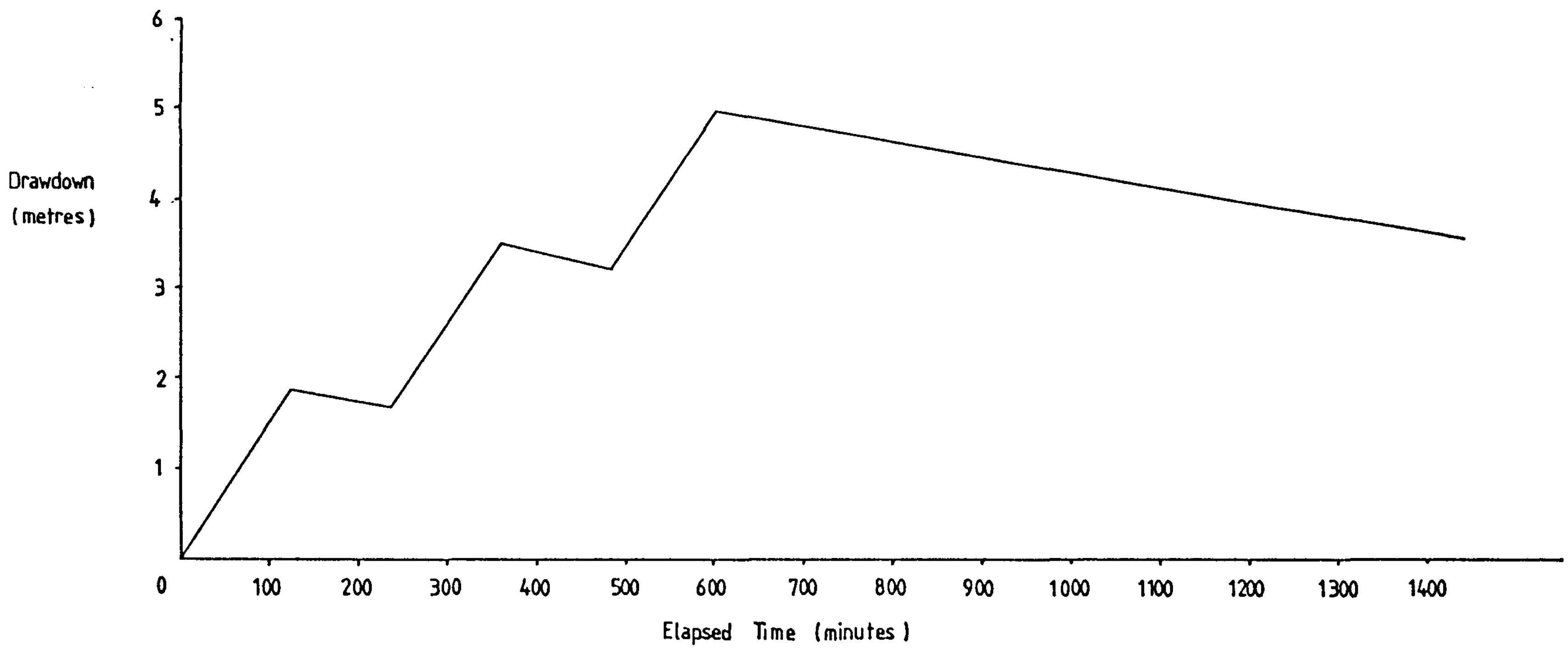
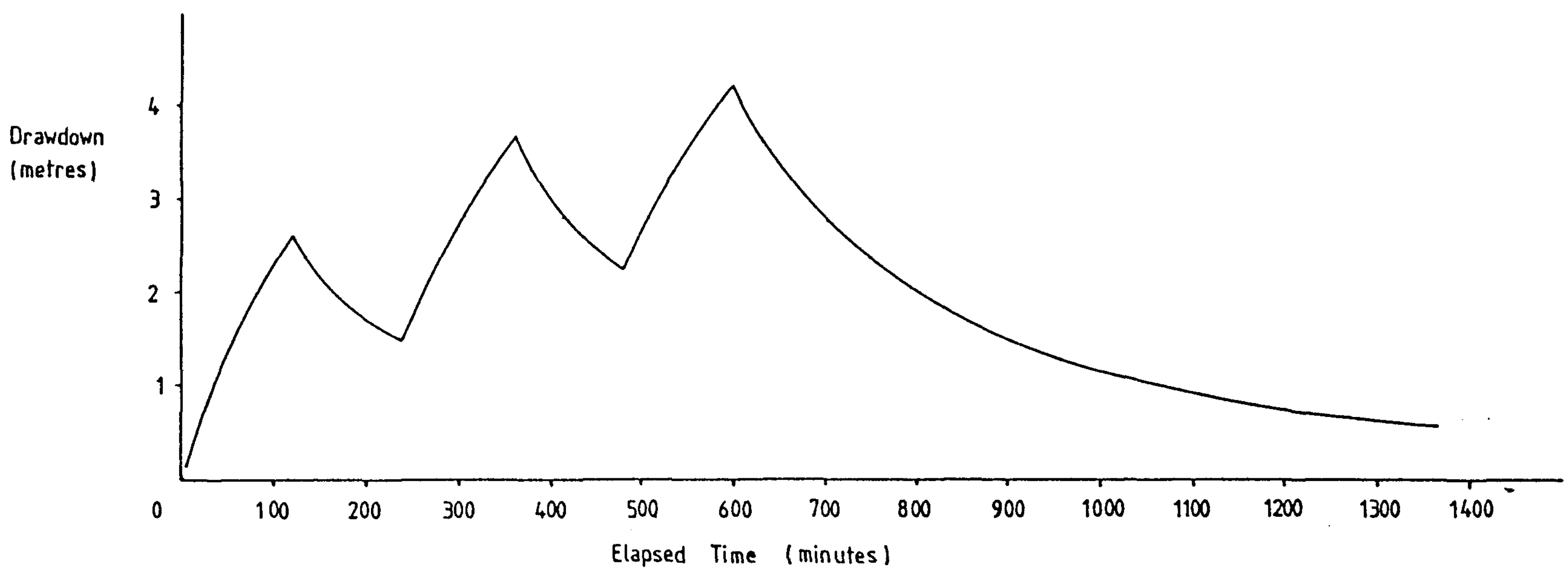


