TECHNICAL REPORT WD/88/31

Final report of the Collector Well Project 1983–1988

E P Wright, R Herbert, K H Murray, D Ball,
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BRITISH GEOLOGICAL SURVEY

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Hydrogeology Series

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Overseas Hydrogeology Group

Report No. WD/88/31 March 1988

FINAL REPORT OF THE COLLECTOR WELL PROJECT

1983 - 1988

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EXECUTIVE SUMMARY

The Collector Well Project commenced in 1983 and has included theoretical and simulation (modelling) studies in addition to experimental programmes in Zimbabwe, Malawi and Sri Lanka. The collector well consists of a central shaft at the base of the which radials are drilled, either horizontally or at angles into the surrounding aquifer. Two drilling rigs, an initial and a later improved version, have been fabricated. Nine wells have been completed in Zimbabwe and two more are in course of construction; three wells have been completed in Malawi. The collector wells in Africa have been of caisson construction and latterly of emplaced concrete segments. Experimental studies are now underway in Zimbabwe to attempt to drill the central shaft. The wells to date have been either of 3 m or 2 m diameter. In Sri Lanka, four collector well conversions of existing large diameter wells were carried out in the main programme. Ten well conversions have been completed in a 50 well project which commenced in mid-1987.

The experimental programmes were carried out in conjunction with local government organisations with varying degrees of financial support. In addition to this Final Report, there have been a number of previous interim reports and publications which are listed in the Introduction.

The results of the studies have demonstrated the feasibility of obtaining relatively large yields (c. 1-6 litres/sec) with small drawdowns (< 3 m) from the basement aquifer. In the context of this aquifer which has a very widespread extent in Africa and South Asia and with substantial recharge in the higher rainfall zones, the collector well appears to have much greater potential than other forms of abstraction to make use of the surplus recharge. The low pumping drawdowns combined with the high yields make collector wells attractive for urban supply and the feasibility in use for low energy pumping equipment such as solar, wind, animal or human power make the method attractive also for small scale irrigation.

The results of the work would seem to justify the setting-up of larger scale development programmes, either concerned exclusively with collector wells for specific demands or integrating collector wells into a general groundwater development project. Such programmes should ensure that a strong element of 'research' is combined with a view to improving the technology and operational efficiency of construction and gaining a better understanding of the aquifer controls to formations which will assist future siting of collector wells.

SUMMARY AND RECOMMENDATIONS

S1. Objectives and Background

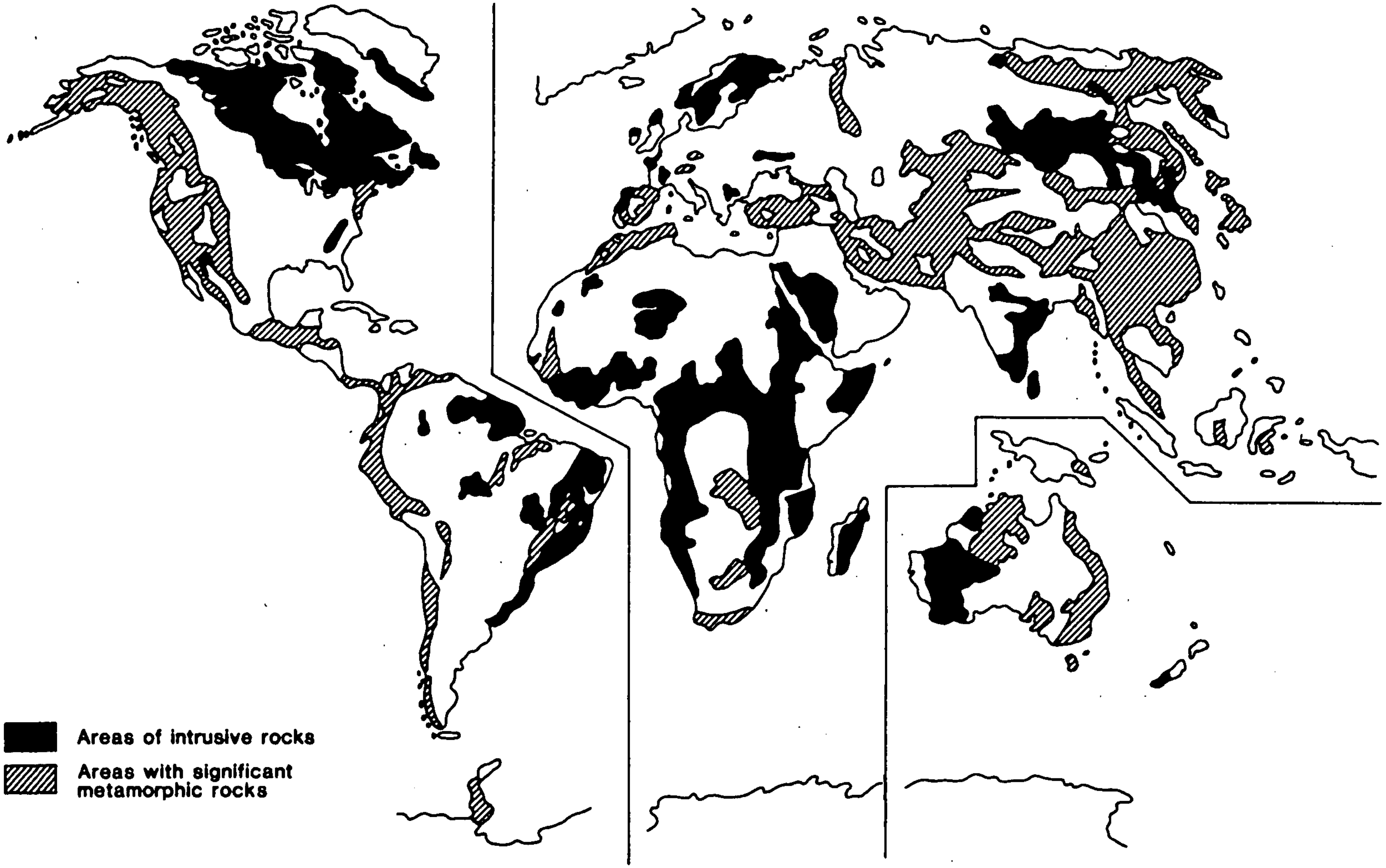
Collector wells are being studied mainly as a means to both maximise and optimise abstraction from thin, extensive and low permeability aquifers, mostly notably the aquifer within the weathered overburden above crystalline basement rocks in tropical regions. Secondary objectives include consideration of the potential of these wells in circumstances where standard boreholes or dug wells are least applicable (thin overburden above tight bedrock); and for use also in the development of sand river aquifers, or for 'skimming' operations, e.g. fresh water over saline.

Despite the occurrence of many hydrogeological constraints, crystalline basement aquifers in the tropical regions of the world are being currently developed on a large scale - a consequence of their widespread occurrence (Figure 14.1) and the difficulties or cost of obtaining alternative sources of supply. These constraints relate mainly to the low permeability of the aquifer in the weathered overburden and the variable and irregular occurrence of the transmissive fracture zones in the underlying bedrock. Alternative surface water supplies are restricted in the vast plain lands, typical of the basement shield regions, more particularly when rainfall is less than 700 mm when streams are ephemeral, but also because the terrain does not favour surface water storage. Surface water is also more sensitive than groundwater to periodic droughts; water treatment is commonly necessary for the former which increases its cost.

Because of the low transmissivity of the basement aquifers, past and present development is mainly by slim boreholes and dug wells fitted with hand pumps and used as point sources of supply for rural communities. For the larger demands of urban supply or small scale irrigation, the occasional boreholes with larger yields can be used but these are relatively few in number (Figure 6.4) and the high drawdown to yield ratios are rarely consistent with irrigation use because of cost factors. Borehole failure rate is also a significant factor, being currently around an overall mean of 30% but much higher, if high yielding boreholes are being sought.

Abstraction from the basement aquifer is determined in part by the volume and nature of the demand (rural, urban, etc.) and in part by the technicalities of abstraction which are reflected in the capital and operating costs. Total demand for a basic supply to rural communities is quite small (25 litres per head per day) and with a mean density of population is equivalent to recharge to the underlying aquifer of some 0.5 mm per annum. Actual recharge may be much higher and has been estimated in the range 50-150 mm per annum, where annual rainfall exceeds 700 mm. A proportion of this recharge may reappear as base flow in streams where it may be utilised. A large proportion appears to be lost by evapotranspiration in valley lowlands. A substantial component of this surplus would be available for additional development subject to the hydrogeological constraints referred to earlier. Standard boreholes and wells cannot be expected to make major contributions in this respect

Figure14.1 WORLD-WIDE DISTRIBUTION OF BASEMENT ROCKS
(after Uhl and Atobrah, 1987)



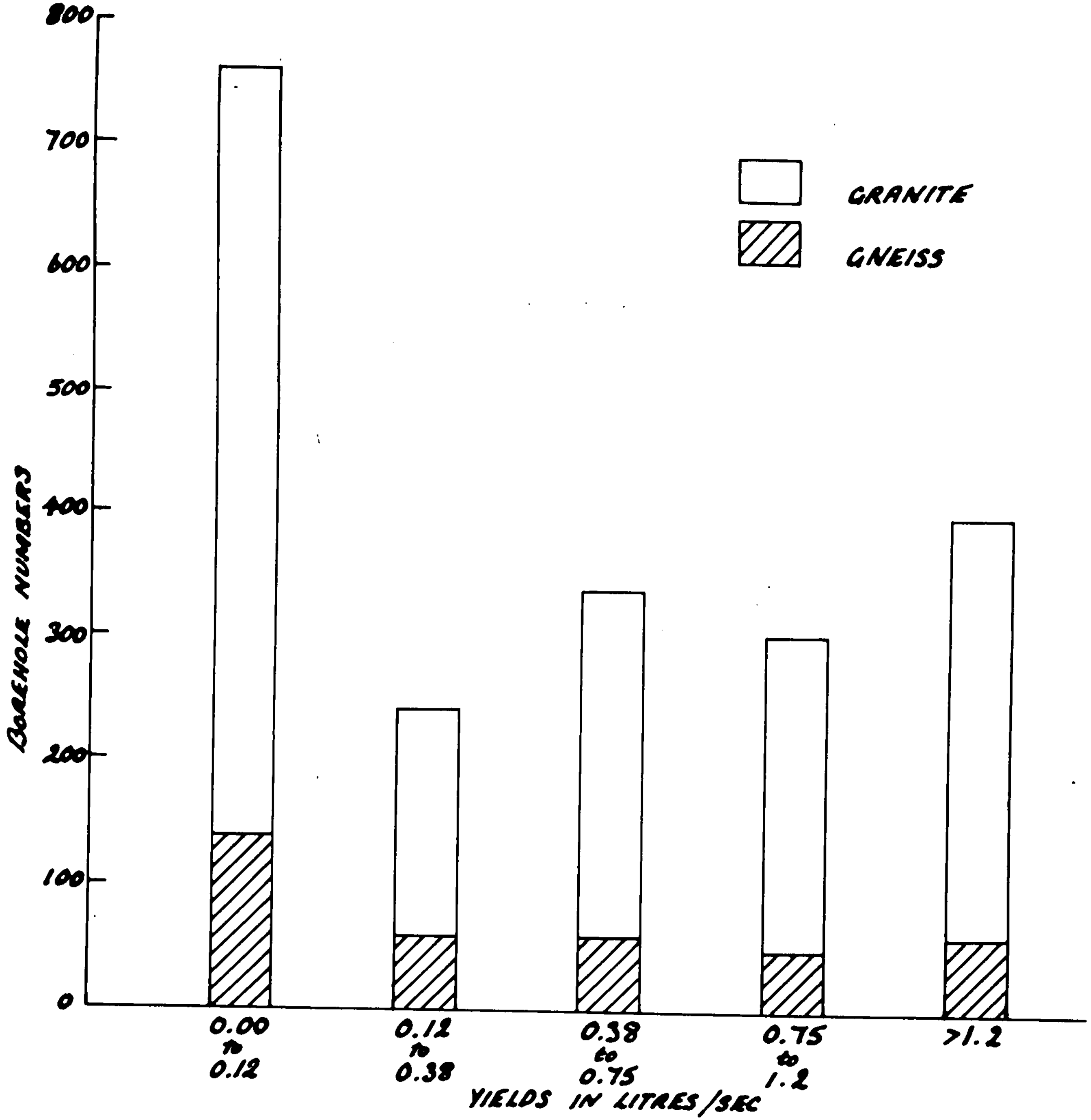


Figure 6.4 FREQUENCY DISTRIBUTION OF SHORT DURATION TEST YIELDS IN BOREHOLES IN ZIMBABWE

because of their high cost-yield ratios. Collector wells do appear to have the potential to abstract much larger volumes with the added advantage of small drawdowns, implying low operational costs. Collector wells may also be more successful in circumstances where boreholes and wells may provide negligible yield such as in aquifers within thin regolith overlying tight bedrock. Sand river development and skimming capability add to the collector well potential.

S2. Review of Work Programme and Results

Experimental studies have been carried out in Zimbabwe, Malawi and Sri Lanka with summary details as follows:-

Zimbabwe (i):	4 collector wells of 3 metre diameter and caisson construction.
Zimbabwe (ii):	3 collector wells of 2 metre diameter and caisson construction.
Zimbabwe (iii):	2 collector wells of 2 metre diameter and concrete block construction.
Zimbabwe (iv):	2 collector wells of 2 metre diameter and currently under construction. It is planned to investigate the feasibility of drilling the large diameter shaft by reverse circulation and to complete with galvanised sheeting. [Construction costs funded by German Aid]
Malawi (i):	2 collector wells of 2 metre diameter, one of caisson construction and one of caisson combined with concrete blocks.
Malawi (ii):	collector well conversion of existing large concrete caisson sunk in river alluvium.
Sri Lanka (i):	4 existing large-diameter wells converted to collector wells.
Sri Lanka (ii):	commencement in mid-1987 of a 50 well conversion project [ODA-TC funds].

The programmes of work were carried out jointly with national organisations in the above countries. In the case of Zimbabwe, all constructional and most exploration costs were met by the Zimbabwe Government. In Malawi, these costs were shared by the Project and the Malawi Government.

The results of the collector well project are listed in Tables 10.1 and 10.2 which are also included in the main text. The most informative figure for comparisons with borehole yields are in columns 11-13 which show the estimated safe yield for a 6-hour pumping day for an extended period (100 or 180 days) in col. 11, a continuous safe yield (col. 12) and a specific capacity for the continuous yield (col. 13). The long term extrapolation is based on the semilog plots of the drawdowns observed in the final long term test (7-14 days) with correlations to determine appropriate yield figures. There is some uncertainty regarding the analytical interpretation of the long term plots* but the extrapolation would seem to have reasonable validity unless affected by changes of condition (leaky artesian to water table conditions, hydrogeological boundary effects, changes in transmissivity due to drawdown) any of which could affect the extrapolation. It should be noted however that the long term tests were carried out in all cases at the end of the dry season when water levels were at their seasonal lowest. This implied a conservative value of the total available drawdown utilised in the calculation. The probable layering in the aquifer with highest permeability near the base minimises the changes of transmissivity in consequence of drawdowns. The results are of course sensitive to the available drawdown. It would be advantageous if the collector wells are carried to greater depths, as has been adopted in the third group of Zimbabwe wells. Reducing the costs of the large diameter well construction and/or improving the technology would promote the possibility.

The specific capacity listed in the last column may be compared with an estimated value for an average borehole in Zimbabwe of .012 l/sec/m (mean yield of 0.35 l/sec and 30 metre drawdown).

Figures are also listed which give the ratios of the recovery times of the collector well and the large diameter well over the same interval. The majority of the ratios are in the range 1.8-2.8 which is consistent with collector well performance in fairly homogeneous aquifers. The higher values (4.5, 11.5, 8) would suggest that the radials had intersected fracture systems which had significantly improved the performance.

S3. Collector Well Siting

With current technology, optimum well sites occur where the diggable regolith is 15 to 20 metres thick and with water levels less than 5 metres below ground level. Important factors affecting the yield, design and constructional problems include the permeability of the regolith and more particularly the geometry of the brecciated zone at the base; the nature of the underlying saprock, whether fractured or tight, the presence of core stones in the regolith and the local configuration of the basal surface of the regolith.

Geological, geomorphological and local site terrain features have all combined in the development of the basement aquifer and increased knowledge of these factors and their interactions will assist in the preliminary assessment of collector well sites. The experimental well sites constructed in this programme have been studied in respect to these various features with a view to reaching more general understanding of the interacting processes. A summary of critical factors is listed below but the most problematic concern the effects of the leaching history of a local area as a result of site terrain factors (Figure 6.1).

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* See Section 10.3

(i) Depth of weathering: mainly related to weathering susceptibility of varying bedrock types in the general order listed below and decreasing downwards

Biotite-rich rocks
Fractured quartzo-feldspathic rocks
Basic gneisses
Quartz-free or quartz-poor rocks

(ii) Saprolite permeability: varies with bedrock type, leaching history and secondary permeability factors

Biotite-rich rocks - clayey, rather low permeability
Quartzo-feldspathic - open, more permeable
Basic gneiss - permeability depends on quartz content
Quartz-free rocks - tight clay

(iii) Saprock permeability: related to initial structural and geological (notably heterogeneity) features in bedrock. Permeability can be enhanced by weathering as in the transition to the sprolite but more rarely reduced as a result of possible mineral precipitations (Fe, Mn).

(iv) Brecciated zone: degree of development

Biotite-rich rocks - thin
Basic gneiss - thicker
Banded gneiss - sometimes wide and irregular
Granites - transitional, closely correlated with fracture density

(v) Geomorphology: (a) Regional - thicker sequences on the older erosional surfaces but variations exist in relation to position on continent and differing climatic history controlled by continental drift effects. (b) Local - more complex and variable and includes the features relating to subordinate erosional surfaces within a major surface in addition to more local geomorphological controls. Effects occur in relation to the configuration of the basal surface of weathering, regolith thickness and permeability, presence of core stones and groundwater flow patterns and hydrochemistry.

Ground and terrain observations should be followed by geophysical surveys designed to predict depths to bedrock and some indication of the permeability of the regolith. Problems of equivalence of solutions in the interpretation of vertical electrical sounding (VES) have sometimes resulted in substantial overestimates of bedrock depth and present evidence would favour the use of electromagnetic (EM) techniques in addition to VES. It is less common for bedrock depths to be underestimated.

Test drilling by a small site investigation rig is recommended to confirm the predicted depth of diggable regolith and the occurrence of core stones. Lithological samples and pumping tests will also confirm the likely permeability. The variability of the regolith is such that a critical abstraction test rate, previously assessed at

0.1 l/sec for 12 hours, is not now regarded as essential if the samples appear to indicate reasonable permeability and the saturated regolith thickness is of an appropriate order. Any test boreholes drilled should ensure that drilling rates are observed and the borehole can be retained for observation purposes.

S4. Collector Well Construction

Two main construction methods have been used to date and a third is in process of experimentation. Full details of the caisson construction method is given in an earlier report (Wright et al., March 1984) and a summary is included in this report along with details of the later concrete segment design. The caisson construction, although feasible, has been demonstrably difficult in practice due mainly to the caisson sticking on core stones (Plate 10.3) and to the difficulty in coping with sand or mud inrushes. The emplacement from below of separate concrete segments, subsequently bolted together, copes better with both these situations. The Zimbabwe Government TC programme on collector well development is currently experimenting with the drilling of the large diameter well shaft using a powerful drill rig and reverse circulation. A 2 m drill bit has been fabricated. If successful, the well will be lined with galvanised corrugated sheeting. The method would be most applicable in a large scale development programme and time and costs should be significantly reduced in comparison with either of the other methods.

S5. Collector Well Costs

Collector well costs occur in four categories: exploration, test drilling, large diameter well construction and radial drilling. The following comments relate to the Zimbabwe programme since the majority of collector wells have been constructed in that country. The drilling cost of a slim borehole is in the range 6,000-10,000 Zimbabwe dollars (Z$) according to depth but taking no account of failure rate. For a collector well development programme, it would be feasible to project reasonable costs of all items except well construction. Geophysical survey and test drilling could be estimated at Z$ 1,500. Radial drilling costs would vary with the scale of the programme in relation to the capital costs of equipment, professional inputs, etc. Construction costs for the caissons have ranged from Z$ 5,000-Z$ 22,000 with depths from 10-14 m. A substantial component of the higher cost constructions must be attributed to technical difficulties of the caisson construction. A significant component must also relate to operational inefficiencies which it should be feasible to avoid. Precise quantitification of these relative effects is not possible to make at present. Cost details of the constructions using concrete segments are not available but it is known that there have been substantial delays relating to equipment operational failures. Although collector well costs seem likely to be significantly higher than the borehole costs, the cost-benefit ratios are strongly weighted on the side of the former where a higher demand exists.

S6. Modelling

Following the successful construction of a model which correlated with the theoretical responses of dug wells and collector wells in homogeneous aquifers, the model was used to carry out sensitivity analysis in relation to a range of parameters - well diameter, specific yield, storativity, transmissivity, pumping rates and pumping regimes. The most critical finding demonstrated the particular applicability of collector wells in low permeability aquifers and emphasised by the horizontal layering effect. The model was then used to simulate actual pumping tests in order to assess whether the standard methods of analysis could be applied to drawdown and recovery data from large diameter/collector well situations in basement aquifers. In some cases the results of modelling and analysis correlated; in others a discrepancy exists for which various possible explanations have been proposed but which require further substantiation.

S7. Potential for Development and Recommendations

The collector well design is clearly more appropriate than slim boreholes or dug wells in abstracting water from the basement aquifer and the yield to drawdown ratios indicate a potential both for the development of the underutilised recharge to basement aquifers, which is not feasible with other methods of abstraction, and for an application for higher demand usages, notably small-urban and small-scale irrigation supply. The main constraints to development are constructional and time costs and hydrogeological limitations on site selection. There is obvious scope for reduction in construction costs by improvements in efficiency and technology and both aspects can be emphasised in a larger scale construction programme. A concrete block construction is likely to be most applicable in a dispersed programme, possibly incorporating self-help. Drilling the central shaft would be more applicable in an intensive development where time is also of importance.

Hydrogeological siting constraints are less easy to assess. The borehole statistics set out in Tables 14.3 and 14.4 do indicate general orders of feasibility, but obviously on the low side. In Malawi, feasible conditions with shallow water levels (< 5 m) existed in 473 from 1534 boreholes with a mean regolith thickness of 29 metres. In Zimbabwe, some 400 boreholes out of 1899 had water levels < 5 m with a mean regolith thickness of 16 m. In the case of Malawi, the regolith thickness will be excessive in some cases but flexibility of choice will become greater as technology of construction improves. The statistics do demonstrate the feasibility of being able to site large numbers of collector wells. Spacings in local areas will depend also on recharge rates but could be as little as 700 metres for a 3 litre/sec continuous discharging well with an annual recharge of 100 mm.

Although studies to date have demonstrated the complex interactions of factors relating to the formation of basement aquifers, it is important to note that even when conditions are relatively unfavourable, a collector well with moderate yield can be constructed. A much lower failure rate than boreholes can therefore be anticipated which is an important factor in overall costing. With increasing knowledge of the processes involved in interaction, site selection should become easier. It should be remembered that as yet very few ells have been constructed.

The results of the work to date would justify the setting up of larger scale development programmes, either concerned exclusively with collector wells for specific demands, or integrating collector wells into a general groundwater development project. For urban supply in basement areas, comparisons can be made fairly simply with the costs of alternative sources of supply. In the case of small-scale irrigation, standards of comparison cannot yet be made since groundwater availability in basement areas of Africa is not such as to promote small-scale irrigation. Studies are therefore required to look at agricultural/marketing aspects and irrigation technology in the context of collector wells. The FAO strongly favours the development of small-scale irrigation in Africa but water supply exercises the main constraint. Collector wells appear the only feasible technique in basement areas to provide such supplies.

Table 10.1
Collector Well Summary of Data: Zimbabwe and Malawi

Location	Total Depth (m)	Static Water Level (time of LT test) (m)	Regolith Thickness for site (m) [1]	T [2] Local (m^2/d)	T [3] Regional (m^2/d)	LD Well Recovery time over given interval (min) [4]	Collector Well Recovery time over same interval (mm)	Ratio [5]	Actual Pumping Rate at LT test (litres/second)	Daily Pumping Drawdown Amplitude (m)	Estimated Safe Yield (litres/second) (pumped 2+2+2 hrs daily) [6]	Estimated Safe Yield (litres/second) with continuous pumping	Specific Capacity for continuous rate (litres/sec/metre)	Specific Electrical Conductance of Collector Well Discharge at end of LT test (microsiemens/cm/23°C)
ZIMBABWE														
Murape, Seki	14.3	2.6	20	-	7.0	500	61.5	8.1	1.5	1.85	1.7*	0.4	0.804	1330
Hatcliffe Windpump	10.0	3.3	26+	12.0	27.0	525	291	1.8	2.6	2.7	3.4*	1.3	0.963	105
Hatcliffe Willowtree	10.8	5.9	14 max.	40.0	50.0	40	22	1.8	3.6	2.6	3.5*	1.5	1.364	Low
St Nicholas Chiota	12.0	4.3	12 max.	1.4	5.0	57	19	3.0	1.5	3.5	1.4†	0.5	0.459	73
Mukumba Chiota	11.0	2.9	11+	0.2	3.0	92	8	11.5	1.5	2.8	1.4†	0.45	0.536	340
St Lioba's Wedza	11.3	3.8	17	1.5	2.8	20	15	1.3	1.0	2.3	1.1†	0.3	0.434	110
MALAWI														
Mponela North	12.0	3.4	20+	26.0	57.0	18	10	1.8	4.0	3.5	6.63†	4.0	1.159	545
Mponela South	12.0	2.8	35+	negl.	4.8	50	26	1.9	0.84	2.1	2.2 †	0.85	0.41	538

Notes:

[1] In the majority of the collector wells, the large diameter well reached the base of the regolith. Values shown are of maximum thickness in the general area.

[2] T local: transmissivity in immediate vicinity of large diameter well from LD well tests.

[3] T regional: transmissivity from long term collector well test based on a Jacob analysis of a semi-log plot of the observed drawdowns at the beginning of the first daily pumping cycle.

[4] Recovery times over equivalent intervals for each well but intervals not the same for all wells.

[5] Ratio of LD recovery to CW recovery over same interval.

[6] Safe yield based on the extrapolation of drawdowns and adjusted values of drawdown and pumping amplitudes for the corresponding pumping rate. Original tests carried out at the end of dry season with water levels at seasonal lowest. * 100 days; † 180 days.

Table 10.2
Collector Well Summary of Data: Sri Lanka

Location	Total Depth (m)	Static Water Level (time of LT test) (m)	Regolith Thickness for site (m) [1]	T [2] Local (m^2/d)	T [3] Regional (m^2/d)	LD Well Recovery time over given interval (min) [4]	Collector Well Recovery time over same interval (mm)	Ratio [5]	Actual Pumping Rate at LT test (litres/second)	Daily Pumping Drawdown Amplitude (m)	Estimated Safe Yield (litres/second) (pumped 2+2+2 hrs daily) [6]
SRI LANKA INITIAL PROJECT											
Anuradhapura Korakahawewa	5.4	1.6	4	20.0	80.0	15	4.5	3.3	5.0	2.0	1.1*
Puttalam Anamaduwa Tattewa	7.0	2.5	7	2.0	13.0	299	120	2.5	5.6	3.7	1.1*
Kurunegala Kumbukwewa	4.9	3.4	4	33.0	29.0	29	6.5	4.5	2.0	0.5	1.7*
SRI LANKA 50 WELL PROJECT											
SLAH Anuradhapura	5.1	3.90	4.9	17.0	96.0	158	80	2.0	1.0	0.5	2.0 †
Ulukkulama	9.7	5.14	7.0	<1	-	120	15	8.0	-	-	-
Maha Balankulama School	7.3	6.8	7.3	43	25.0	24	15	1.6	0.8	0.7	1.0 †
Helambawa	6.8	5.3	6.8	1	2.5	40	26	1.5	0.8	0.35	0.3 †
Karuwalagasheena Temple	10.1	-	4.3	<1	------------------ Well cave-in 2 months after drilling ------------------						
Wellagala Temple	5.6	0.60	5.5	25	68	168	60	2.8	6.5	3.6	5.0 †
Police Camp Kurunegala	8.5	3.04	8.5+	3	4	140	75	1.9	2.3	1.0	2.0 †
Kumbulwana Oya	7.1	3.60	6.0	<1	11	155	65	2.4	1.62	1.1	0.8 †
Nikaweratiya CTB Depot	9.0		9.0+	2.6	) no details available						
Yauwanagama	6.7		6.7+	<1	)						

Notes:

[1] In the majority of the collector wells, the large diameter well reached the base of the regolith. Values shown are of maximum thickness in the general area.

[2] T local: transmissivity in immediate vicinity of large diameter well from LD well tests.

[3] T regional: transmissivity from long term collector well test based on a Jacob analysis of a semi-log plot of the observed drawdowns at the beginning of the first daily pumping cycle.

[4] Recovery times over equivalent intervals for each well but intervals not the same for all wells.

[5] Ratio of LD recovery to CW recovery over same interval.

[6] Safe yield based on the extrapolation of drawdowns and adjusted values of drawdown and pumping amplitudes for the corresponding pumping rate. Original tests carried out at the end of dry season with water levels at seasonal lowest. * 100 days; † 180 days.

Table 14.3

Selected Borehole Data from the Computerised Data Base for the Malawi Strip (Figure 14.2).

(A) Total Boreholes in Data Base.	
No. of boreholes with a depth given:	1453
Mean depth (m):	43.1
No. of boreholes with RWL data:	1425
Mean RWL (mbgl):	9.8
No. of boreholes with data on regolith thickness:	435
Mean thickness of regolith (m):	31.8
(B) Selected Boreholes.	
No. of boreholes with RWL < 5 m:	473
Mean regolith thickness (m) when RWL < 5 m:	29.4[1]
No. of boreholes with RWL < 10 m:	1073
Mean regolith thickness (m) when RWL < 10 m:	31.2[2]

[1] 131 boreholes
[2] 306 boreholes

Table 14.4

Selected Borehole Data from the Computerised Data Base for the Zimbabwe Strip (Figure 14.3).

(A) Total Boreholes in Data Base.	
No. of boreholes with a depth given:	1610
Mean depth (m):	42.6
No. of boreholes with RWL data:	1190
Mean RWL (mbgl):	11.1
No. of boreholes with data on regolith thickness:	680
Mean thickness of regolith (m):	18.2
(B) Selected Boreholes.	
No. of boreholes with RWL < 5 m:	388
Mean regolith thickness (m) when RWL < 5 m:	15.8[1]
No. of boreholes with RWL < 10 m:	873
Mean regolith thickness (m) when RWL < 10 m:	16.2[2]

[1] 152 boreholes
[2] 282 boreholes

THE COLLECTOR WELL PROJECT: 1983-88

FINAL REPORT

1. INTRODUCTION

1.1 Background Review

This is the Final Report on the BGS/ODA Collector Well Project which commenced in 1983 and has included theoretical, simulation (modelling) and field experimental studies. The latter were carried out in Zimbabwe, Malawi and Sri Lanka in conjunction with national organisations. Follow-up development programmes with Technical Co-operation (TC) funding from ODA are now in progress in Zimbabwe and Sri Lanka, utilising the drilling rigs supplied for the original experimental programme. In Zimbabwe local funds for the development programme are being met from national government sources and German Aid.

1.2 Acknowledgements

There has been a particular involvement in Zimbabwe of Mr L L Hindson, Hydrogeologist, of the Ministry of Water Resources and Development throughout the course of the experimental programme and he is now supervising the development programme. In Sri Lanka, the development programme is being supervised by Mr D K Ball, on secondment from the Overseas Hydrogeology Group of BGS.

Particular acknowledgement must be made to Mr P Rastall, BGS Contract Drilling Engineer throughout the Project who has worked in all three countries. In the later stages he became involved in the Large Diameter Well construction work and well testing in addition to the actual drilling. He has provided sustained and innovative efforts throughout the programme in operating, maintaining and modifying (as required) the drill rigs and associated mechanical equipment.

Other individuals who have contributed to the Collector Well Study include:-

Mr T Howley and Mr M Parks, Drilling and Geoservices Ltd.

The following members of the Water Supply Branch of the Public Works Department in Malawi:

Mr S de Sousa, Water Engineer in Chief
Mr S Phiri, Water Engineer
Mr S Mainala, Chief Hydrogeologist
Mr J Chilton, BGS, Hydrogeological Adviser
Mr J Lewis, Malawi Government Chemist

The following members of the Ministry of Water Resources and Development, Harare, Zimbabwe:

Mr P Sinnett-Jones, Chief Hydrogeologist
Dr P Wurzel, Hydrogeologist
Mr J Johnstone, Chief Hydrologist (ex)
Mr R Wannell, Chief Hydrologist (current)
Mr K Bligh, Design Engineer

Mr K Elliot, Director, Hatcliffe Agricultural Engineering College.

The Headmasters of the schools at Murape, Marikopo, Chisengeni, St Nicholas, St Liobas and Makumba.

The following members of the Sri Lanka Water Resources Board:

A G N Wijesekera
I D P Rodrigo
N Karunaratna

1.2 Previous Reports and Publications

The following reports and publications have been submitted during the course of this project:

1982 (Project Proposal): Exploitation of widespread near-surface aquifers of low permeability by collector (Ranney) wells. BGS Internal Report, E P Wright.

March 1985: BGS/ODA Zimbabwe Government Collector Well Project. E P Wright et al. BGS Internal Report.

June 1985: BGS/ODA-WRB Sri Lanka Collector Well Project. R Herbert et al. BGS Internal Report.

August 1985: World Water (article on collector wells).

October 1985: Collector Wells in Basement Aquifers. E P Wright and R Herbert. Waterlines, Vol. 4, No. 2.

March 1986: Collector well programme in Zimbabwe and Malawi, 1986-7. E P Wright et al., BGS Internal Report.

April 1986: Report on the application of geophysical surveys to groundwater exploration in crystalline basement terrain, 1985. R M Carruthers, BGS Internal Report.

April 1986: Summary Review of Collector Well Project, 1985-6. E P Wright, BGS Internal Report.

April 1987: (In press) Collector wells in crystalline basement aquifers: review of results of recent research. E P Wright et al. Paper presented at the XXI Congress of the International Association of Hydrogeologists 'Hydrogeology for Development.

December 1987: Nomograms for the analysis of recovery tests on LD wells. J A Barker and R Herbert. (to be submitted to the Quarterly Journal of Engineering Geology).

January 1988: Groundwater in the regolith aquifer of the hard rock area of Sri Lanka and its exploitation. R Herbert et al. Paper presented at the Symposium/Workshop on the 'Groundwater of Sri Lanka' at the 4th Annual Session of the Geological Society of Sri Lanka.

2. PROJECT OBJECTIVES AND CONTEXT OF DEVELOPMENT

Collector wells are being studied as a means to increase and to optimise abstraction from extensive low permeability aquifers, most notably the aquifer within the weathered overburden which overlies crystalline basement rocks. Development of the basement aquifer by slim boreholes or dug wells is constrained by the typically low permeability of the weathered overburden or by the discontinuous nature of the underlying zones of higher fracture permeability. Because of this constraint, current abstraction is mainly by handpump for point source supply to rural communities. Economic constraints also limit the numbers of boreholes and wells which it is feasible to construct in the basement aquifers.

At the time of writing approximately 26% only (1983 Water Decade Assessment) of the rural population of Africa which totals some 200 million, has access to a clean basic supply (25 litres per head per day), such as is produced by a properly designed borehole or protected well. Perhaps upwards of a million water points will be required to meet total Water Decade requirements in Africa for rural supply with projected costs in the range of 10-20 thousand million dollars. Much of this supply will be of groundwater and much will come from basement aquifers. The total requirement in volumetric terms is relatively small in terms of probable resource occurrence. For a rural community of standard density, the volume of water required to meet the Decade assessment for a basic supply is less than the equivalent of 1 mm of recharge to an underlying aquifer.

Present evidence now indicates that groundwater recharge may be much higher, perhaps in the range of 50-150 mm per annum where mean annual rainfall exceeds 700 mm. A proportion of this recharge reappears as base flow in surface runoff where it may be utilised as a supply source; the greater proportion is lost by evaporation and transpiration from low-lying valley areas. At least some of this surplus could be used for other and higher demands, if development is both feasible and economic. The cost of standard development by slim boreholes and dug wells in relation to typical yields precludes the construction of the large numbers which would be required. The deep pumping levels in boreholes implies high cost of abstraction whether by handpump (maintenance costs) or by motor pump (fuel + maintenance). The maintenance of large numbers of dispersed water points in rural areas constitutes a financial burden which most developing countries are finding hard to contain and this must affect the numbers of water points which can be constructed.

The collector well produces relatively high volumes of water at low pumping levels. The test yields of the collector wells constructed to date have been in the range 1-6 litres/sec which can be sustained for 6 hours pumping a day and for some 200 days without recharge. Most of the long term tests were carried out towards the end of the dry season and this extrapolation is therefore conservative. Pumping drawdowns have been typically 2-3 metres with total pumping levels in the range 4-8 metres below ground level. This must be compared with boreholes where test yields commonly refer to the maximum available drawdowns which are likely to be in the range 40-

70 metres. The yields of collector wells make them a consideration for small urban supply and small scale irrigation. The shallow pumping levels make development feasible by such low energy methods as solar, wind and animal power.

3. COLLECTOR WELLS: BASIC PRINCIPLES

Collector wells or Ranney wells as they are sometimes called consist of a central shaft at the base of which radial boreholes or 'collectors' are drilled in varying numbers and lengths. Ranney wells were first developed for use in thin, highly permeable aquifers such as river gravels, which are hydraulically connected to a source of adequate recharge such as a perennial stream or permanent surface water body.

The analytical response for collector wells in homogeneous aquifers was first evaluated by Hantush and Papadopulos, 1962. The time variant analysis applied only to long durations of pumping and could not be used to predict short term changes in the close vicinity of the well. Modelling studies by Huisman, 1972, showed that the steady-state behaviour of collector wells can be predicted by Dupuit's formula where s_0 is the drawdown and Q_0 the pumping rate:

$$s_0 = \frac{Q_0}{2kb} \ln (R/r_0) \quad .... (1)$$

In equation 1, k is the permeability, b is the aquifer thickness, R is the assumed radius of the hydrogeological system and r_0 is the equivalent radius of the collector well which in this instance is given by equation 2 below

$$r_0 = C (1 + r_c) \quad .... (2)$$

where 1 is the length of a collector and r_c is the shaft radius. The factor C was first calculated by Huisman (op.cit) at 0.25 but with much larger values, c. 0.7, being obtained from model tests and field investigations.

For discontinuous abstraction, the storage in the central large diameter shaft can sometimes by manipulated to advantage although changes in transmissivity in consequence of excessive drawdowns may offset such effects (Holt and Rushton, 1984). With continuous abstraction from a collector well in a homogeneous aquifer, the response relates essentially to the increased 'effective' radius of the well resulting from the collectors. As will be shown in the next section, the performance of a collector well in heterogeneous aquifers is much affected by the layering and other features which give an apparent increase in transmissivity.

4. COLLECTOR WELLS IN BASEMENT AQUIFERS

The aquifer in crystalline basement rocks occurs within the weathered overburden (regolith) and underlying fractured rock (saprock and bedrock). Figure 4.1 illustrates a typical sequence. The junction between saprolite and saprock appears relatively sharp and the basal saprolite tends to have a higher permeability than the more clayey saprolite above in which weathering is more advanced. The saturated regolith has low permeability but high storativity. The fractured saprock and bedrock may exhibit high permeability in structural zones with open and interconnected fracture systems but such occurrences are discontinuous, usually of narrow width and variable. The thickness of the regolith varies from negligible to several tens of metres and is greatest below the flat undissected plains of the older erosional surfaces, some of which date back to Cretaceous times or even earlier. Water levels will vary with relief but on the flat plainlands are never deep, generally less than 20 metres and often less than 10 metres below ground level.

The main target of the horizontal radials is the high permeability zone within the basal saprolite. The radial boreholes may also intersect steeply dipping fracture systems, fragmentary quartz bands or stone lines, all of which are likely to promote advantageous effects on well yield. Yields from slim boreholes are constrained by the limited hydraulic connection with the horizontal zone of high permeability and by the variable and discontinuous nature of target fracture systems in the underlying rock. Vertical boreholes have also less likelihood of intersecting steeply dipping fracture systems.

Where discontinuous abstraction is feasible as for rural water supplies or small scale irrigation, the well storage can become a significant factor in performance, more particularly when the regolith aquifer is layered with highest permeability near the base. Transmissivities are not therefore so significantly affected by deeper pumping drawdowns in cyclic pumping and use can be made of the recovery periods. Not only can larger amounts of water be abstracted from the aquifer in this fashion, but the wider and flatter drawdown response of the collector well, as compared with the cone of depression around a slim borehole, results in improved aquifer management with induced recharge from any recharge boundaries, e.g. surface water storage, and may also promote increased recharge in the subsequent wet season. Shallow groundwater bodies may rapidly commence discharging after heavy rain when water levels reach ground surface.

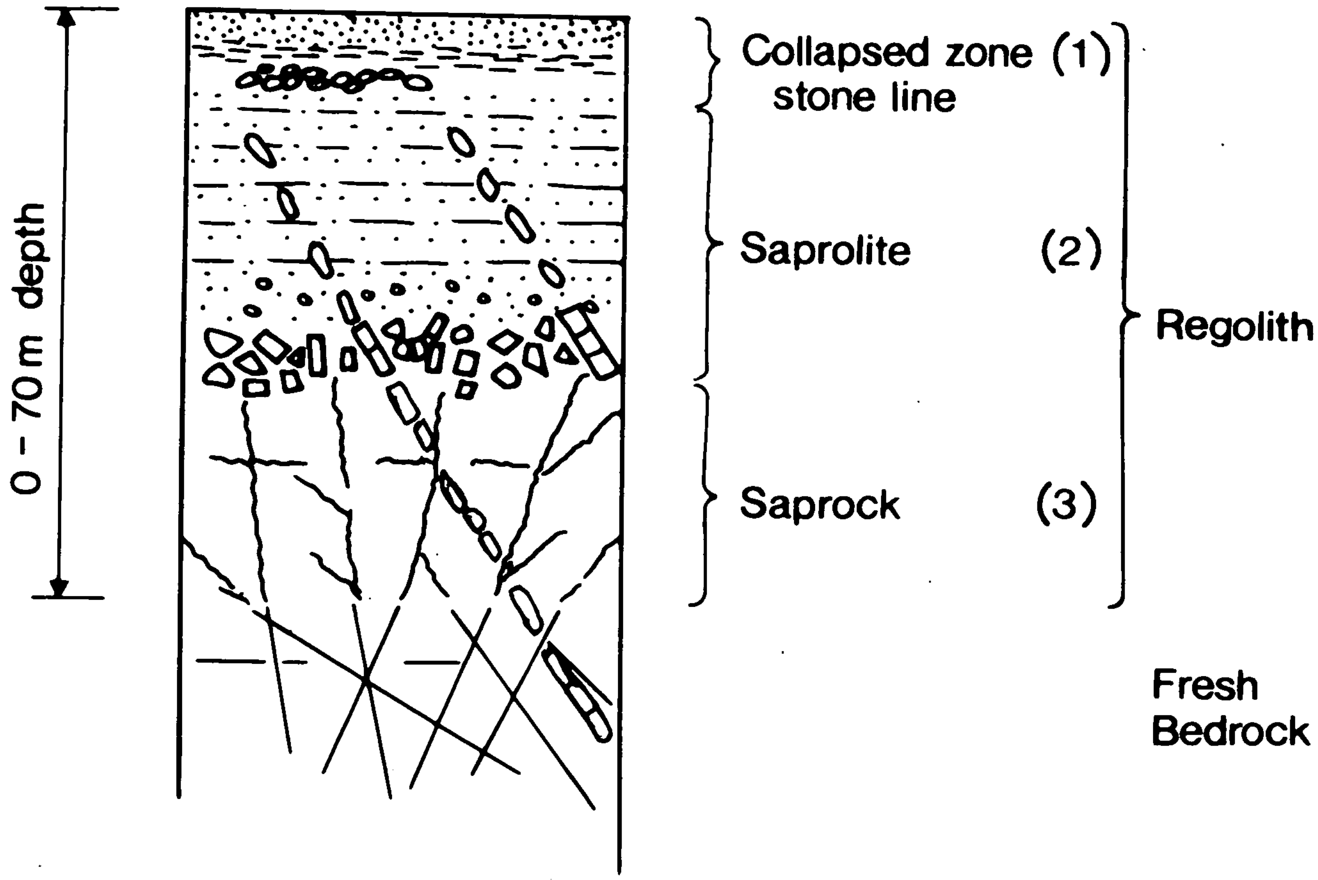


Figure 4.1 Typical weathered profile above crystalline basement rocks.