Figure 8. Modelled response of a collector well in same aquifer of smaller diameter but otherwise same aquifer parameters.

2 × Well Radius : 2 m S_u = 0·1 S_c = 0·001 T_H = 5 ADITS



The characteristics of the recovery can be deduced using the principle of superposition:

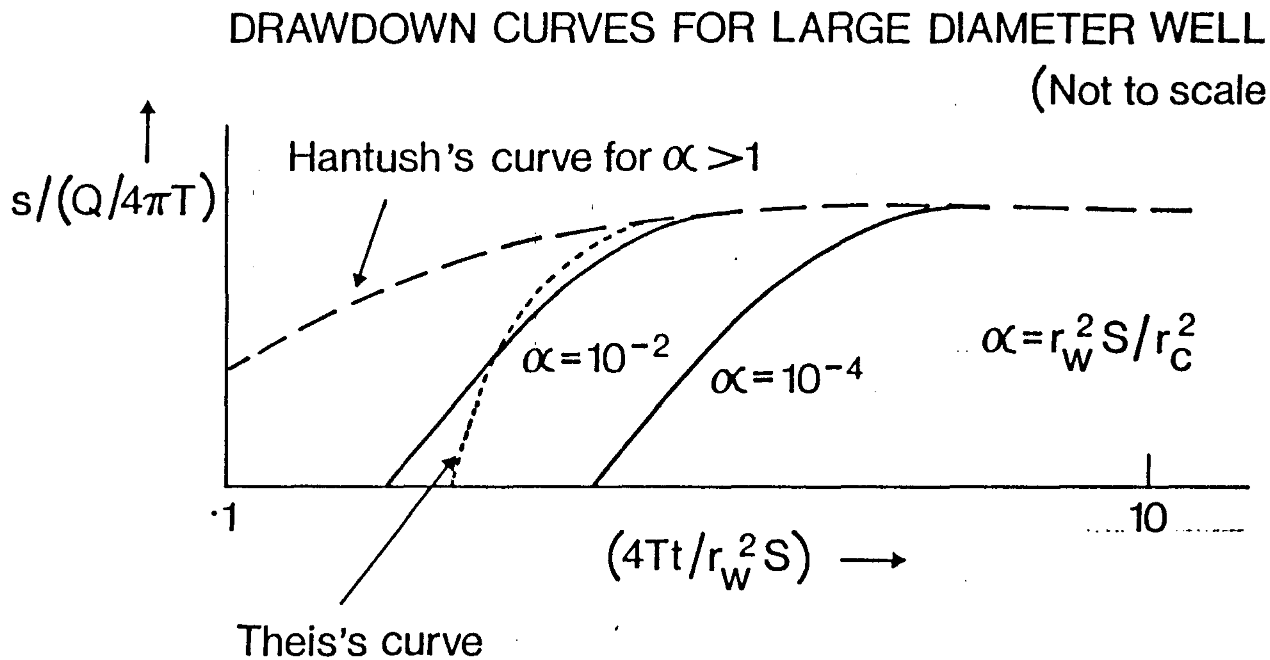
Curve (1) in Figure 9 shows a typical drawdown curve of a large diameter well, for which α is small. It is in two parts. The early part is of length of time, t_o, roughly equal to $25r_c^2/T$, and the rate of drawdown is approximately linear and represents a reduction of well storage without significant contribution from the aquifer. The late part is adequately described by the Theis non-steady equation and rates of drawdown are much slower. Two different kinds of recovery response can be predicted. Figure 10 shows the development of recovery curves for two different assumed times of pumping, t_{p1} and t_{p2}. The curves are deduced by assuming an image well starts pumping at an equal and negative rate at the time t_p. The drawdown of both wells are summed to achieve the recovery response. If the time of pumping is short, $t_{p1} < t_o$, recovery will be like curve (1b). If the time of pumping is long, t_{p2}, recovery will be like curve (2b). Hence we can deduce that when α is small the rate of recovery will be slow until total time passed is greater than $25r_c^2/T$.