Notes:

(1) Collapsed zone. This may show marked lateral variations but is generally sandy on watershed areas with illuviated clay near the base and sometimes a 'stone line'; on valley slopes, colluvial material accumulates and in dambos, secondary clay minerals predominate. Slope bottom laterites may also occur which can result in perched water tables. Permeabilities vary in accordance with lithology although on watersheds the collapsed zone normally occurs above the water table.

(2) Saprolite is derived by in-situ weathering from the bedrock but is disaggregated. Permeability commonly increases at lower levels due to paucity of secondary clay minerals.

(3) Saprock is weathered bedrock. Original features are likely to be more open than in the fresh bedrock and in the absence of illuviated clay, permeability could be high.

5. DUG WELLS

It is pertinent at this stage to discuss dug wells more generally because the collector well represents an extension of the dug well but with some very important additional advantages.

The dug well is the most common form of traditional development of groundwater. Although enormous numbers have been constructed in Sub-Saharan Africa, the majority are of very simple design and lack the expression of skills associated with wells in the Middle East or South Asia. Siting and construction are typically self-help although there is now increasing support from governments and international or charitable agencies in the provision of materials. It is a matter of regret that generally little hydrogeological information is recorded or retained, and even fewer studies are concerned with issues of well siting or well design. Boreholes and wells are often complementary in relation to geological site conditions and both constructions may be used to advantage in a single design (Figure 5.1).

Dug wells have certain advantages in use which may be summarised as follows:

(i) Simple to construct and relatively cheap where water levels and digging conditions are favourable.

(ii) Manipulation of well storage with discontinuous abstraction can be advantageous.

(iii) More appropriate than boreholes for certain site conditions, notably in thin regolith overlying hard and unfractured bedrock (Figure 5.1).

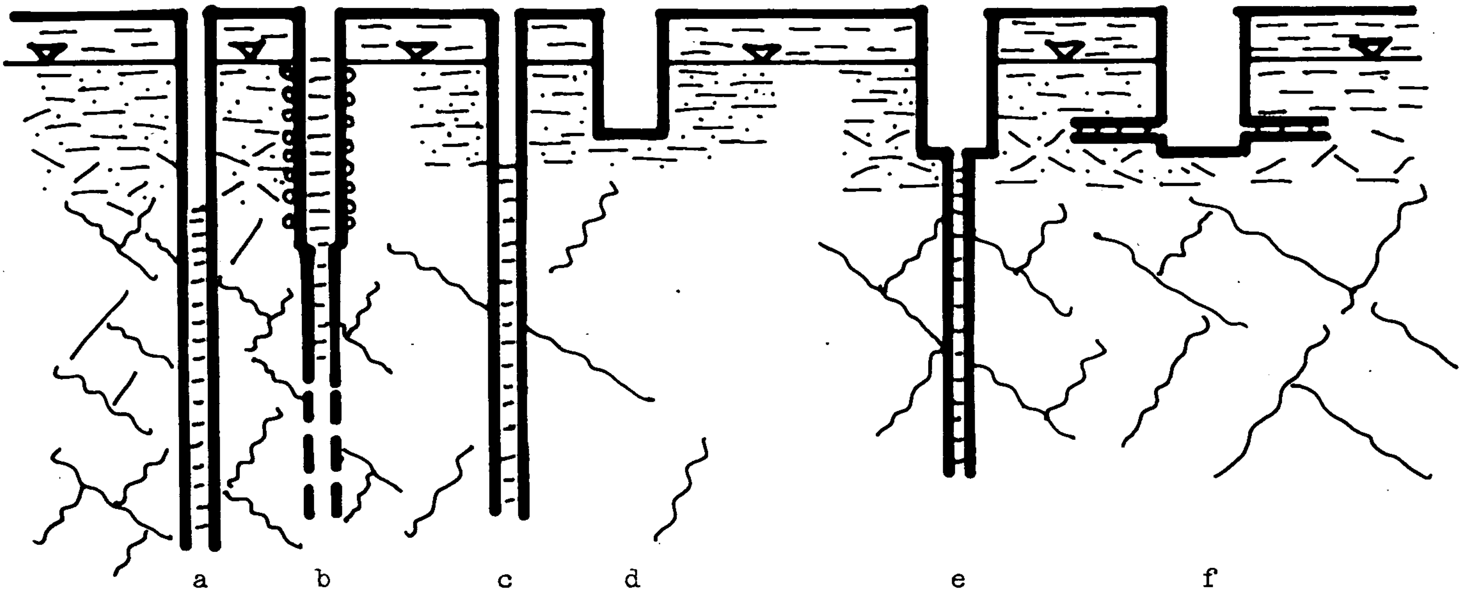
(iv) Self-help construction brings in socio-economic advantages.

Dug wells can have a number of critical disadvantages in use as follows:

(i) Generally low productivity except in alluvial sequences of high permeability. Hydraulic access to the high permeability zone in the basal regolith is restricted by the limited width of this zone and sometimes its substantial depth below ground level.

(ii) Dug wells are more susceptible than boreholes to pollution, whether from outside sources with transfer facilitated by shallow water levels or as a result of open-ended construction or low technology abstraction methods.

(iii) Susceptible to drought. Most wells are constructed to shallow depths below the water table and quite small changes in water level will have major effects on well storage and performance.



Water table can vary in position. This can affect well or borehole performance.

a Borehole completed in fractured bedrock

b Borehole completed in overburden (with gravel pack) and in fractured bedrock.

c Borehole completed in bedrock but unsuccessful because there are few fractures.

d Dug well at same location as 'c', but successful since drawing upon aquifer in overburden and making use of large storage.

e Dug well above vertical borehole in fractured rock.

f Dug well with radial collector boreholes drilled in overburden.

Figure 5.1 (a-f) Basic designs of boreholes, dug wells and collector wells constructed in aquifers within crystalline basement rocks.

(iv) Deep wells which require the use of high technology (jack hammers, explosives or dewatering pumps) are costly to construct and generally compare unfavourably with boreholes in cost-production ratios.

5.1 Dug Well Design

Traditional water holes are shallow, of wide diameter and with rudimentary or no lining. They are commonly stepped at one side to allow convenient access. The standard, more modern design is an open-ended construction with a concrete or brick lining through collapsing material and open hole below. Depths rarely exceed 10 metres and water levels are usually less than 5 metres. Abstraction is usually by bucket and windlass. The modern 'protected' well (Figure 5.2) is some 1 to 1.5 m in diameter and lined with concrete rings which are porous below the water table. In one version of this type, the lining is limited to the basal 2/3 metres terminating in a concrete slab through which the rising main of a handpump is inserted and sealed. The section above is backfilled and topped off with a second concrete slab at ground level. This design increases the protection against pollution but does not allow the well to be deepened should this become desirable as a result of falling water levels. This can be effected if the hole is lined by concrete throughout and with a top slab at ground level through which the rising main of the handpump or bucket pump is sealed.

The large diameter shaft of the collector well differs in a number of important particulars from the standard dug well. Most importantly, it is designed to penetrate more deeply below the water table, of the order of 5-10 metres or more. This circumstance creates advantages in several important respects:

(i) A larger volume of well storage becomes available and also a greater surface area of inflow into the well.

(ii) The regolith is commonly more clayey in composition and therefore of lower permeability in the upper levels; deeper penetration is likely to intersect less clayey regolith and in particular the more basal saprolite.

(iii) Deeper penetrating wells are less susceptible than shallow wells to seasonal or cyclic water level changes.

PROTECTED DUG WELL - MALAWI
(After Smith-Carington and Chilton, 1983)

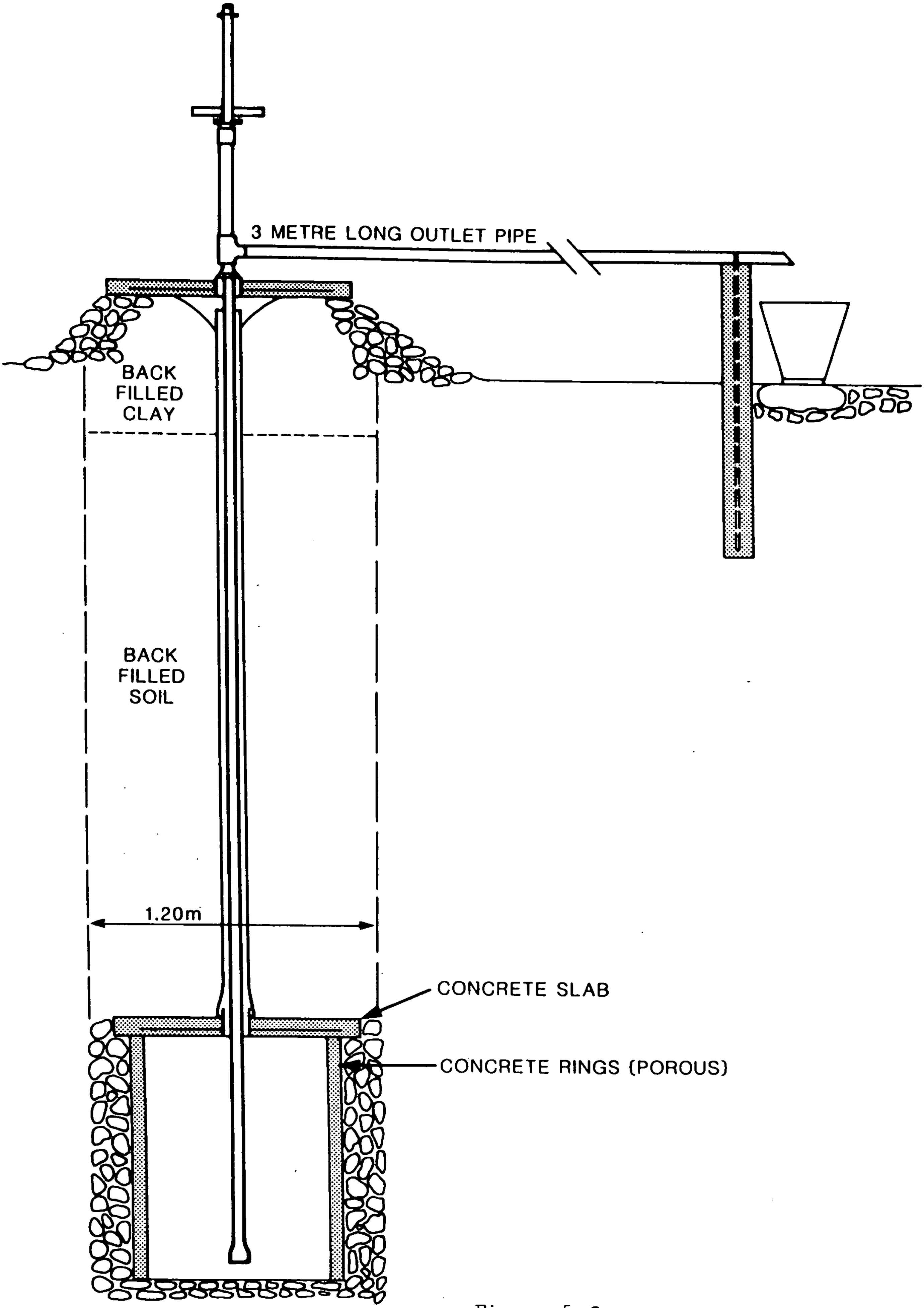


Figure 5.2

6. RELATIVE PERFORMANCE: DUG WELLS, COLLECTOR WELLS AND BOREHOLES

6.1 Dug Wells and Collector Wells

It is becoming accepted that dug wells and boreholes have a complementary role. In consequence, current integrated projects include both types of construction in their programmes. The assumptions should not be carried too far. It does not follow, for example, that if there have been one or more failed attempts to drill a borehole, then a dug well is inevitably more appropriate. The decision has to be based on hydrogeological circumstances which also relate to the economics of development. It is unfortunate that few records are available on dug well programmes, including failure rates. There is a real need to initiate and maintain records in the future. There will be difficulties in implementing such a proposal since many dug wells are constructed privately and by self-help methods. Large numbers are being constructed by the charitable agencies, such as OXFAM, Christian Care and the World Lutheran Federation. Arrangements need to be made with these organisations to ensure that proper records are maintained.

The regolith aquifer above crystalline basement rocks commonly exhibits features which are unfavourable to dug well construction and performance, perhaps most notably being the generally low permeability of the saprolite horizon (Figure 6.1). The advantage of storage availability provided by the large diameter is obviously reduced when recovery rates are very low. The main means to offset this disadvantage, either very large diameter excavations as are practiced in South Asia, or very deeply penetrative wells are both costly to undertake. For the latter constructions, high technology equipment and materials are required such as explosives, jack hammers and mechanical dewatering pumps. Such wells would probably compare unfavourably with boreholes in cost-yield ratios, unless the hydrogeological conditions are very unsuitable for the latter. It must therefore be clearly recognised that there are many possible constraints, both hydrogeological and economic, to the construction of dug wells. They are most appropriate in low-lying areas where water levels are shallow and where the aquifer is mainly within high permeability formations such as alluvial sands/gravels or within the more sandy 'collapsed' zone of the regolith profile.

Comparisons have to be made between a collector well and large diameter dug wells in the same aquifer to assess whether the additional costs of the former's construction are justified. There are advantages to be gained by the deeper penetration of the collector wells central shaft but as explained earlier these have been obtained at high cost. Modelling studies which will be described later, demonstrate that in a homogeneous and high permeability aquifer, a 3 m well without radials will perform little differently to a 2 m well with radials. There are however many differences between this situation and the typical basement aquifer and some consideration of the observed yield relations is informative.

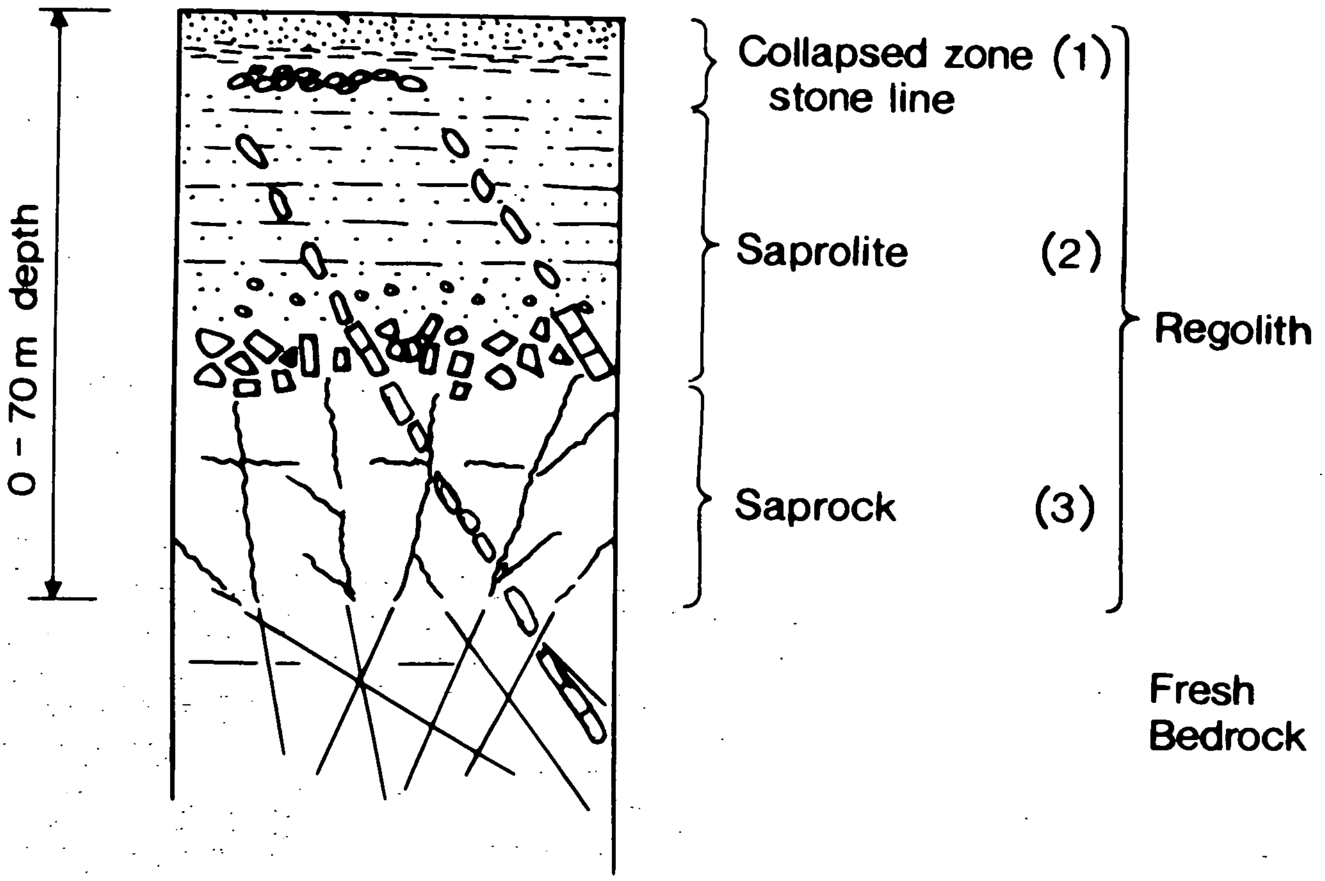


Figure 6.1 Typical weathered profile above crystalline basement rocks.

Notes:

(1) Collapsed zone. This may show marked lateral variations but is generally sandy on watershed areas with illuviated clay near the base and sometimes a 'stone line'; on valley slopes, colluvial material accumulates and in dambos, secondary clay minerals predominate. Slope bottom laterites may also occur which can result in perched water tables. Permeabilities vary in accordance with lithology although on watersheds the collapsed zone normally occurs above the water table.

(2) Saprolite is derived by in-situ weathering from the bedrock but is disaggregated. Permeability commonly increases at lower levels due to paucity of secondary clay minerals.

(3) Saprock is weathered bedrock. Original features are likely to be more open than in the fresh bedrock and in the absence of illuviated clay, permeability could be high.

As was shown in Section 3, equation 1, the steady-state drawdown is a function of ln (R_0/r_c) where r_c is the radius of the well or the effective radius of a collector well. For a homogeneous aquifer, the improvement or reduction in drawdown in a collector well as compared with a large diameter well of the same radius is the central shaft will be of the order of 1.6-2.5 (160-250%). This calculation is based on the assumption that factor C (equation 2, Section 3) is 0.7 and R_0 is in the range 100 to 1000 metres. In Table 6.1 below are listed some of the actual results of tests on collector wells and large diameter wells constructed to date. The results cannot be compared too closely with the analysis above since they are based in part on short term tests but some general order of comparison is justified. The local transmissivity has been determined from the long term pumping test on the collector well using semi-log plots and the drawdowns occurring at the beginning of each daily pumping cycle. (Figures 6.2 and 6.3).

Table 6.1
Selected Well Test Data

Site	Relative Recovery Times [LD/CW]*	Regional/Local Transmissivity	Regional Transmissivity (m^2/day)
Murape	8.1	-	7
Hatcliffe Windpump	1.8	2.25	27
Hatcliffe Willowtree	1.8	1.25	50
St Nicholas	3.0	3.60	5
Makumba	11.5	15.00	3
St Liobas	1.3	1.90	2.8
Mponela North	1.8	1.80	58
Mponela South	1.9	6.00	4.8
Anuradhapura K.	3.3	4.00	80
Puttalam A.T.	2.5	6.50	13
Kurunegala K.	4.5	0.90	29

* Ratio recovery times over equivalent intervals for the large diameter and subsequent collector well.

The relative recovery times which are an expression of the improved effectiveness of the collector well over the deeply penetrative large diameter well (LD) are in the general range of 2-4 with two extreme cases where the improvement was considerably more. The ratio of regional to local transmissivity is always greater than one, with one exception and in most cases the increase in transmissivity is substantial. The feature is surprising since a more random variation is to be expected. A possible source of error may lie in the method of analysis since with high values of the effective well radius (c. 22 m) and low value of transmissivity (T), mainly less than 10 m^2/d, it could take several days before u becomes <0.01 and the semi-log drawdown plot becomes valid for analysis. A more likely reason may relate to the layering and aquifer heterogeneity and the interaction with the collector well geometry. The radials are located in the basal, and generally more

Fig. MPONELA NORTH COLLECTOR WELL

LONG TERM PUMPING TEST

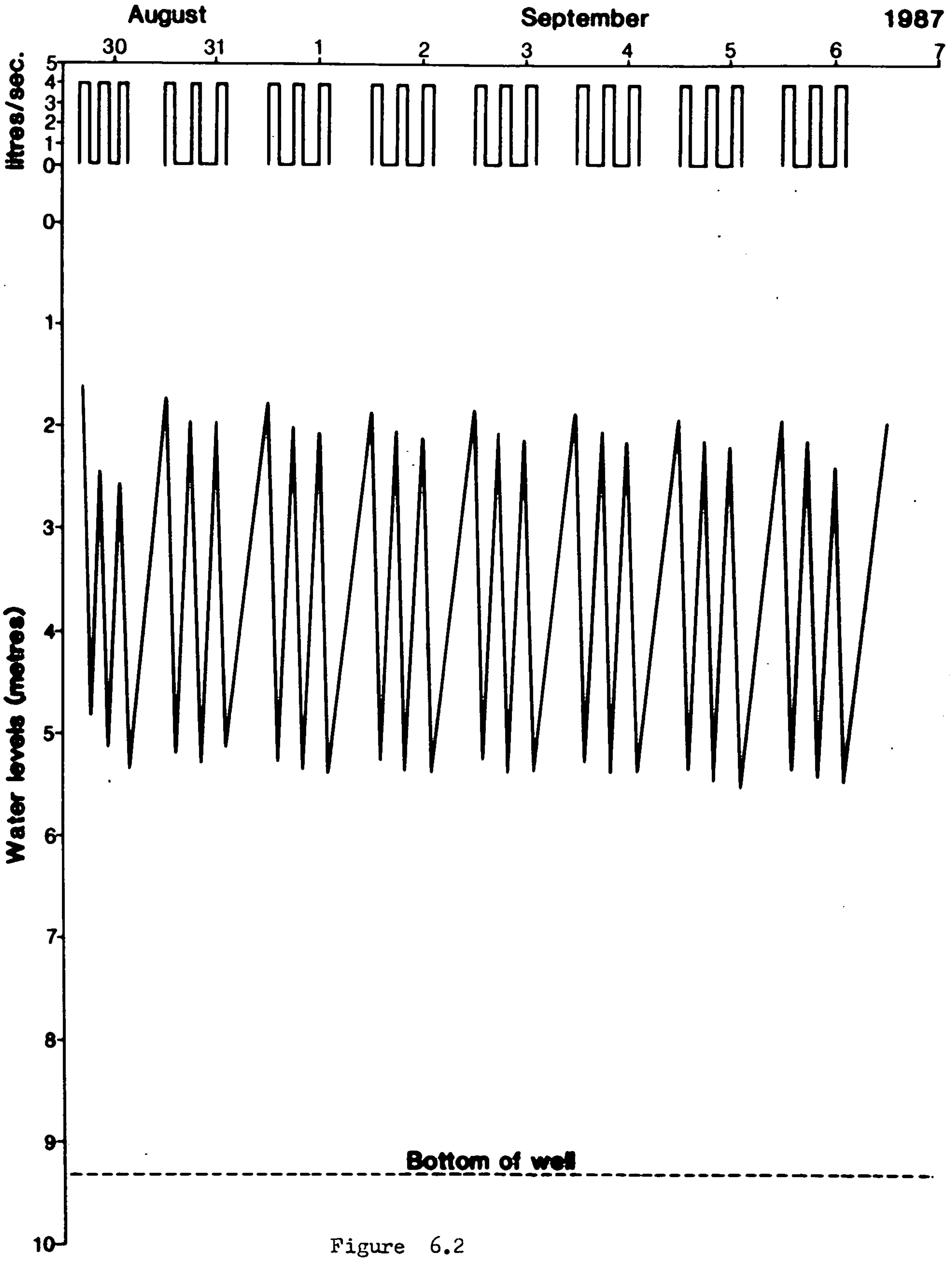


Figure 6.2

Fig.

MPONELA NORTH : LONG TERM TEST
PLOT OF WATER LEVELS AT [illegible] OF FIRST OF DAILY PUMPING CYCLES

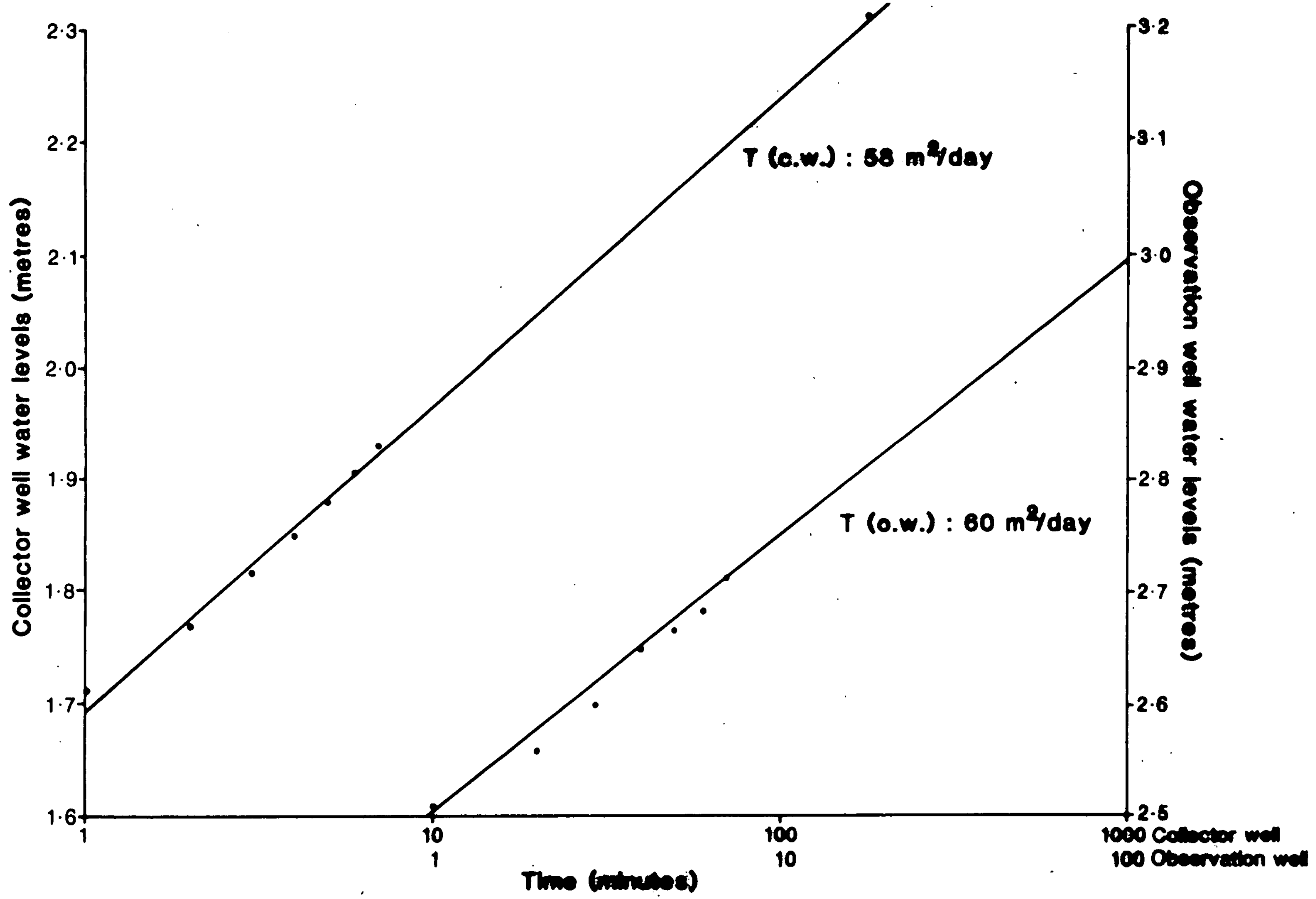


Figure 6.3

permeable layer of the saprolite, and may also have encountered steeply dipping and interconnected fracture systems. Either occurrence would tend to increase the hydraulic efficiency of the well-aquifer system, thereby reducing the drawdowns and apparently increasing the transmissivity as compared with analysis of the flow system to the central vertical well.

The regional transmissivity values are mostly less than 50 m^2/day. As will be shown in the modelling section, these represent the conditions in which the collector well shows most marked improvements over the LD well. The results of the experimental programme confirm the modelling results.

6.2 Boreholes and Collector Wells

Collector wells are designed to give high yields and low drawdowns. They generally demonstrate a major increase of yield over dug wells except perhaps where these have been excavated in highly transmissive aquifers. For very high demands or for sand river abstraction schemes where it is inappropriate to sink the well into the sand river alluvium, the collector well can also be advantageous.

Comparisons with boreholes require much more detailed evaluation since the latter are relatively cheap and can be drilled and completed in short periods of time. It is convenient to discuss relative merits under separate headings.

6.2.1 Failure Rate

Insufficient numbers of collector wells have been completed to date which would allow detailed comparisons. It may be noted that although considerable exploration has been carried out at all the experimental sites, only one has been rejected on the basis of the pumping test data in the shallow test borehole. The impression being gained is that provided the saturated aquifer thickness is moderate, in excess of 5 metres to the base of the regolith* and that well depths allow the radials to be completed in the transition zone between saprolite and saprock, failure of the collector well to give a moderate yield, c. 1 litre/sec, is unlikely to occur even though the large diameter well may prove to give almost negligible yields on test. The feature probably reflects the influence of the transitional saprolite-saprock zone and steeply dipping fracture systems and stone lines/quartz bands. The transition zone provides only a narrow cross-section to a vertical borehole/well and the steeply dipping fractures etc. have less chance of being intersected as compared with the radial collectors. Failure rates in slim boreholes are about 30% overall in basement aquifers which reflects the difficulty of siting boreholes in aquifers of variable fracture permeability. Success rates rise where the regolith is thick enough to give adequate yields to boreholes completed only within that horizon.

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* In Sri Lanka, the aquifer appears to occur mostly in the weathered bedrock (saprock).

Where the regolith is thin, the permeability and specific yield are more critical parameters in the collector well performance. Heavy clay saprolite develops over basic rocks and is less favourable for a collector well site, particularly if the regolith is thin.

Two factors may contribute to the attainment of low failure rates in siting collector wells. Surface features combined with geophysical surveys may assist in more accurate definition of the shallow subsurface conditions as compared with borehole siting in which predictions at depth may be required. Secondly, the cost of test drilling with a lightweight site investigation rig is small and the results should give a definitive answer. In the case of a borehole the main costs lie in the final drilling which has to be carried out after the geophysical survey.

It is also feasible to convert an existing, perhaps a poorly productive borehole into a collector well if the requisite conditions of regolith and saturated regolith thickness are satisfied. The borehole could indeed remain as a central vertical collector. A moderately high yielding borehole might have the facility to convert into a highly productive collector well suitable for the larger and more important demands such as urban supply or irrigation.

6.2.2 Cost Comparisons

At the present time, the experimental collector well constructions are 2-3 times more costly than a standard slim borehole but this does not take account of relative yields. Precise cost comparisons which take account of yield are not easy to make at present but all evidence demonstrates a significant imbalance on the side of the collector well.

There are good reasons to anticipate that the present high costs may be substantially reduced by improved methods of construction and design, some of which are now being experimented with. Reduced unit costs would also be anticipated in larger scale development programmes where more advanced technology could be considered to aid construction. There will always be occasions when self-help schemes are applicable but they do need to be combined with periodic or specific inputs of high technology.

6.2.3 Maintenance and Sociological Aspects

Including collector wells as a possible choice for water supply increases the likelihood of finding a water supply point conveniently close to the centre of demand. Boreholes have often to be located at considerable distances away from the centre of demand, particularly in the fissured aquifer development. Collector wells could prove to have more flexibility in site positions, reflecting perhaps the more areally consistent nature of the regolith aquifer.

The discharge of collector wells as constructed to date are remarkably sediment-free and the feature may reflect the low velocities of inflow through a screen with lengthy hydraulic access.

Sand pumping in basement boreholes is a major source of wear in the pumping equipment. There are also advantages in capital and maintenance costs in the use of a single pump within a large yielding well as compared with several pumps each in small yielding boreholes.

Collector wells are more vulnerable to surface pollution than are the deeper boreholes but where there is a moderate thickness of clayey saprolite in the unsaturated zone, pollution may be avoided providing the well sides and surrounds have an adequate sanitary seal.

For distribution to storage, the large yield of collector wells has obvious advantages, more particularly for small urban supplies. If necessary, additional chlorination at the central tank can be provided.

6.2.4 Yield

The most important comparisons are with yields and specific capacity. Figure 6.4 shows the test yields of a substantial number of boreholes drilled into basement aquifer rocks in Zimbabwe. Although drawdown data are rarely available, it can be reasonably assumed that for the lower test yields at least, the boreholes were being pumped at maximum drawdowns with pumping levels of between 40-70 m below ground level. The duration of testing is normally in a range of 1 to 5 hours. Some 50% have test yields which are less than 0.38 litres/sec. Taking a mean value of 0.25 litres/sec and assumed pumping drawdown of 30 metres, the specific capacity is 0.008 l/sec/m. Comparisons can be made with Table 6.2 which shows the estimated safe yields extrapolated from long term pumping tests at the end of the dry season for a further 180 (occasionally 100) days pumping, 6 hours daily, without recharge. The specific capacity values are in a range from 0.41-6.1 l/sec/m which represents a major increase on standard borehole values.

Table 6.2

Estimated Safe Yields for 100/180 days without Recharge and for 6 hours daily. Specific Capacity values determined from Observed Pumping Drawdowns.

Site	Safe Yield l/sec	Specific Capacity l/sec/m
Murape	1.5	0.54
Hatcliffe Windpump	2.8	1.03
Hatcliffe Willowtree	3.6	0.75
St Nicholas	1.4	0.41
Makumba	1.4	0.53
St Liobas	0.9	0.43
Mponela North		
Mponela South		
Anuradhapura	1.1	2.50
Puttalam A.T.	1.1	1.50
Kurunegala K.	1.7	6.10

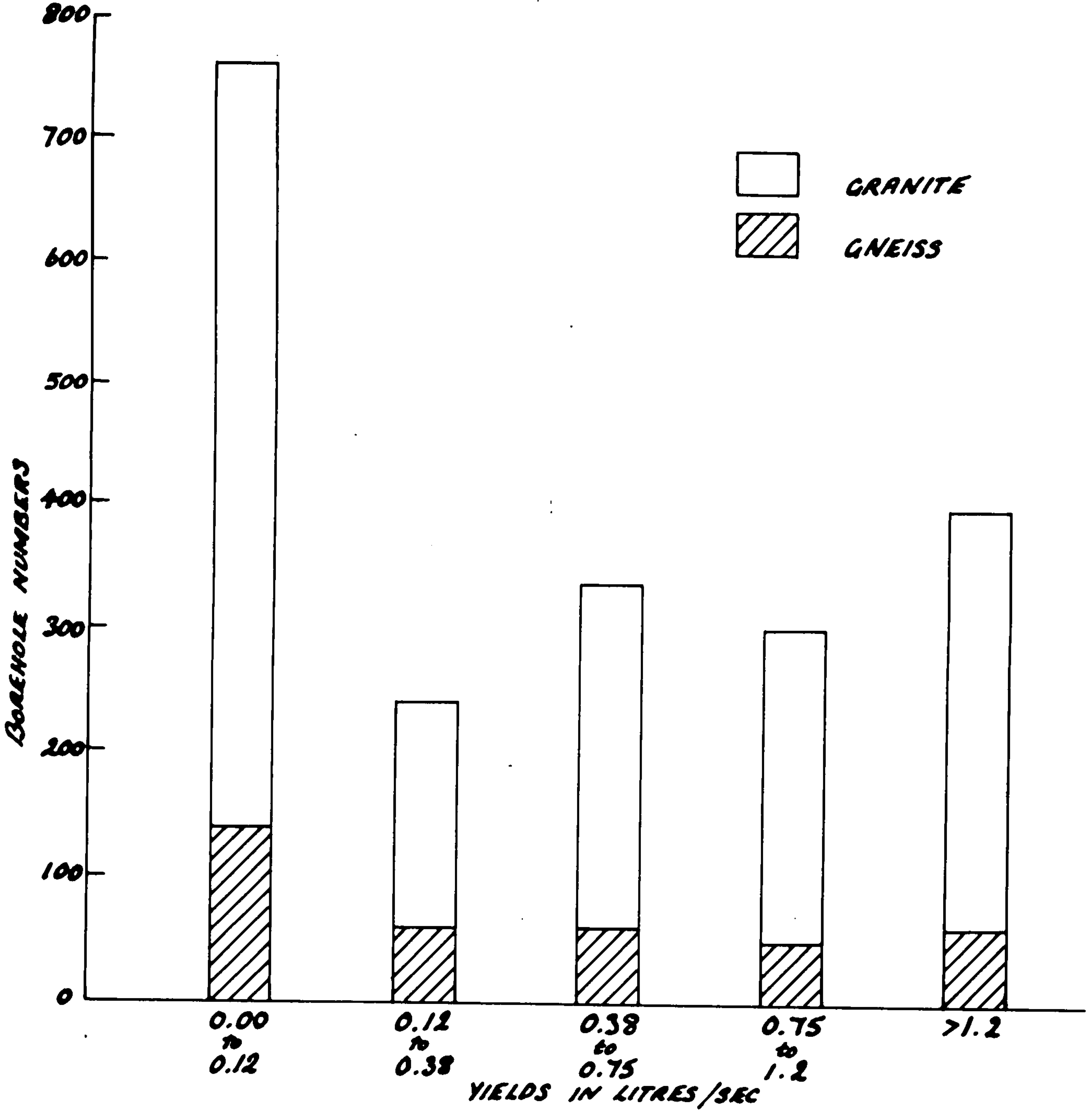


Figure 6.4 FREQUENCY DISTRIBUTION OF SHORT DURATION TEST YIELDS IN BOREHOLES IN ZIMBABWE

It would be particularly valuable if direct comparisons could be made with boreholes in the general vicinity of the collector wells. Unfortunately this is rarely possible. The Zimbabwe collector wells are mostly sited in the vicinity of schools which are rarely provided with boreholes. Additionally, schools tend to be located on rocky elevated ground strategically sited in relation to the villages of an area but not favourably located in respect to borehole or well sites. At seven of the Zimbabwe collector well sites, no boreholes occur in the general vicinity. At one site, St Liobas, a borehole was drilled close to the school and although it apparently gave a good yield on test, according to the drilling records, was abandoned a short time after completion. It is suspected that a seasonal fall in water levels caused the borehole to dry up.

At only one site (St Nicholas) do boreholes occur for comparison. Three boreholes were constructed in January-March 1985, apparently to supply the school and surrounding settlements. Two of these boreholes were capped and the third fitted with a handpump. The reasons for this lack of use are unclear but may relate to the borehole's distance from the school which is in excess of a kilometre. Because of this distance, a collector well was requested. The actual site now completed is close to the school and conveniently located for both domestic supply and garden irrigation.

Brief notes on the borehole tests are given below which include the original tests on completion and further tests carried out by the collector well project team in order to provide yield comparisons.

S3896 (southernmost)	January-March 1985	11-12 November 1986
0-16 m soft rock	9 hour test	6 hour test
16-60 m hard rock	0.53 litres/sec	0.48 litres/sec
	(no drawdown data)	Drawdown: 23 m
S3895 (central)	9 hour test	5 hour test
0-42 m soft rock	0.30 litres/sec	0.28 litres/sec
41-61 m hard rock	(no drawdown data)	Drawdown: 41 m
S3894 (northernmost)	9 hour test	11 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	Drawdown: 19 m
43-56 m soft rock		

All boreholes were successful and two with well above average yield for a basement borehole. They are sited on a marked structural feature apparent on air photographs which is also a seepage line. Borehole S3896 overflowed on completion. The boreholes are spaced about 300/400 m apart. The drawdown data obtained in the test carried out by the Project team in 1986 (S3896) has been analysed using semi-log plots. The calculated transmissivity is 7.2 m^2/day and a storativity of 0.1. For a pumping rate of 0.5 l/sec continuously, the drawdown would reach the bottom of the borehole in about 7 days. For the longer term yield, it might be assumed that the rate of drawdown could only be tolerated to the base of the regolith at 16 m when both S (and perhaps T also) might significantly reduce with a resultant increased rate of drawdown. The correlated discharge (Q) for 180 days with these parameters would be 0.61 l/sec as compared with the estimated 1.5 l/sec for 6 hours daily or 0.38 l/sec continuously with comparative equivalent drawdowns of 16 and 5 m respectively. The longer term yield of the collector well is 6-7 times higher and taking drawdown also into account, yield per metre of drawdown, there is a 15 times greater improvement. These calculations are based on certain assumptions and calculations which are reasonable but better correlations based on longer term continuous tests in both collector wells and boreholes would be helpful.

7. COLLECTOR WELL SITING

7.1 General Objectives

In order to keep construction costs low apart from possible hydrogeological considerations, collector wells are preferably located where water levels are shallow, less than 5 m. The site should be as close as is feasible to the location of demand but taking account of possible sources of pollution (cattle kraals, latrines etc). The low pumping drawdowns are advantageous in this respect. From the pollution standpoint as well as convenience, the site should not be subject to seasonal flooding. Considerations of possible usage such as garden irrigation may also need to be taken into account.

The subsurface profile should have the following characteristics.

(i) Static water levels in a convenient and acceptable seasonal range such as 3-7 metres bgl.

(ii) Total 'diggable' regolith thickness preferably not greatly in excess of 20 m. The present radial drilling equipment can operate at maximum depths of 20 m, but this constraint could be modified if need be. However, construction costs also increase with depth.

(iii) Adequate saturated thickness of regolith, at least 5 metres.

(iv) Adequate permeability of the regolith (i.e. not comprised of heavy clay throughout the saprolite zone as tends to occur above basic rocks). The requirement becomes more critical when the regolith is thin.

(v) General lateral continuity of profile characteristics over the site area.

(vi) An absence of large core stones in the profile below the planned excavation.

There are advantages to be gained if the well can be excavated to the base of the saprolite. The radial collectors can be drilled horizontally within the basal, more permeable zone which results in improved hydraulic access. If it proves to be not feasible to excavate to this depth, the deficiency can be offset to some extent by angle drilling, although obviously with a loss of hydraulic efficiency. The situation occurred at Mponela South where the regolith extended to below 35 m and for various reasons the excavation had to be limited to 15 m.

Indications of profile permeability and characteristics can be obtained from a variety of sources: geophysical survey, lithological samples obtained during drilling, borehole tests, observations on surface outcrops, knowledge of geomorphological evolution and so on.

Poorly permeable regolith particularly if thin and overlying tight and unweathered bedrock constitute the most unsuitable conditions for a collector well. A fuller discussion on the geological and geomorphological features of significance in well siting is given in section 8.

7.2 Geophysical Survey

7.2.1 General Comments.

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 depth 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 quantitatively 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. Conductivity 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.

7.2.2 Results from 1985 Fieldwork (included here since not fully reported on previously)

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 possibility of success, accepting that the risk factor would be high. The work done and the results obtained have been described elsewhere (Carruthers, 1985) and what follows is a summary, reviewing the surveys in the light of the latest information.

Mukumba School, Zimbabwe

Resistivity interpretations had indicated that depths to bedrock could be as much as 18 m for a regolith resistivity of 60 ohm.m in the area recommended for drilling to the west of the school: in fact, none of the four boreholes here penetrated more than 6 m before encountering hard rock and apart from some seepage through the superficial layers there was no water. This discrepancy was accounted for within the range of equivalent solutions that fitted the field curves though it meant reducing the resistivity in the regolith to about 20 ohm.m and the introduction of an intermediate layer of 150-200 ohm.m above resistive bedrock. Even with this correction the depths to bedrock, now associated with the upper surface of the intermediate layer, came out somewhat too deep. The sounding curves were of H-type (having a minimum) and, with high values from surface to 2-5 m, measured apparent resistivities did not fall below 100 ohm.m. There was, therefore, no evidence that the regolith had such a high conductivity; the range of equivalent solutions was also increased because the field data were subject to minor distortions due to near-surface variations.