On the other hand, if α is large, the drawdown curve will tend towards that described by Hantush, 1964 on Figure 8, and recovery will be relatively rapid. A collector well is qualitatively like this latter case having $r_o >> r_c$ and we can assume that recovery will be quick providing $r_o^2S/r_c^2 > 0.1$.

To summarise, it can be deduced that long term yields will be highest if recovery is quick and that implies either $25r_c^2/T$ is small, say 0.1 day, or r_o^2S/r_c^2 is >0.1.

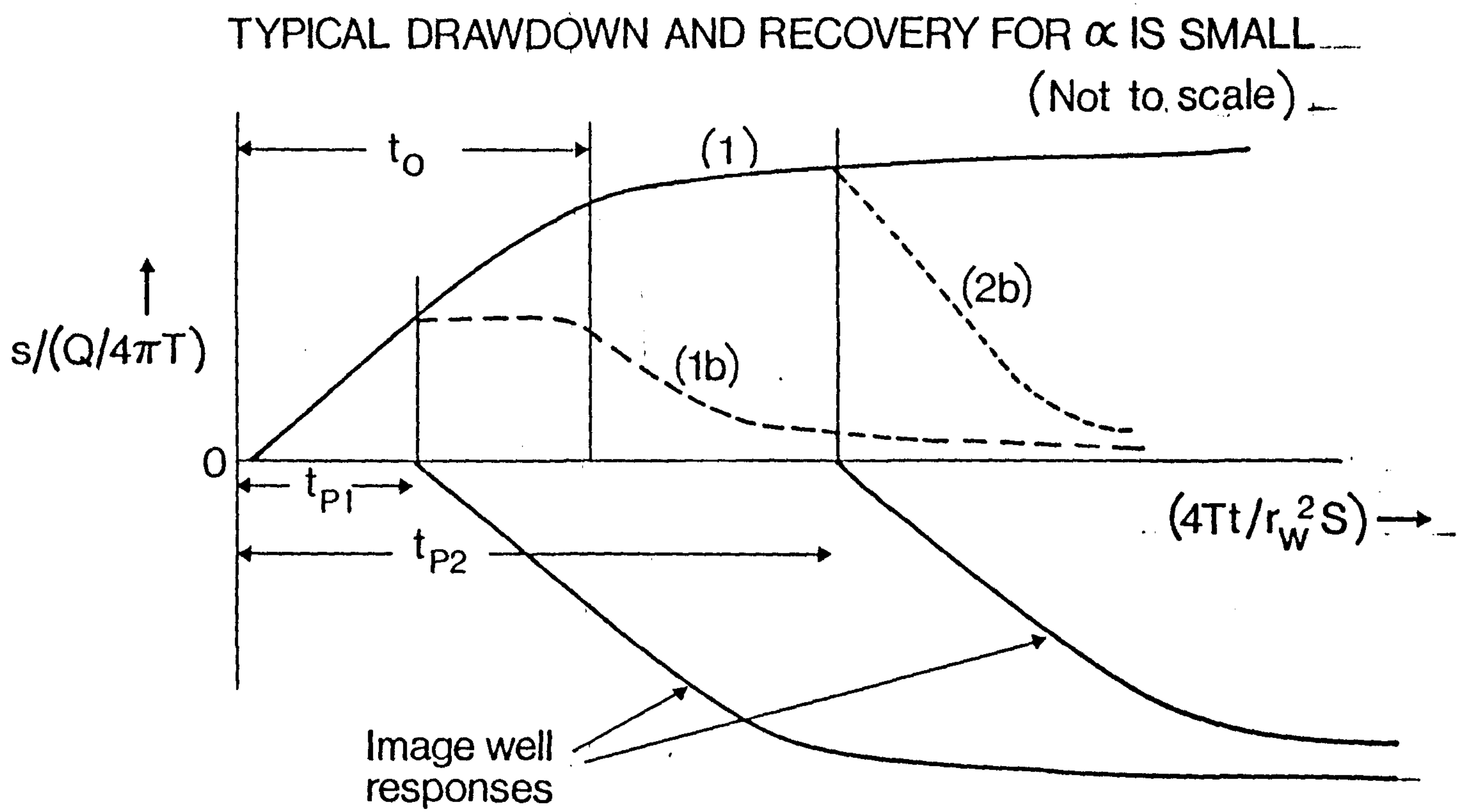
One final note on collector well behaviour should be made. Yield is dependent on numbers of collectors and their length. Some modelling studies as well as straightforward application of the Hantush and Papadopulos formula show that yield is best maximised by increasing length of collector rather than increasing the number of collectors. This will ensure a minimum drilled length for a given yield. This result only applies if a minimum of four collectors are used.