Some control was in fact available which limited the number of acceptable interpretations. This was provided by the EM34-3 equipment for which readings can be simulated from a layered-earth resistivity model. The EM response is more sensitive to changes at higher levels of conductivity and so the problems of equivalence occur over a different range. That is to say, equivalent resistivity models can give significant differences in predicted EM34-3 values. In this instance the EM34-3 readings corresponded more closely with the model having a thinner, conductive regolith though the variation was relatively small. The most sensitive parameter for detecting the difference was the ratio between horizontal coil readings at 10 m and 20 m separation: in one example this was 1.15 for the original interpretation and 1.4 after adjustment to fit the borehole depths more closely; the observed EM34-3 value was 1.65 which implies an even thinner conductive layer. Another useful indicator in these circumstances is the ratio between vertical and horizontal coil readings at a separation of 20 m: with a thicker conductive layer this is close to or slightly less than one, while in the other case it is 1.13. Clearly, with a more complete analysis of the data at the time of the survey, drilling of these sites would have been avoided.

An area on the opposite side of the road to the east of the school appeared more favourable on the basis of both resistivity and EM34-3 data, though only a limited amount of work was done because a supply point here would not have been convenient. There was a marked lateral variation with EM34-3 values at 20 m coil separations increasing from 7-8 mS/m to over 15 mS/m in a distance of 100-200 m. Resistivity interpretations put resistive bedrock at depths of at least 20 m below a sequence comprising 1-2 m of resistive soils, conductive saprolite of 20-40 ohm.m to a depth of 7-12 m and an intermediate layer of 50-100 ohm.m. The one borehole drilled into this zone encountered 'very hard' granite at a depth of 11.5 m. While this clearly represented an improvement on the initial sites the bedrock depth was still about 50% less than predicted and the hole was bailed dry within a short time. The problems of equivalence were less severe and the only explanation available is that the hard rock itself has a surprisingly low resistivity, and equates with the intermediate layer. The possibility that the bedrock was layered with bands of hard rock separated by weathered fracture zones within its upper section, or that boulders had been encountered, was not borne out by the drilling results though only 1-2 m of the rock were penetrated. Again there is not enough control on the mineralogy to say whether more than one rock type is present. The pattern of resistivity variation across the area does indicate some zoning and, even if this arises from the nature of thickness of the regolith, it probably reflects properties of the bedrock.

The only other data which seemed worth further investigation were picked from the earlier survey. Two resistivity soundings near the marshy area of the 'vlei' west of the school showed a conductive superficial layer. The rising, A-type curves, gave a better indication of the intermediate layer resistivities though suppression rather than equivalence meant that the sequence was not resolved clearly. Depths to resistive bedrock were still in the range 13-18 m with two components to the overlying material at about 30 ohm.m and 100 ohm.m. From the previous drilling there was no reason to suppose that the regolith would prove to be any thicker here but, in the event, better results were obtained and a well site was located. Six holes drilled over a distance of 150 m illustrated the degree of lateral variation with depths to hard rock ranging from 6 m to over 17 m. This was perhaps reflected in the EM34-3 readings with 20 m horizontal coils which oscillated between adjacent stations; it is more difficult to obtain reliable data with the coils in this orientation but the results elsewhere were noticeably more consistent. Additional sounding curves also showed distortions due to lateral changes.

St Nicholas' School, Zimbabwe

Surveys were undertaken initially working downslope and west from the school towards an existing borehole. A series of eight soundings supplemented by EM34-3 data showed a distinct change in response from the regolith/weathered bedrock across a zone of standing water associated with a spring line. Above the spring line the minimum layer resistivity was about 200 ohm.m to a depth of 12-18 m and there appeared to be no significant development of saprolite. Further downslope the conductivity increased steadily throughout the sequence. This may indicate a change in lithology but it was attributed mainly to a thin, upper layer with compact, if weathered, rock still occurring at shallow depths; EM34-3 results did reveal some more promising zones though they were too far from the school to be of immediate interest.

The results from close to the school were not encouraging as the conductance of the regolith was so low. However, an EM34-3 traverse had shown slightly higher values near the southwest perimeter fence and additional work here confirmed that conditions were more favourable. Sandy soils gave very high resistivities and the excessive electrode contact resistances reduced the accuracy of the measurements; they also led to problems with equivalence when interpreting the results. Nevertheless, depths to compact rock of 12-18 m were derived for regolith resistivities of about 60 ohm.m. The upper resistive layer extended to 4-6 m at which depth either water table or a transition from clean sand to clayey sand was expected.

In the light of the drilling at Mukumba it was anticipated that the saprolite would prove to be thinner and more conductive than the original interpretations suggested; the EM34-3 values correlated better with a model putting rockhead at no more than 10 m. The boreholes actually proved to be consistent with an intermediate case giving depths to bedrock of 11-14 m and a site to the southeast of the school was selected for the well; the first hole was shallower but this was located further downslope to the west as a check on the 'resistive regolith' and on the existence of a shallow water table. Variations in conductivity were mapped using both resistivity and EM equipment though results from the EM34-3 are thought to be more reliable. The response is determined by the conductance of the saprolite, that is a combination of its thickness and conductivity/resistivity, and so the changes cannot be correlated directly with the depth of bedrock. Higher readings at the 10 m horizontal coil orientation are a good indication that a conductive saprolite (due to clay or water content) is present; if, also, the ratio of vertical to horizontal coil readings at 20 m spacing is close to or less than one then depths to resistive bedrock should exceed 10-15 m though the precise relations depend on the layer parameters.

St Lioba's School, Zimbabwe

Little time was available for extra work at this site and the objective was to see if an inferred fault had any geophysical expression by which its location could be fixed, on the basis that it might represent a zone of enhanced permeability. EM34-3 traverses beside existing exploratory borehole sites - which had been selected following extensive resistivity surveys - showed that they lay within a localised zone of relatively high conductivity. Drilling had proved depths to bedrock exceeding 20 m but at three of the six sites there were bands of hard granite at higher levels and low permeability clayey material occurred in others. The form of this zone was not fully defined but it clearly died out quite rapidly towards the 'fault' to the north. Resistivity soundings on either side of the lineation prove a resistive sequence to the north and a more conductive regolith to the south, similar to the results found west and east of St Nicholas's school. By assigning a resistivity of 80-100 ohm.m to the saprolite south of the contact a depth to resistive bedrock of 18 m was derived. Subsequent drilling at the same point (borehole 8) encountered very hard granite at only 4.5 m. The conductivity of the saprolite must be significantly higher than initially assumed and the site was probably too close to the northern margin of the transition zone, but even after allowing for this it is not possible to reconcile the data; the depth to 'bedrock' lies within the resistive cover overlying the conductive layer in any model and the readings available from two orthogonal soundings gave consistent results with no indication of lateral effects. It seems that either the bedrock itself is conductive here - which is inconsistent with the EM34-3 data, or the hole went into an isolated raft of hard rock, or there was a location error.

EM34-3 traverses across the lineation suggested that it lay just inside the limit of an area of shallow, resistive bedrock to the north and it might represent a major joint; there was no anomaly that could be associated with a zone of fracturing. The contact demarcates a change in rock type - from granite to a micaceous gneiss for example - which ties in with the rising contours on the bedrock surface derived from the drilling data. The geophysical results show a boundary that swings round to the south rather than following the more easterly heading of the lineation: a resistivity sounding 30 m east of borehole 8 resembled that to the north while to the west of the borehole a saprolite response was maintained. This is consistent with the fact that the well site, where bedrock was nearly 19 m below surface, was found only 50 m to the southwest of borehole 8.

Mponela, Malawi

Preliminary geophysical surveys at Mponela took as their starting point an existing borehole, IR50, which had produced a high yield from relatively shallow depth. In view of the extensive sulphate deposits associated with a large dambo to the west of the town, most of the work was concentrated in the smaller dambo system to the east of the main road.

Results obtained near IR50 could be interpreted simply in terms of conductive saprolite overlying bedrock at a depth of 10-12 m; alternatively, the introduction of an extra intermediate layer of 30 ohm.m between 8 m and about 25 m depth produced an improved fit to the sounding data and was more consistent with the driller's borehole log on the assumption that it represented weathered bedrock. An EM34-3 traverse eastwards from IR50 across the dambo showed that the conductance of the regolith decreased significantly approaching the dambo and maintained a lower level beyond it at least as far as the second tributary channel. High values from over the dambo itself were typical of the response due to a thin cover of grey/black smectite clays. A resistivity sounding on the east flank of the dambo also produced a typical curve showing relatively resistive material at a depth of 6 m: this has been shown to relate elsewhere to hard rock separated by zones of much softer, weathered material.

Data from near the site selected for the northerly well predicted bedrock depths of about 25 m though there was some evidence that lateral variations in lithology and saprolite thickness might be significant. An EM34-3 traverse again showed that the sequence became more resistive approaching the dambo while highly conductive graphitic schists occurred within 400 m to the north. Three resistivity soundings in the area gave slightly different responses which could have quite different implications for a collector well site. One, oriented N-S about 50 m west of the well site, suggested a thick saprolite, to as much as 25 m; a second, some 70 m further south and aligned W-E, gives either a shallower resistive bedrock at 16-18 m or a harder band above weathered rock at this level; the third, 150-200 m to the south, is similar to the IR50 site and distinguishes conductive saprolite from an intermediate layer (?weathered rock) of 50-60 ohm.m below 8 m to a depth of 20-25 m. Results from an exploratory borehole near the well site were most consistent with the last interpretation in that harder material was encountered towards the bottom at about 20 m. The dug well did not penetrate the saprolite though it was becoming harder below 11 m; the type of material encountered here is consistent with the resistivity results and without a known depth to the bedrock the interpretation cannot obviously be modified. It is not clear whether the different resistivity models represent genuine lateral variations within the sequence or if they are a function of the ambiguities inherent to the method. The change along the EM34-3 traverse does suggest that the well is sited within the more resistive environment of the dambo and beyond the area of thicker saprolite to the west.

Results near the southerly well site showed a higher conductance for the material above resistive bedrock. The conductive zone was divided but the resistivity of the deeper component was only 25 ohm.m for a depth extent of 8-35 m: this suggests the presence of thicker saprolite here rather than the weathered bedrock found at the northern site. High resistivities in the top 3-4 m were consistent with the occurrence of laterites. The exploratory borehole PC3 confirmed the resistivity interpretation to the extent that a thick weathered sequence was proved and massive bedrock had not been encountered at the final depth of 35 m; the high clay content, and thus poor aquifer properties, matches with the relatively low layer resistivity.

Other data from closer to and east of the dambo again showed a change to a more resistive environment: about 250 m beyond the dambo a sounding, R9, indicated the presence of harder, resistive material within 12 m of the surface. Thus it appears that the nature of the regolith changes markedly from west to east. Test drilling at the resistivity sites R2 and R9 confirmed the interpretations in a qualitative sense with the predicted depths to 'bedrock' of 6 m and 20 m respectively, relating to a thickening of the weathering profile of this order. .

Two soundings by the large dambo west of the main road had sand/lateritic soils and a more resistive saprolite than at the other sites. An interface at 12-15 m depth could relate to the base of this saprolite over weathered rock though again the important intermediate layer is poorly defined. If water quality problems were not a consideration this area would seem best suited for a collector well if the thickness attributed to the saprolite is correct and its higher resistivity reflects a lower clay content.

7.2.3 Conclusions

At most of the sites investigated in Zimbabwe the resistivity interpretations proved to be overoptimistic in predicting bedrock depths. This only serves to emphasise the value of the reconnaissance surveys in discounting large areas from further investigation. Without widespread drilling control it is not possible to say that some good sites may have been rejected but all the evidence suggests that high resistivities are associated with hard rock at shallow depth.

Where interpreted depths were too large this resulted from the use of too high a resistivity for the saprolite: the 'typical' mean values selected had to be resolved into two components, a thin, conductive saprolite overlying an intermediate zone which was hard but which had a reduced resistivity attributed to a degree of alteration within the rock matrix or a network of micro-fractures.

A more careful, quantitative analysis of the EM34-3 data in combination with the resistivity interpretations would have reduced the depth range attributed to the saprolite. EM34-3 data collected with 10 m and 20 m coil separations are considered to be more reliable and more diagnostic than resistivity traversing; the need to maintain correct coil alignment can be offset against the fact that no direct electrical contact has to be established with the ground.

When starting work in a new district it is necessary to build up some experience of local conditions before realistic models can be established as a basis for interpretation. Thus better results should be obtained if more sites are required in a limited geographical area. Similarly, it is important that geophysical surveys form part of an integrated exploration approach with drilling control provided at an early stage and the results reviewed regularly as a project progresses.

There was no evidence that standard electrical methods by themselves have sufficient resolution to locate well sites in marginal conditions or to assist in fixing directions for radial drilling. Seismic techniques might provide better control but they also will be subject to error if ground conditions vary over short distances. The main role for geophysics is to eliminate areas underlain by shallow bedrock and to indicate where distinctive variations occur so that exploration boreholes can be sited effectively. The results should be reviewed after each hole has been completed to avoid unnecessary drilling, to update the interpretation model and to do more fieldwork if necessary.

7.3 Test Drilling and Aquifer Testing

7.3.1 Drilling

The main purpose of test drilling is to confirm predictions of the geophysical survey in relation to aquifer thickness, depth and permeability characteristics. It should also confirm the suitability or otherwise of the site - water levels, diggability, presence of core stones etc.

Test drilling can be carried out by a small site investigation rig. Since the regolith includes unconsolidated material, air or water rotary flush is preferable. Auger drilling can also be considered but is unable to penetrate core stones or hard bands. Samples should be collected at metre intervals and the drilling rates carefully monitored. Simple borehole logging, gamma and resistivity, would be informative, particularly when investigating areas with little existing borehole information.

7.3.2 Test Pumping

Initially there has been a strong emphasis on the results of pump testing a borehole drilled to the base of the regolith. Requirements have been gauged by a test hole producing at least 0.1 litres/sec for at least 10 hours continuous pumping. The variability of the characteristics of the regolith may be such that it could require several test holes before one satisfies the condition. Although test yields of this order do give good confirmation of regolith suitability it is now thought sufficient if the regolith has an appropriate depth, saturated thickness and a character indicative of moderate permeability. Pump testing should still be carried out and samples of discharge collected for chemical analysis.

7.3.3 Existing Boreholes

Any existing or disused boreholes in the vicinity of the proposed collector well site should be investigated. Observations could include water levels, test pumping drawdowns, and geophysical logging plus fluid conductance. The results of test pumping should be analysed to provide detailed comparisons with the collector well, particularly in the context of long term yield. It may also be feasible to use an existing borehole for conversion to a collector well with the borehole acting as a vertical collector.

8. GEOLOGY AND GEOMORPHOLOGY

The development of the surficial mantle of weathered rock, regolith, varies substantially in tropical areas. Depths of over 100 m are known and, on an intra-regional scale in the study area in Malawi, for example, the depth can vary from over 70 m to nil, fresh rock outcropping at the surface as inselbergs, koppies or dwalas (whalebacks). The preferred requirements for collector well siting, with current technology, are a regolith thickness of some 20 m, so that the base of the well sits on brecciated saprock at the bottom of the profile, and a water level no lower than 5 m below the surface. The relationship of the well to the various horizons in the weathering profile is shown in Figure 8.1.

This chapter attempts to summarise the main geological and geomorphological constraints on the development of the weathering profiles in Malawi and Zimbabwe, with a view to:

(i) understanding and anticipation of the locations where the specific regolith requirements may be met.

(ii) understanding in the variation in performance of some of the collector wells in Zimbabwe and Malawi, ultimately with a view to planning the location so as to maximise the yield.

Three groups of factors interplay to give the variety of regolith development that occurs.

(i) geology - rock type (and its weathering response) and fracturing.

(ii) the age of the erosion surface.

(iii) the leaching history of the local area - site factors.

Because of this interplay, guidelines for collector well location must inevitably differ substantially in different areas. Those that apply to the African Surface in Malawi are not directly relevant to the African Surface in Zimbabwe or to areas of Post African Surface. Good location therefore depends on some understanding of the fundamental constraints that apply and the options they provide as well as an appreciation of the general geological and geomorphological characteristics of the area in question.

8.1 Geology

From the study areas in Malawi and Zimbabwe, some general indications are as follows (and these accord with sporadic comment in the published literature).

8.1.1 Depth of Weathering

Biotite-rich rocks are most susceptible to weathering to the saprolite stage. Hence the basal surface of weathering, the boundary between saprolite and saprock, can be expected to be lower where such rocks occur. Well fractured quartzo-feldspathic rocks

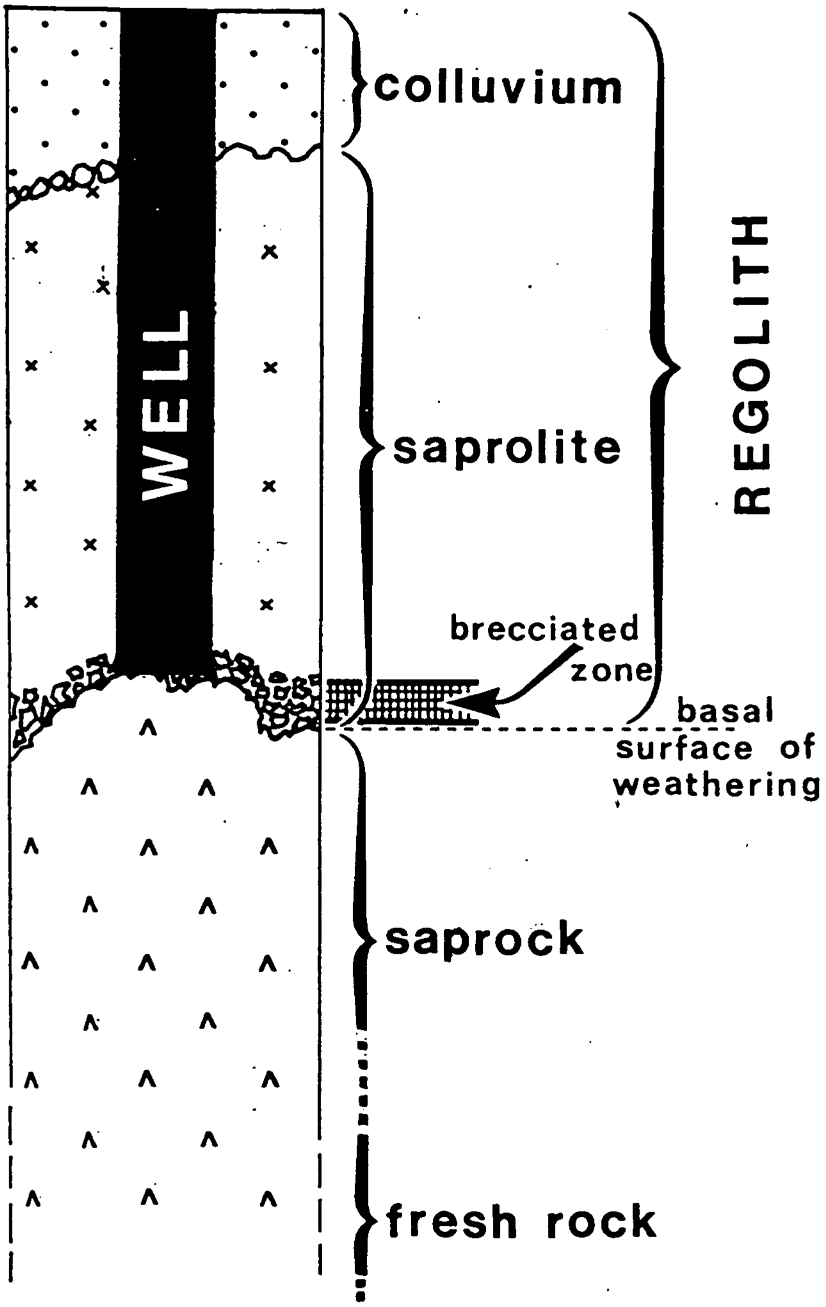


Figure 8.1 The preferred relationship of a collector well to the various horizons in the weathering profile. The well should penetrate the saprolite (soft, in situ, weathered rock) to reach the brecciated zone at the upper limit of the saprock (hard, slightly weathered rock).

rank second to biotite-rich rocks and over more basic gneissic facies, rich in dark minerals, weathering penetration is less. Quartz-free or quartz-poor rocks, e.g. basic extrusives and greenstones are least readily penetrated by weathering. Weathering of I-granites is heavily dependent on the fracture frequency.

Clearly, from this, geological guidelines for collector well siting must vary according to the regional regolith thickness. Thus, where regolith is well developed and thick (Figure 8.2a), as for example on the African Surface in Malawi, the biotite-rich rocks are least favourable because the weathering is likely to be too deep for the well to reach the base of the regolith. Where weathering is less deep (Figure 8.2b), appropriate depths may be associated with biotite-rich or quartzo-feldspathic rocks, but where weathering is very thin, the biotite-rich rocks may present the only option

8.1.2 Saprolite Permeability (Primary)

Biotite-rich rocks weather to a clayey, rather tight saprolite. In a quartzo-feldspathic saprolite, a more open texture results from the quartz skeleton. The openness of the saprolite developed from the more basic gneissic facies again depends on the quartz skeleton. Quartz-free or quartz-poor rocks, e.g. basic extrusives and greenstones, weather to a tight, 'muddy' clay. Thus, given a situation, as in Figure 8.2b, in which appropriate thicknesses of regolith are to be found where biotite-rich or quartzo-feldspathic rocks occur, the former presents the less desirable option. Where weathering is very shallow, as in Figure 8.2c, there is little choice; the clayey saprolite from the biotite-rich rocks may present the only option.

8.1.3 Secondary Permeability

The secondary permeability is largely provided by fractures and quartz or pegmatite stringers. There are some indications that the partial weathering of fresh rock to form saprock, develops or enlarges existing fractures and may open up new or incipient ones along zones of stressed crystals. There may also be incipient brecciation caused by hydration of primary minerals within the mass of the largely unweathered rock. Hence saprock is likely to have a significantly higher permeability than the fresh rock. Fractures appear to remain open in the zones of 'inferior alteration', generally below the water-table. In the zone of 'superior alteration', kaolinisation, generally above the water-table, there are some indications to the effect that overall permeability is reduced. For example, the upper parts of the zone of 'superior alteration' in Malawi seem to function as semi-confining; water strikes which coincide with the boundary between 'superior' and 'inferior' alteration are many metres below the rest level. The reason for the apparently lower overall permeability is not yet clear. An increase in the percent of clay is unlikely to be the essential cause because the boundary, in Malawi, is largely characterised by the alteration of early clay minerals to more advanced clay rather than by a major change in the proportion of clay resulting from primary mineral to clay conversion. Manganese and iron precipitation have been observed in the fractures of the

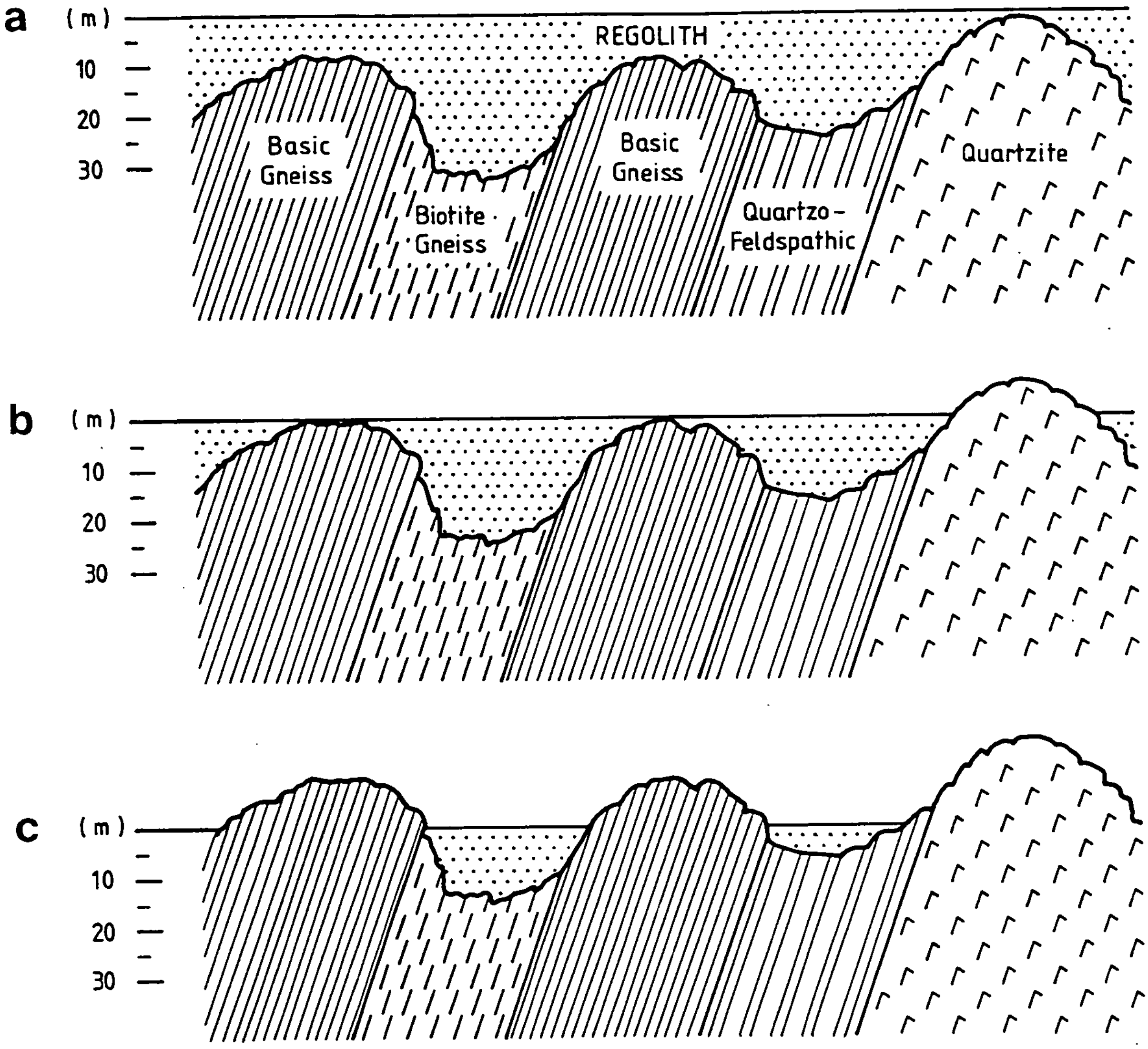


Figure 8.2 Differences in regional thicknesses of regolith limit the geological site options for collector wells. For explanation see text.

kaolinised zone and it is possible that these reduce the secondary permeability.

8.1.4. The Brecciated Zone

The formation of the thin, high yielding, brecciated saprock at the regolith/saprock boundary appears to vary with rock type. Preliminary indications are that with rocks very rich in biotite, the transition from saprolite (soft) to saprock (hard) is rapid and the brecciated zone thin. With the more basic gneissic facies, thicker development of brecciated saprock is indicated. For example some 4-5 metres of brecciation appears to occur in an interfluve core at Chimimbe in Malawi and in one of the collector wells at Mponela (North well) at least 2 metres of brecciated saprock (hornblende gneiss) were encountered. Where there are alternating bands of quartzo-feldspathic and micaceous rocks, the recognition of a saprock component and indeed the recognition of the boundary between regolith and saprock is difficult because soft micaceous saprolite alternates with very hard quartzo-feldspathic saprock over considerable depths. Such boundaries could be very productive. The weathering of the micaceous layers requires water access, this implying fracture routeways through the saprock bands. In such banded situations, where digging is terminated by a hard saprock band, the drilling of 'laterals' angled down into the underlying horizons could be very beneficial. The brecciated zone in a coarse grained equigranular I-granite is difficult to recognise, as such, the saprock grading almost imperceptibly through coarse 'gruss' (gravelly clusters of primary minerals) into gritty saprolite.

The indications that brecciated zone and saprock are favourably permeable have clear implications for collector wells. That the well should reach the brecciated zone is already understood. In addition, the nature of the saprock now appears to suggest that its interception by laterals is also highly desirable. Since the basal surface of weathering is irregularly basined, a well could be in one of two subtly different situations, as shown in Figure 8.3. In the case of (a), with the well in a 'low', normal laterals would intercept both the brecciated zone and the saprock. In the case of (b), with the well on a slight rise on the basal surface of weathering, the normal laterals would intercept progressively high parts (relatively) of the weathered profile, completely missing both the high yielding brecciated zone and the saprock, in effect leaving the well sitting on top of the most productive part of the profile. Clearly, in situations where weathering is often too deep for collector wells (Figure 8.2a) and exploration is directed at finding profiles sufficiently shallow for the well to reach the base, then the probability is that case (b) pertains. Likewise, where well siting is aimed at sufficiently deep pockets of weathering in more shallowly weathered terrain, then case (a) is the probability. To maximise well performance, angle drilling down into the saprock is likely to be beneficial in case (b).

8.1.5 The Configuration of the Basal Surface of Weathering

On the macroscale, the basal surface of weathering follows the configuration of the landsurface in areas of African surface in

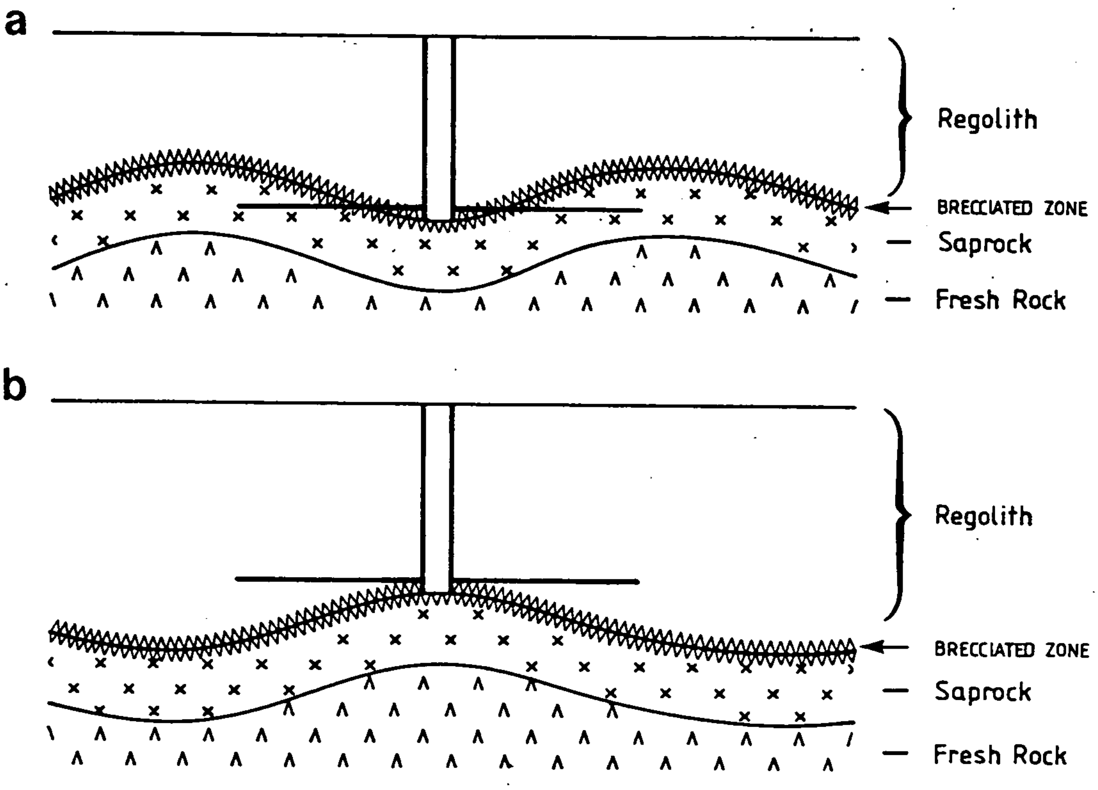


Figure 8.3 The variable relationship of laterals to saprolite, brecciated zone and saprock. For explanation see text.

Malawi and Zimbabwe, that is, it is higher under the interfluves and lower under the valleys. Superimposed on this are local variations - 'highs' and 'lows' - which relate to geology. The ease with which weathering penetrates different rock types has already been outlined and, if rock type varies abruptly, it is to be expected that the basal surface of weathering will have very sharp rises and falls. The most problematic basal surface of weathering, from both the point of view of identifying its configuration by geophysics and drilling and also from the point of view of well excavation, occurs in (but is not exclusive to) areas of I-granites with variable fracture frequency, e.g. the Younger Granites of Zimbabwe. The weathering response of these rocks produces a highly irregular basal surface of weathering, with tor-like features and core stones of various sizes suspended within the regolith. The Mukumba area (Figure 8.4) exemplifies this type of problem. On the interfluve (Figure 8.4a) at the head of the dambo (a) there are no rock outcrops. On the flat interfluve to the west of the dambo (b) apart from one or two corestones barely protruding above the regolith, there are no rock outcrops. Similarly for the eastern interfluve. At the site of Mukumba school (c) on a small rise above the general slope down into the dambo, core stones occur in groups at the surface and also at shallow depth (ca. 1 m) in hand-dug wells and latrines. Below the school, hand-dug wells in the seepage zone, at (d), again expose core stones at shallow depth. No exposures were found on the floor of the upper part of the dambo, but on a transect across the dambo floor, where the well is sited, rounded outcrops occur in the seepage zone (e). Outcrops increase in frequency in a downstream direction along the seepage zone and also begin to appear on the floor of the dambo itself (f). Small, tor-like features protrude from the dambo floor (g) above the head of an invading gully (h). From this, a schematic long profile of the valley floor and the interfluve may be deduced to be as shown in Figure 8.4b. Dambo insetting (McFarlane, 1988a, in press) has, in effect, exposed progressively more of the basal surface of weathering, in a downstream direction. Quite clearly, although no outcrops occur on the floor of the dambo near its head, in the vicinity of the well, reconnaissance of the general area has demonstrated a style of weathering which allows anticipation of a 'tor and core' configuration of the basal surface of weathering.

The variable depth to what was taken as the basal surface of weathering is evident from the exploratory drilling. Figure 8.5 shows the location of the drill holes and depth to bedrock (Wright et al., 1987). It is likely that drilling was terminated when fresh rock was first encountered and so the depth recorded may be an underestimate, if the encounter was with a corestone suspended in the saprolite. The drilling of the laterals at Mukumba well are more informative (Figure 8.6). They clearly show a situation in which the laterals are probing through a veritable jungle of subsurface tors and cores, with a frequency of occurrence in the order of 10 to 20 metres. Clearly, if exploratory drilling has a lesser frequency than this (here ranging from 10 to nearly 200 m and averaging over a hundred) it is less than the frequency of variation in the basal surface relief and the results concerning depth to bedrock are largely fortuitous. Site exploration for collector wells in this kind of context faces the same problems as those with

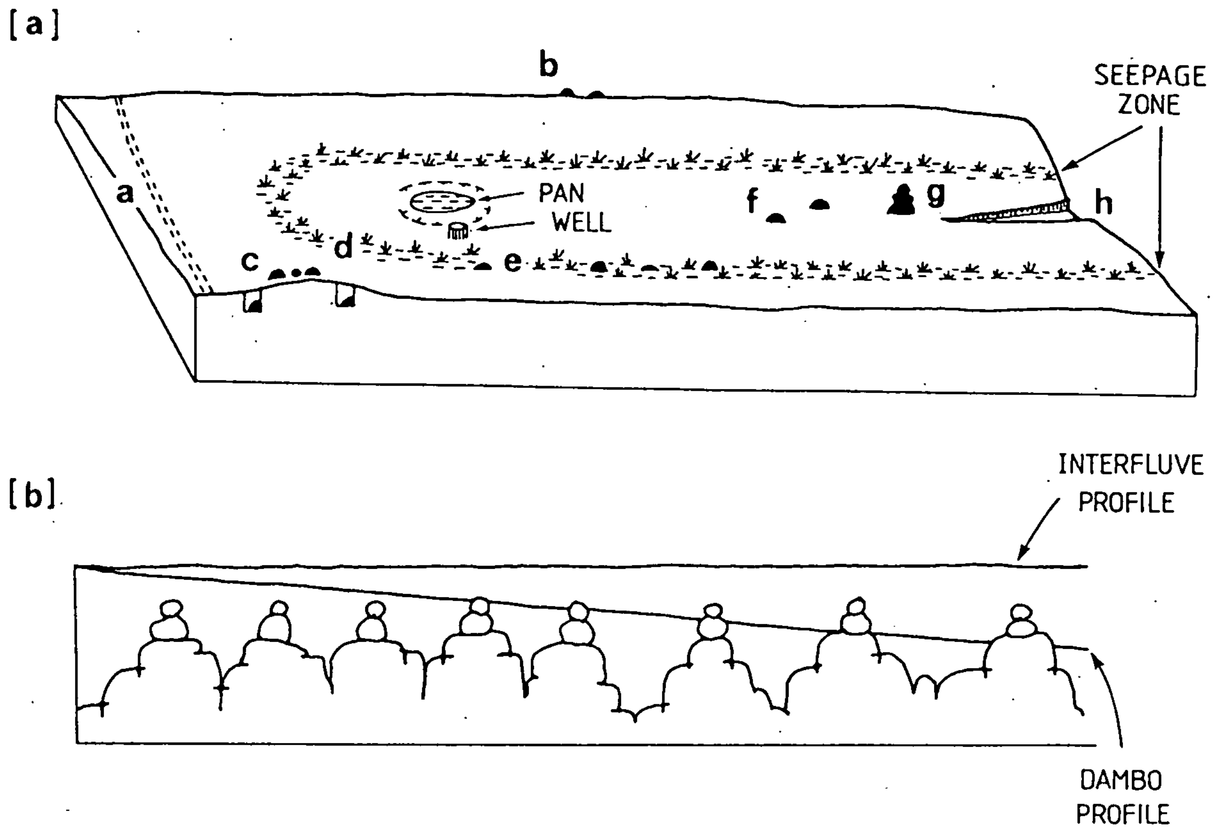


Figure 8.4 The location of Mukumba well, in an area with a problematic 'core and tor' basal surface of weathering. For explanation see text.

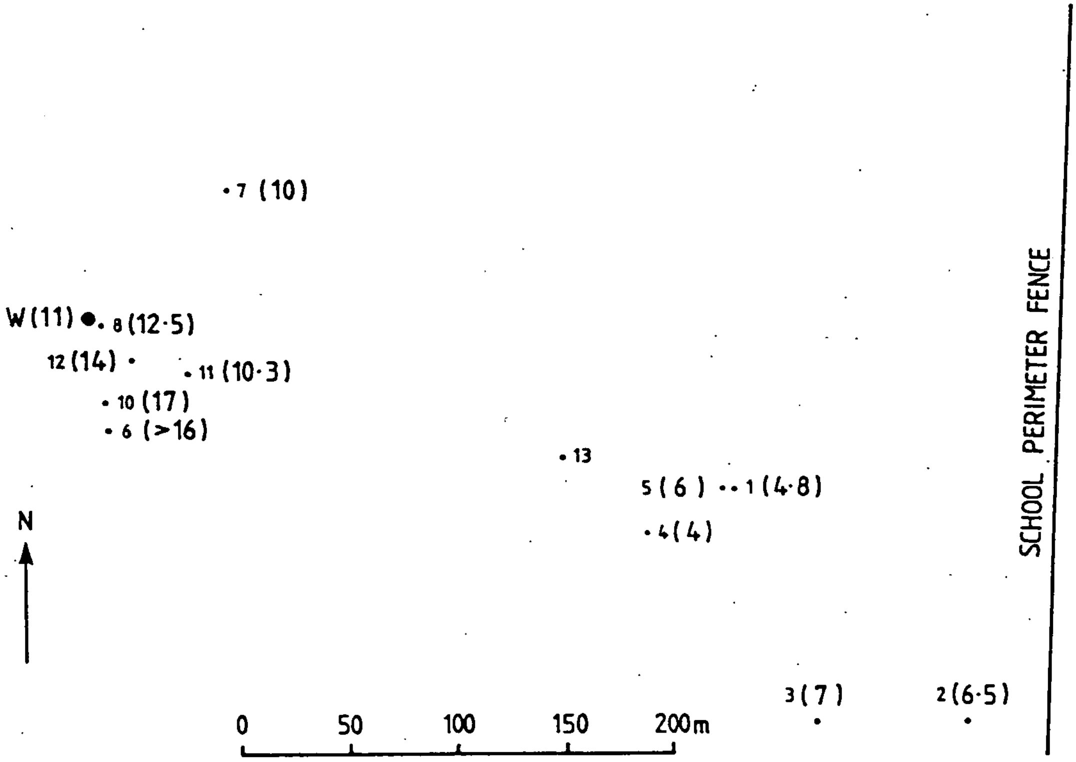


Figure 8.5 'Depth to bedrock', from exploratory drilling, in the Mukumba area. (Numbers in brackets represent the depth in metres).

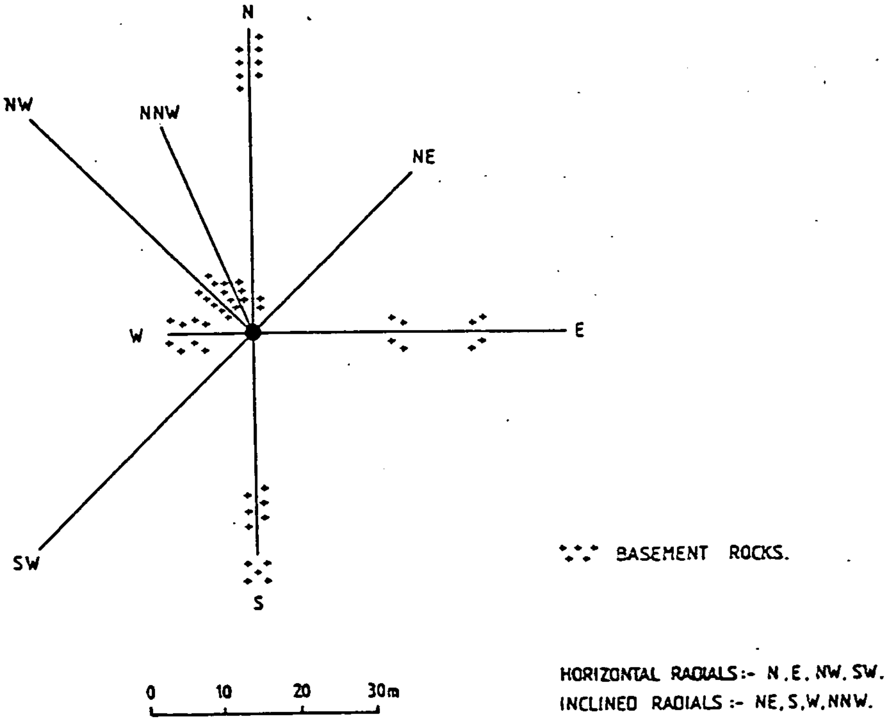


Figure 8.6 Fresh rock encountered by the Mukumba laterals.

which lateritic nickel silicate exploration is faced; the required sample interval is simply too frequent to be economically feasible, and there is little likelihood that geophysical exploration can locate such local tors, cores and 'lows' between them. Given this situation, it seems that the best approach would be to have, as was the case here, an initial, widely spaced drill plan, which can locate local deep weathering (fortuitous) in combination with appropriate thicknesses of saturation. At this stage it would be wrong to assume that because two holes show appropriate thickness of regolith the well can safely be placed between them (Figure 8.7a). Having located, by drilling a single site where regolith thickness is sufficient, the security of the actual site could be further explored by a ring of closely spaced drill holes (about five to ten metres apart), cost permitting, to examine the possibility that it lies hard up against a massive 'high' (Figure 8.7b) and the well might be better placed further away from it. Alternatively, having located the single site, E.M. traversing might be a more cost effective means of further exploring the immediate vicinity. The relevance of such a 'high' would depend on its nature. For example (Figure 8.7c), in an area of I-granite, the high could be expected to be least fractured. Drilling of laterals would be difficult and there is in any case little to be gained by drilling through the least fissured bedrock. L1 would therefore be expected to be less beneficial than L2 which attempts to reach the deeper but more fissured granite. If the 'high' occurs in a granitic gneiss, it is likely that this is a more basic facies with a thick saprock component which could be high yielding. Thus, L3 could be expected to be of greater contribution than L4, which probes into the area of deeper weathering where more micaceous rocks could be expected, which may well have a poorly developed saprock zone.