Figure 9.



DRAWDOWN CURVES FOR LARGE DIAMETER WELL
(Not to scale
s/(Q/4πT)
Hantush's curve for α >1
α=10⁻²
α=10⁻⁴
α=r_w² S/r_c²
·1
10
(4Tt/r_w² S)
Theis's curve

Figure 10.



TYPICAL DRAWDOWN AND RECOVERY FOR α IS SMALL
(Not to scale)
t_o
(1)
(2b)
(1b)
$s/(Q/4\pi T)$
0
t_{P1}
t_{P2}
$(4Tt/r_w^2 S)$
Image well
responses

Table 1

Site Conditions of Second Series of Collector Wells in Zimbabwe.

Location	Total depth (m)	Static water level (time of LT test)	Regolith thickness at well site (m)	Regolith thickness in vicinity (m - range)	Bedrock type	Erosion surface	Relief
ST NICHOLAS	12.0	4.3	12	7-14	Granite	African (2)	Low
MAKUMBA	11.0	2.9	11	4-17	Granite/Basic	African (2)	Low
ST LIOBAS	11.3	3.8	17	14-23	Adamellite Granite	Post African	Moderate/High

Table 2

Summary of Aquifer Testing Results.

Location	Test Borehole				LD Well	Collector Well						
	1 l/sec	2 hours	3 l/sec/m	4 m^2/d E-L	5 m^2/d	6 m^2/d	7 m^2/d	8 %	9 l/sec	10 m	11 l/sec	12 l/sec
ST NICHOLAS	0.1	15	0.013	0.21-9.3	2.0	2.3	5.0	300	1.5	3.5	0.428	1.4
MAKUMBA			0.032	1.03-2.6	0.13	0.10	3.0	1150	1.5	2.8	0.54	1.4
ST LIOBAS	0.1	20	0.012	0.41-0.88	28/1.5	2.4	2.8	33	1.0	2.3	0.43	0.9

Table 2

Explanation.

Test Borehole

Column 1: Pumping rate for borehole with best and/or most sustained production

2: Duration of pumping

3: Specific capacity (cf Column 11)

4: Transmissivity from recovery plots; E: early time recovery, L: late time

Large Diameter Well

5: Mean transmissivity from recovery tests, shallow and deep drawdown

Collector Well

6: Transmissivity from recovery of short duration pumping test carried out immediately after completion (cf Column 5)

7: Transmissivity from long term pumping tests by Jacob analysis; test at end of dry season

8: % improvement on LD well response, based on recovery time over comparable period

9: Test rate for long term test

10: Pumping drawdowns superimposed on general drawdown trend

11: Equivalent specific capacity

12: Safe yield for further 180 days pumping without recharge

Table 3

Constructional Costs of Large Diameter Wells.

	Zimbabwe Dollars
ST NICHOLAS	21,593
MAKUMBA	15,205
ST LIOBAS	15,093