Mukumba is an area of low relief and the problems here are great. There are grounds for believing that they become even greater in areas of higher relief. In the break zones between flat landsurfaces, the relief of the basal surface of weathering increases, in effect exaggerating the problems encountered at Mukumba. St Liuba provides an example. It lies in a horseshoe-shaped valley, set within an amphitheatre of inselbergs in the major break zone between the lower component of the African Surface and the Post African Surface. Exploratory drilling revealed numerous corestones suspended within the saprolite, well above the basal surface of weathering. Figure 8.8 shows some of the profiles (following Wright et al., op. cit., but representing the corestones with their width approximately equal to their penetrated vertical thickness, to avoid the impression of platy structures, for which there is no evidence from reconnaissance of outcrops in the vicinity).

In short, the configuration of the basal surface of weathering is very varied. Local variations, understanding of which is crucial for collector well siting, are difficult and in some cases virtually impossible to identify by geophysics and may also be missed or misrepresented by exploratory drilling. Reconnaissance of the

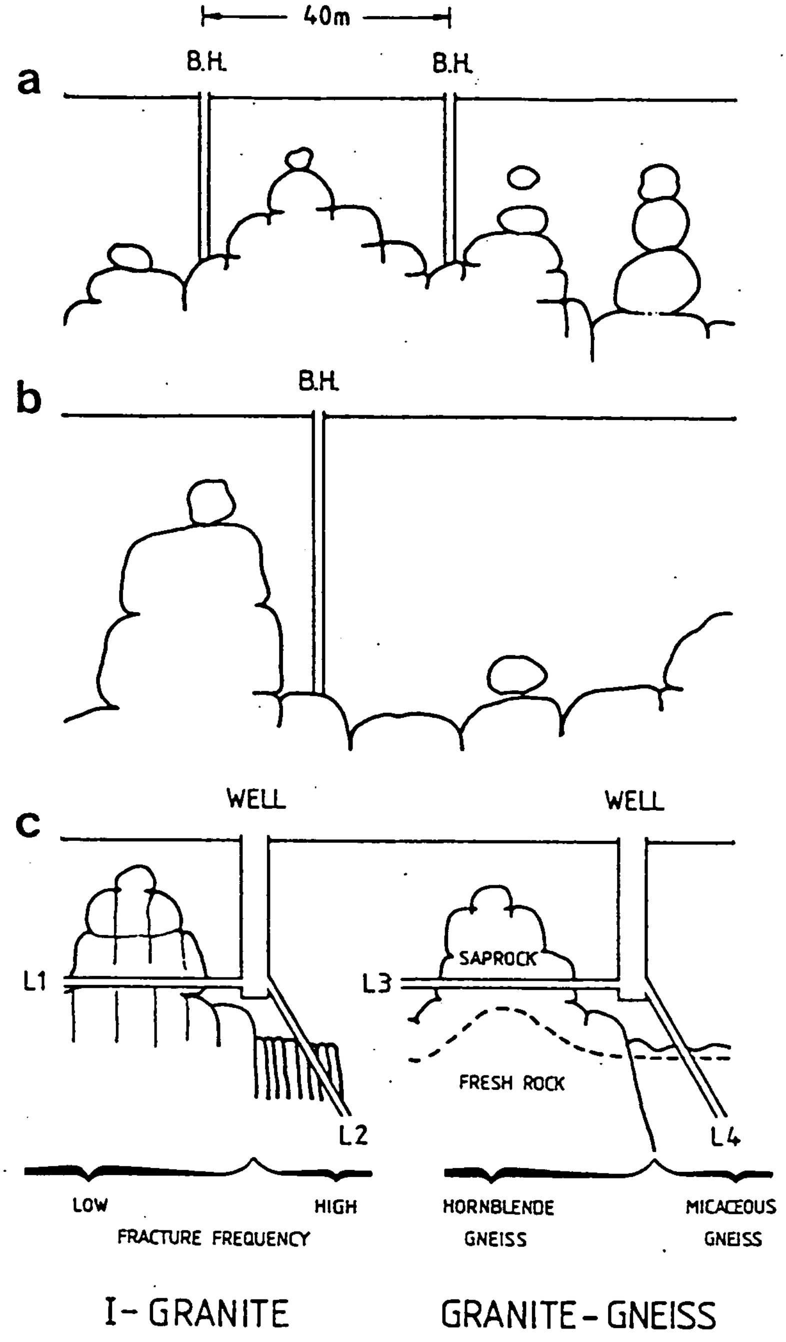


Figure 8.7 (a) In a 'core and tor' situation, where there is a frequency of variation in the bedrock boundary which is greater than the frequency of drilling, it is unsafe to place a well between two holes which encounter the required depth of weathering.

(b) A close circle of drill holes around a prospective site, where the required depth has been found, will establish if the well is hard up against a massive 'high' and might be better located further from it.

(c) The location of the laterals in relation to a 'high' depends on the lithology. For explanation see text.

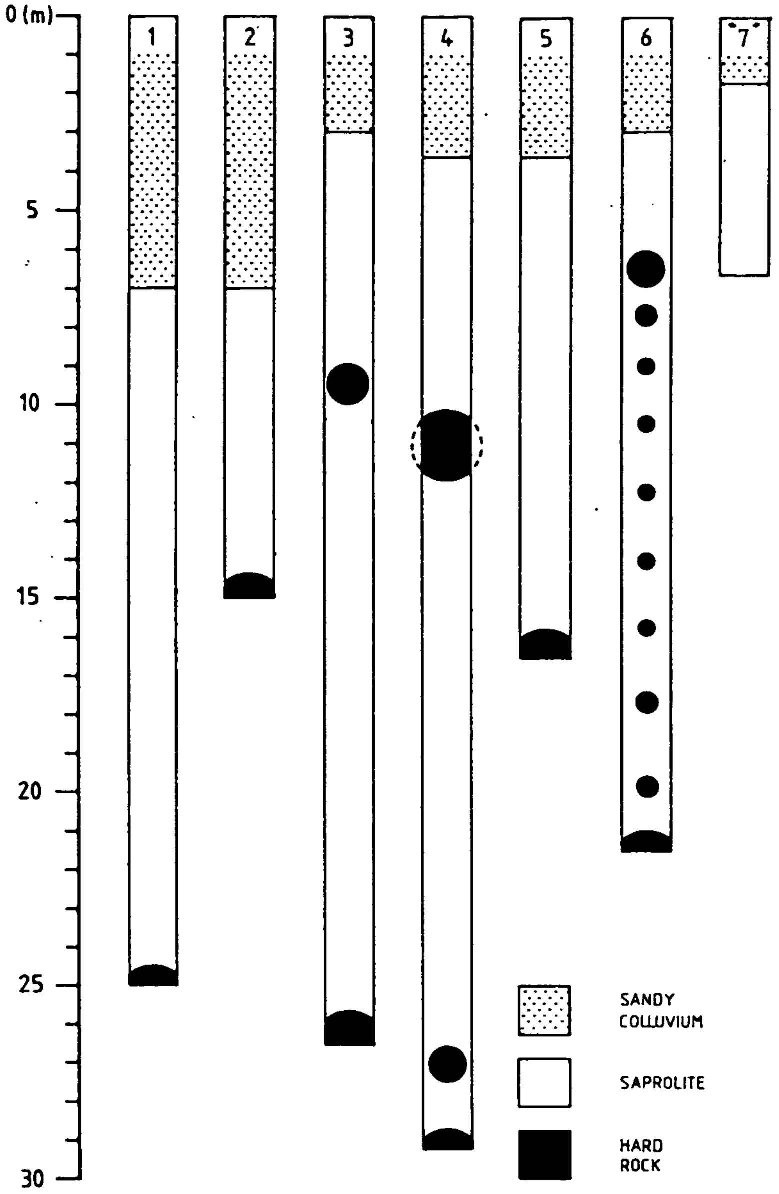


Figure 8.8 Examples of the distribution of core stones encountered by the exploratory drilling in the St Liuba area (following Murray, op. cit) where the 'core and tor' problem is more acute than at Mukumba because of its location in the break zone running down from African to the Post-African Surface.

context of the site can provide valuable information about the style of weathering and hence allow the drilling program to be adapted so that it appropriately tackles the specific problems presented in the area, thus avoiding unnecessary and uninformative drilling.

8.1.6 Advancement of Weathering

Depth of weathering and advancement of weathering are not synonymous (McFarlane, 1988c, in press). For example, very deep saprolite can develop from biotite-rich rocks, with the weathering predominantly at a very early stage - the conversion of biotite to hydrobiotite and vermiculite (Figure 8.9). Conversely, the thin profiles over basic rocks may show very rapid advancement through to the kaolinite stage.

Study of weathering profiles by French scientists has provided the distinction between 'superior alteration' of the saprolite above the water-table and 'inferior alteration' below it. The essential difference is purported to be that the 2:1 clay minerals (e.g. illite, vermiculite, smectites) which are typical of the zone of inferior alteration, are converted to more advanced leaching products, the 1:1 clay minerals (kaolins), by the more aggressive leaching of the vadose zone. Because a fundamental requirement of collector wells is a high water-table, it follows that the bulk of the profile should lie in the zone of inferior alteration.

Advancement of weathering, up profile, generally means progressively more replacement of primary minerals by secondary clay minerals. In the case of sedimentary materials there is usually a close relationship between particle size and permeability; the higher the proportion of clay, the lower the permeability. It must be emphasised, however, that such a direct relationship does not necessarily pertain in weathering profiles. The orientation of the platy clay minerals often follows that of the primary minerals which have been replaced, so that they are arranged like a house of cards rather than a pack of cards. In extreme cases, leaching can result in the upper horizons of a profile being composed almost entirely of clay size gibbsite, but with the crystals arranged in such a way that the material is extremely permeable. A one metre core of bauxite from Trombetas, Amazonia, is said to 'shake down to a handful of clay' (Aleva, pers. com.). In the case of the Malawi and Zimbabwe profiles, there are indications that the permeability at the base of the profile relates to the type of clay produced. If the clay is a mix of hydrobiotite and vermiculite, with a significant proportion of hydrobiotite, permeability can be expected to be lower than if the conversion is directly from biotite to vermiculite, by-passing the hydrobiotite stage. The type of clay produced depends on leaching aggression and this is closely related to the geomorphological context and local site factors, as exemplified by the five collector well profiles studied (see later). It also relates, indirectly, to the susceptibility of the rocks to weathering. Thus, preferential deep weathering of an area of biotite-rich rocks creates a local basin on the basal surface of weathering and such basins are likely to have very sluggish evacuation of solutes, that is, low leaching aggression. This would favour hydrobiotite formation. Thus, returning to the options

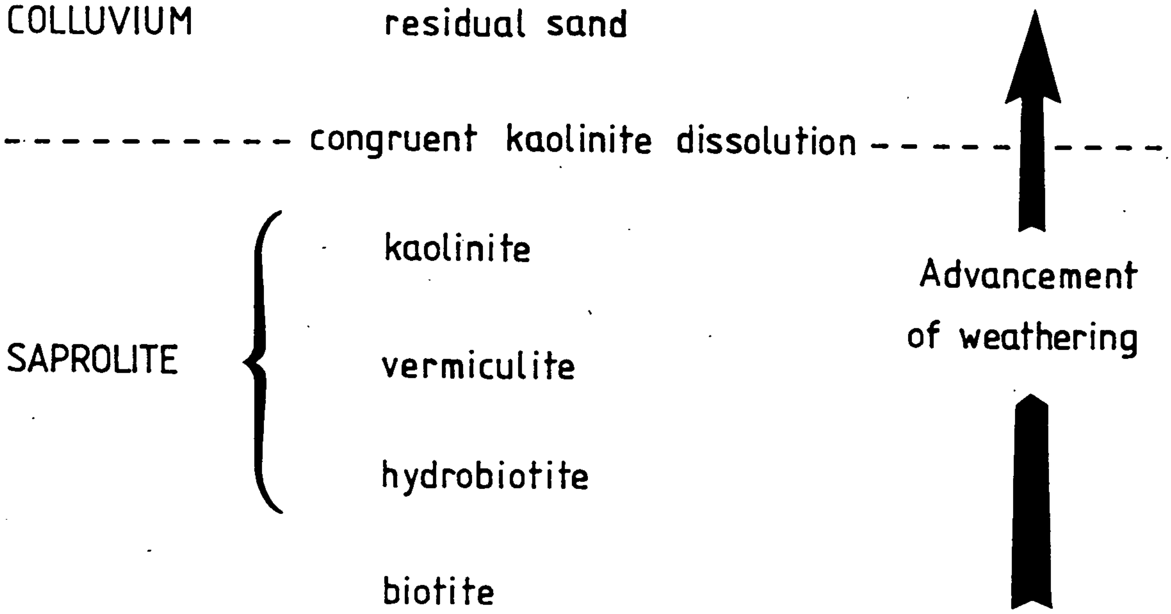


Figure 8.9 A characteristic weathering progression for mica. For explanation see text.

outlined in Figure 8.2, it can be appreciated that where weathering is shallow (Figure 8.2c), as in Post African areas in Zimbabwe, in addition to the innately tight saprolite formed from gneissic rocks rich in orientated biotites, an additional permeability disadvantage results from the local basining which would promote hydrobiotite formation. A further problem, salinity, can be added to this. Conversely, in areas where the general weathering is commonly too deep for collectors and site selection is aimed at finding sufficiently shallow bedrock (Figure 8.2a), as in Malawi, the fact that these comprise the 'highs' of the basal surface of weathering means that they have the advantage of more free leaching at the base of the profile and micas are likely to alter directly to vermiculite if not to kaolinite.

The five collector well profiles provide some insight into the permeabilities associated with different mineral assemblages but further study of permeability and associated assemblages is needed, particularly in conjunction with study of the geomorphology, which controls the leaching aggression, in order that the terrain characteristics can allow better anticipation of the nature of the profiles.

8.2 Age of Erosion Surface

It is well known that older surfaces tend to have better developed weathering profiles than younger surfaces because the leaching history is longer. Leaching is not terminated by incision, but enhanced by it, since the constraint of poor solute evacuation is removed. In areas of African and Post African Surfaces the geomorphologically controlled variations in depth of regolith is generally as shown in Figure 8.10. In some circumstances incision does not have the effect of deepening the profile of the older landsurface. Where surviving residuals are small, the aggressive leaching may promote advancement of weathering and thinning of the profile rather than deepening. However, small, elevated residuals usually have low water-tables, and more relevant to collector wells is the association of thinned profiles with insetting dambos in areas of extensively surviving African Surface. This has been described more fully elsewhere (McFarlane, 1988a, in press). In brief, an effect of the incision of an ancient low relief landsurface is that the area of dambo (seasonally waterlogged lowland) is reduced and the dambo surface becomes inset into the ancient landsurface (Figure 8.11a). The peripheral areas of former dambo clay (smectite), with quartz float, are then leached and the smectites desilicified to form kaolinite. Ultimately the kaolinite is congruently dissolved, leaving residual sand (Figure 8.11b). Slope-bottom laterite is precipitated in the clay which survives under the surficial sand, the source of the iron being the upper horizons of the interfluve profiles and the translocation being brought about by shallow interflow. This post-incision leaching history alters the relationship between thickness of regolith and topographic position. Thus, although the basal surface of weathering follows the landsurface, being higher under the

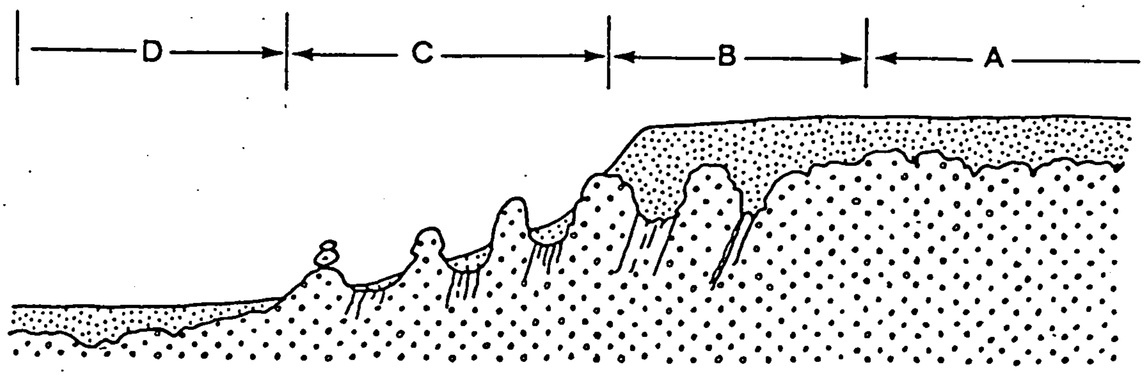


Figure 8.10 Variations in depth of weathering at the boundary of African and Post-African Surfaces. At the margins of the older surface (B) the increased freedom of drainage allows deeper pockets of weathering to develop where lithology is more susceptible, so that the relative relief on the basal surface of weathering is greater than in more central areas of the old surface (A). In the aggressively leached break zone (C) the highs of the basal surface are exposed as outcrops, with pockets of deep weathering between them. On the younger surface weathering undermines and destroys the highs, again tending towards the development of a more even (on the macroscale) basal surface of weathering (D). Weathering is nevertheless generally thinner than at (A) as a result of the shorter time available.

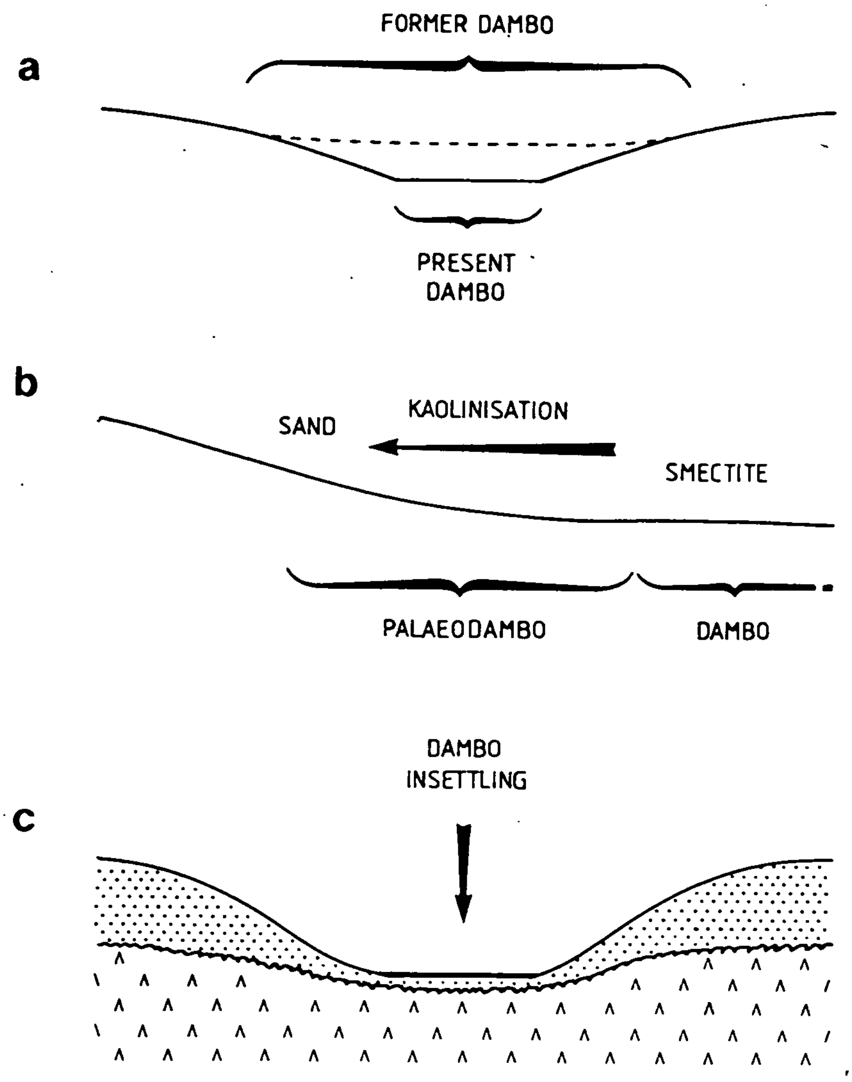


Figure 8.11 The effects of dambo insetting on the mineralogy of surficial horizons and the thickness of the regolith. For explanation see text.

interfluves and lower below dambos, its overall form (excluding local geological effects) is more subdued, so that the regolith is thicker under the interfluves and thinner under the dambos (Figure 8.11c).

In short, given a situation where a sequence of landsurfaces occurs, each can be expected to have different profiles because each has a different leaching history. The recognition of areas of differently aged landsurface therefore becomes important to the assessment of regional hydrogeological potential. It must be emphasised that, for hydrogeological purposes, the actual dating of the landsurfaces is not only difficult but largely irrelevant because knowledge of the date of a surface does not provide a 'package' of known conditions- depth of weathering, thickness of saturated zone, characteristic mineral assemblages and permeabilities. Such 'packages' do not exist because climatic change and continental drift have combined to give each surface of a known date a different local face (McFarlane, 1988b, in press). The African Surface profiles in Malawi, for example, differ significantly from African Surface profiles in Zimbabwe. In Malawi, the profiles are better developed in the sense that they are deeper and weathering is also more advanced.

The major landsurfaces have already been mapped by geomorphologists (King, 1962; Lister, 1965, 1979). However, it is already known that the major surfaces are subdivisible into minor components. If the altitudinal separation of the components exceeds the general profile thickness, then clearly each of the minor surfaces has a chronologically and genetically different profile which may differ significantly in its characteristics and hydrogeological potential. The mapping of these separate surfaces therefore becomes relevant. Techniques for surface identification and mapping have been described elsewhere (McFarlane, 1988b, in press) and have been applied in the collector well areas of Malawi and Zimbabwe, in order to place the well profiles in their proper geomorphological context.

In the case of the Malawi study area (Figure 8.12), what was formerly believed to be a single surface (the African Surface) tilted down to the west, away from the shoulder of the Rift, transpired to be a flight of eight small and apparently undeformed surfaces descending, in step fashion, generally westwards (Figure 8.13).

In the case of the Zimbabwe study area (Figure 8.14), terrain analysis allowed the subdivision of the "broad brush" African Surface into two units, and surviving areas were further subdivided, on hydrogeological grounds, in terms of different relief and post-incision leaching history, as shown (Figure 8.15). The three collector wells could then be recognised to occupy distinctive positions within this framework, as shown in Figure 8.16.

8.3 The Leaching History of the Local Area - Site Factors

Given an understanding of the distribution, elevation, characteristics and mode of formation of the regional erosion surfaces, it becomes possible to assess individual sites within a rational scientific framework. Each site is no longer a single

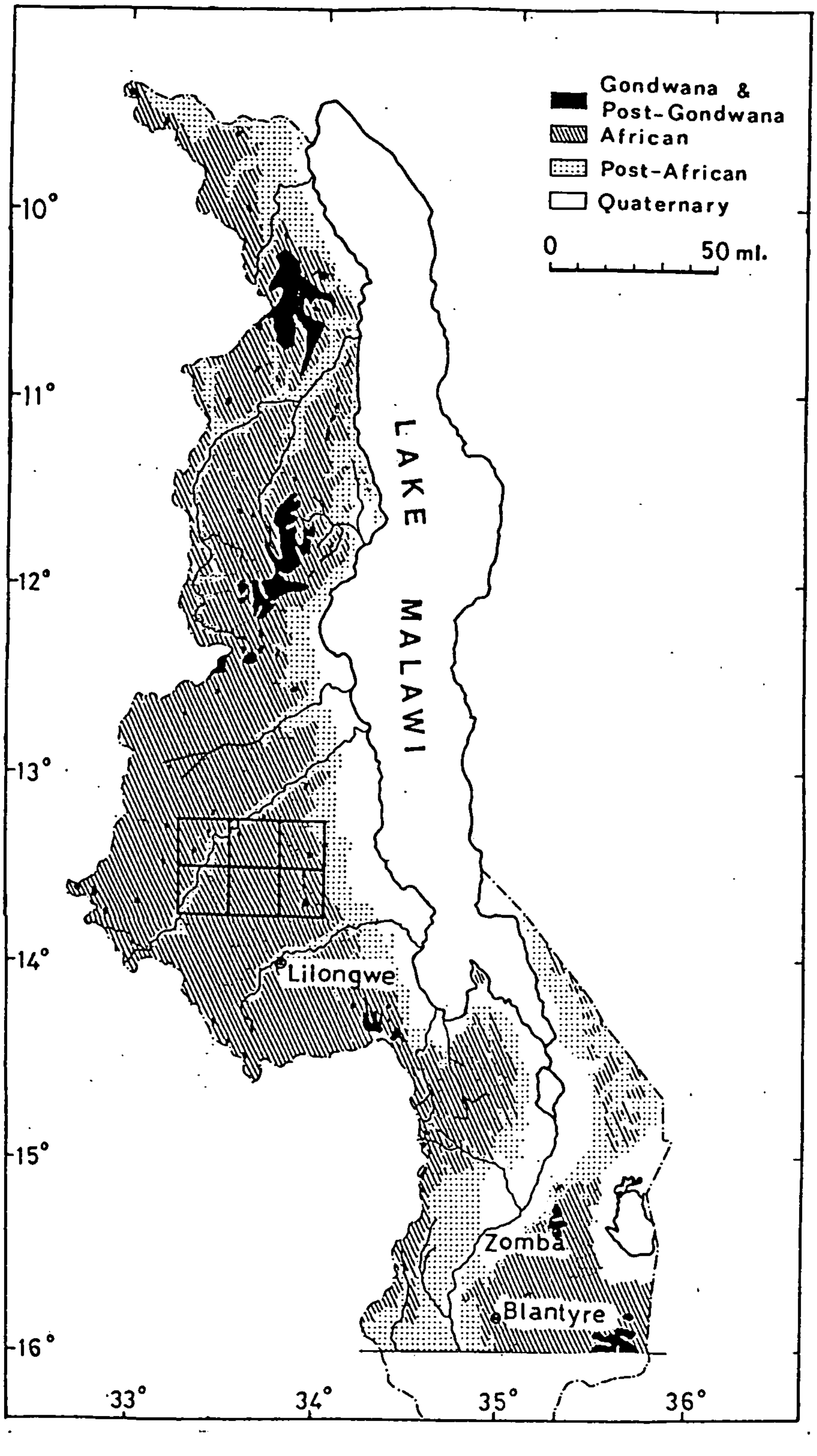


Figure 8.12 Location map of the study area in Malawi, in the context of the major erosion surfaces (after Lister, 1965).

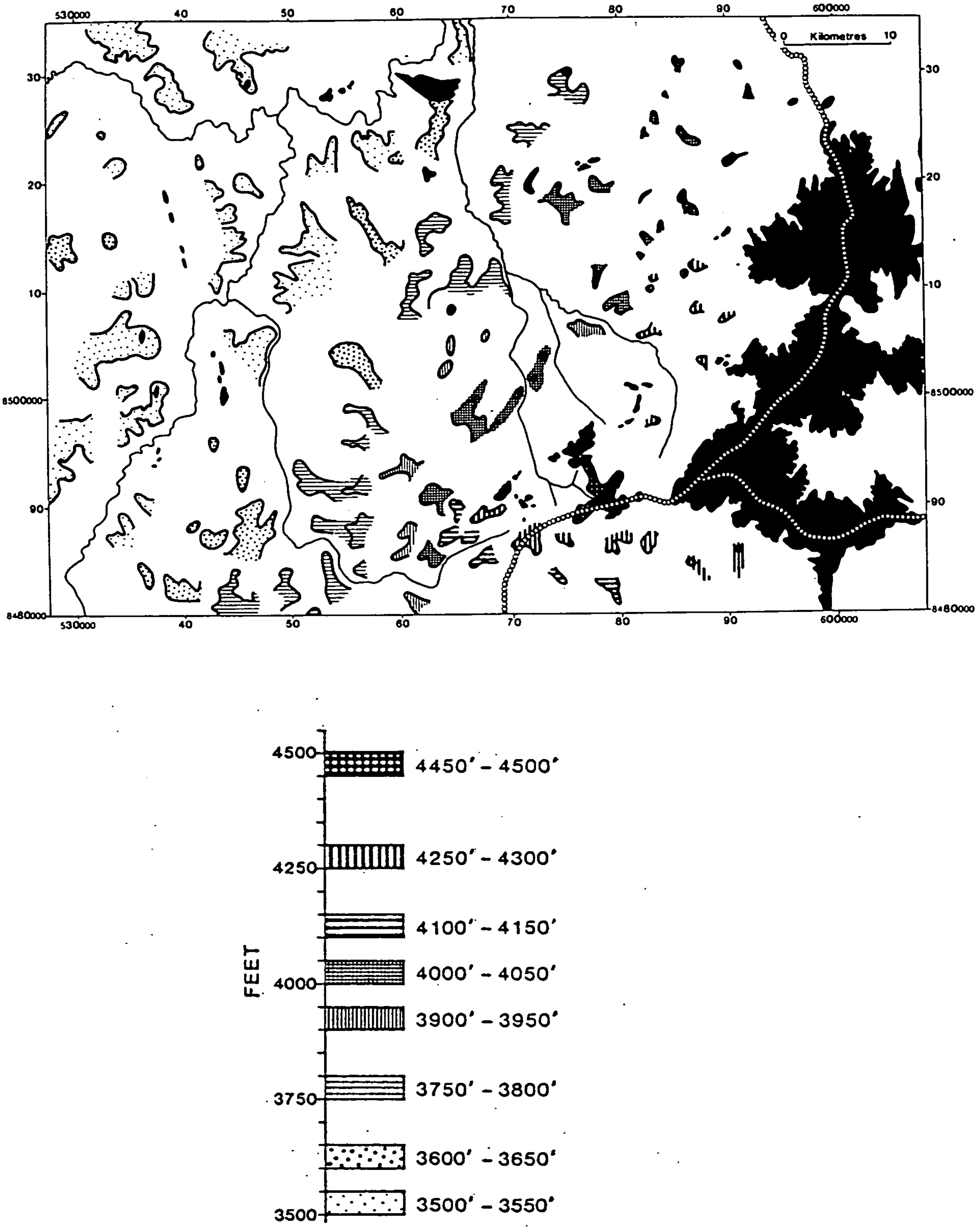


Figure 8.13 Erosion surfaces in the Malawi study area.

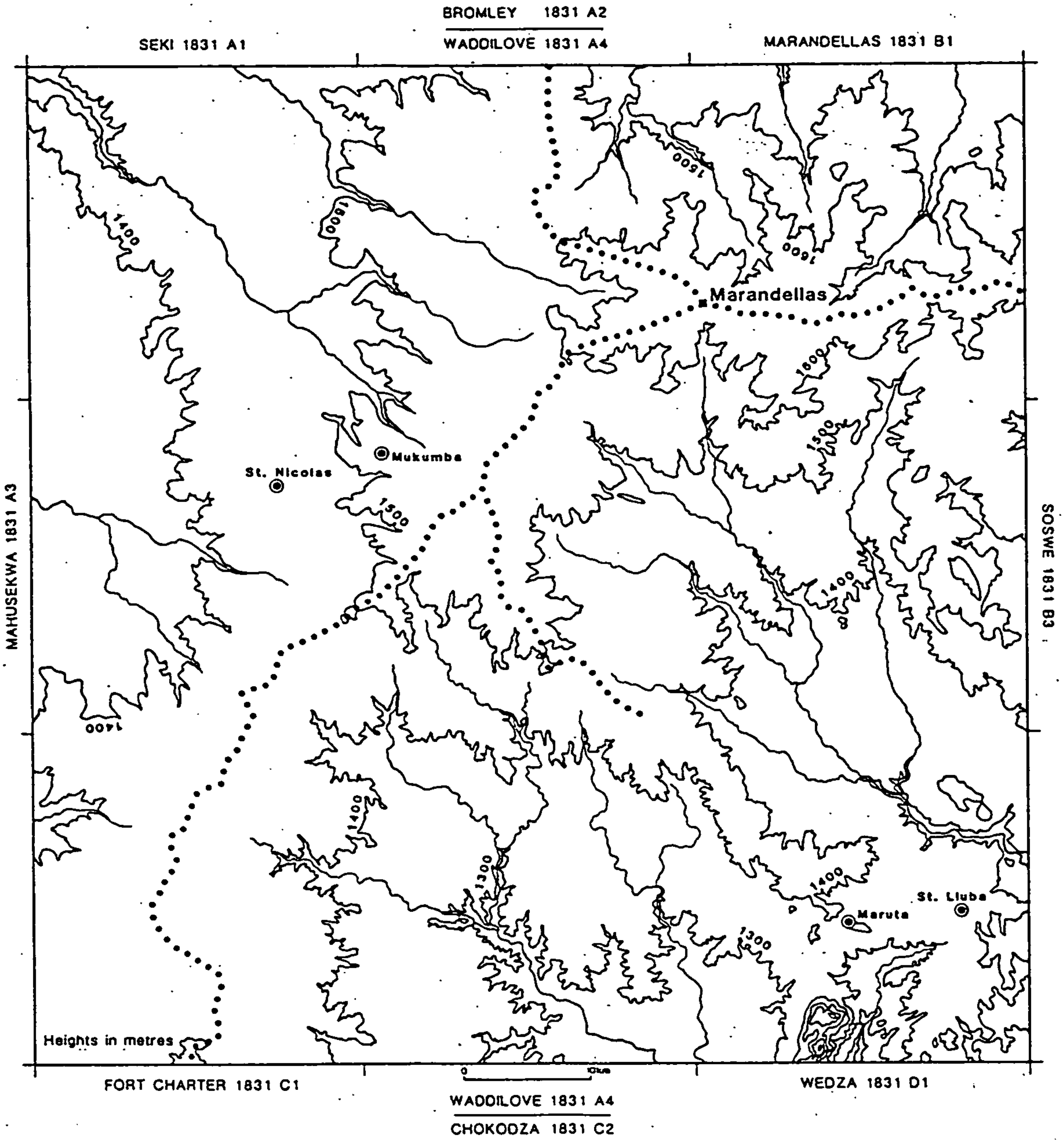


Figure 8.14 Location of the study area in Zimbabwe.

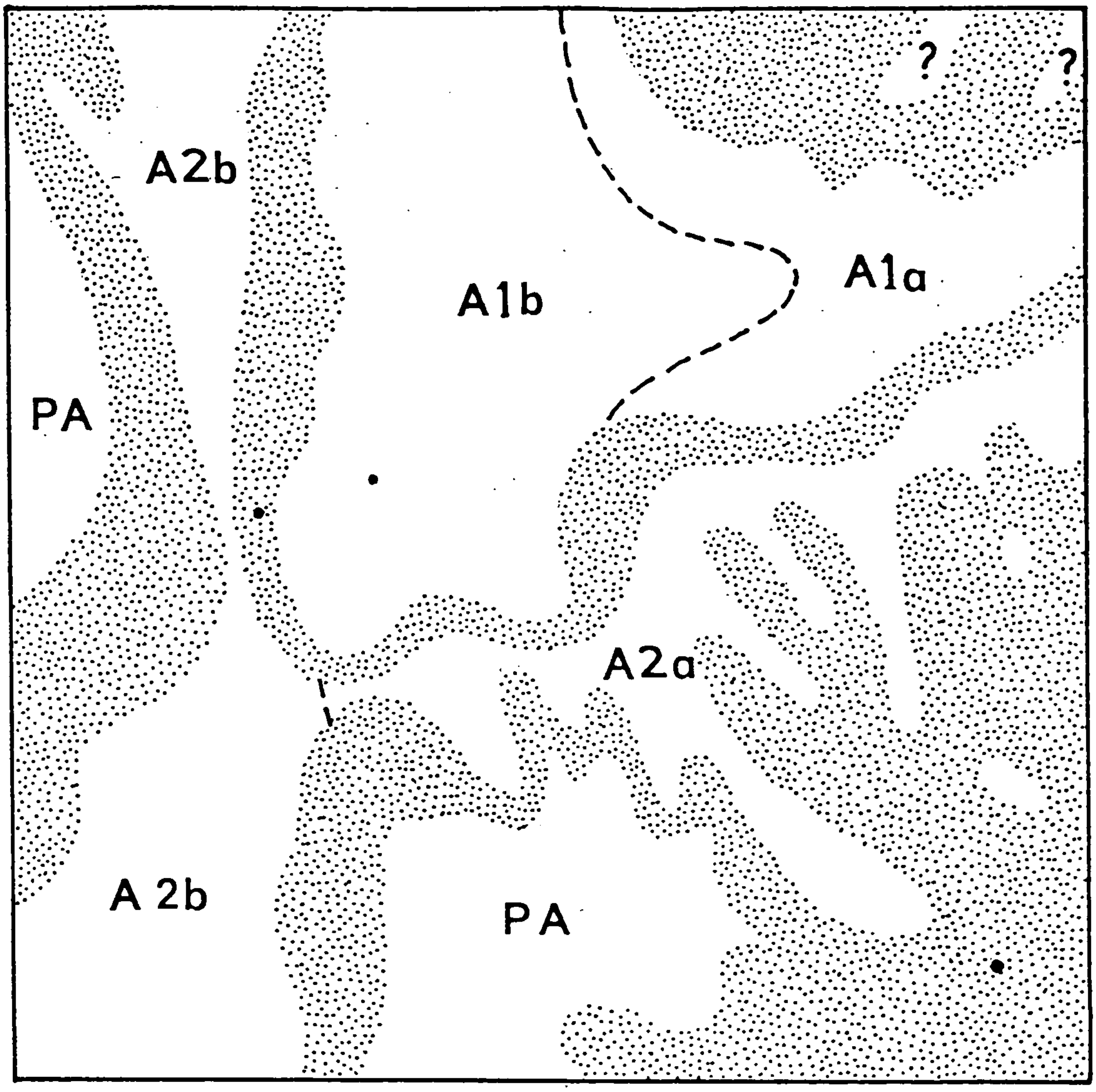


Figure 8.15 Provisional map of the geomorphological units with potentially different hydrogeological characteristics.

A1 - higher component of the African Surface, subdivided into areas with higher (a) and lower (b) relative relief.
A2 - lower component of the African Surface, subdivided into well-incised areas (a) and poorly incised, extensively surviving areas (b).
P.A. - Post-African Surface
Stippled areas are break zones between the main units.

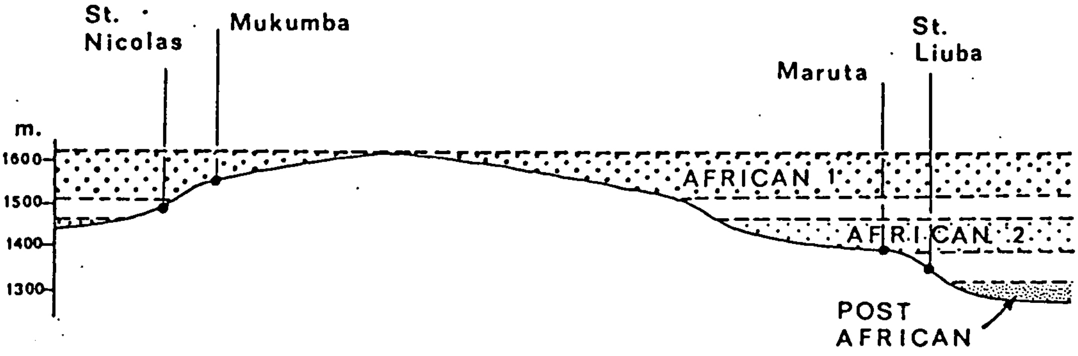


Figure 8.16 Schematic transect to show the location of the collector wells, in the context of the erosion surfaces in the study area of Zimbabwe.

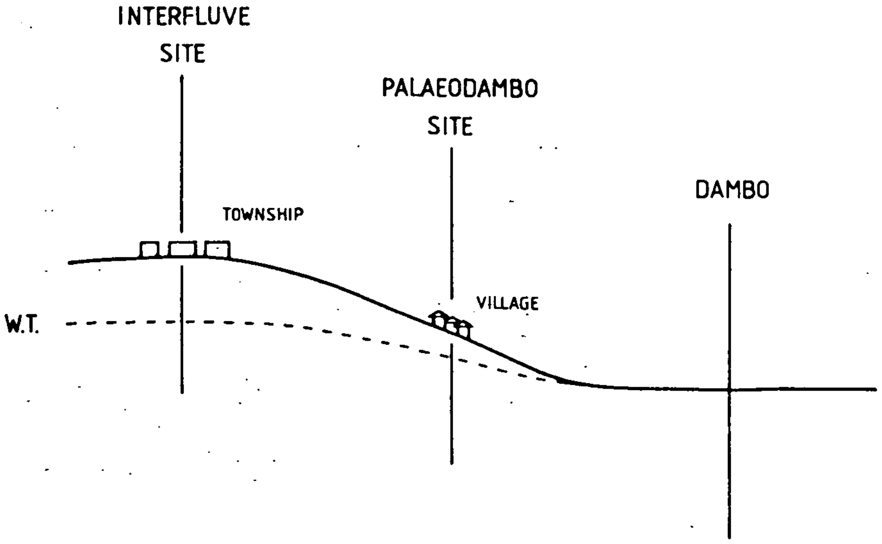


Figure 8.17 The site options for collector well, in the catenary context, Malawi. For explanation see text.

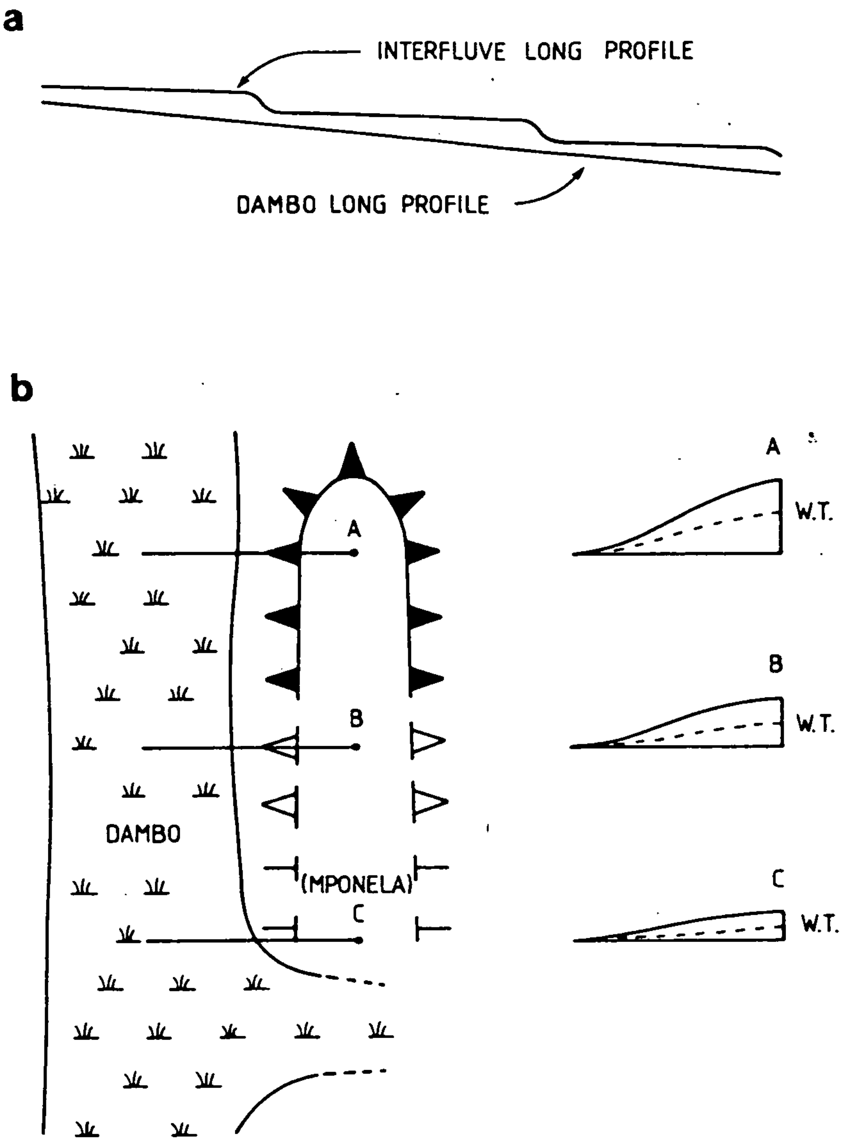


Figure 8.18 (a) Schematic long profile of interfluves and dambos to show the increasing proximity of interfluves and dambos at the back (upper end) of each small erosional surface.

(b) Site options in different positions along an erosion surface on an interfluve. For explanation see text.

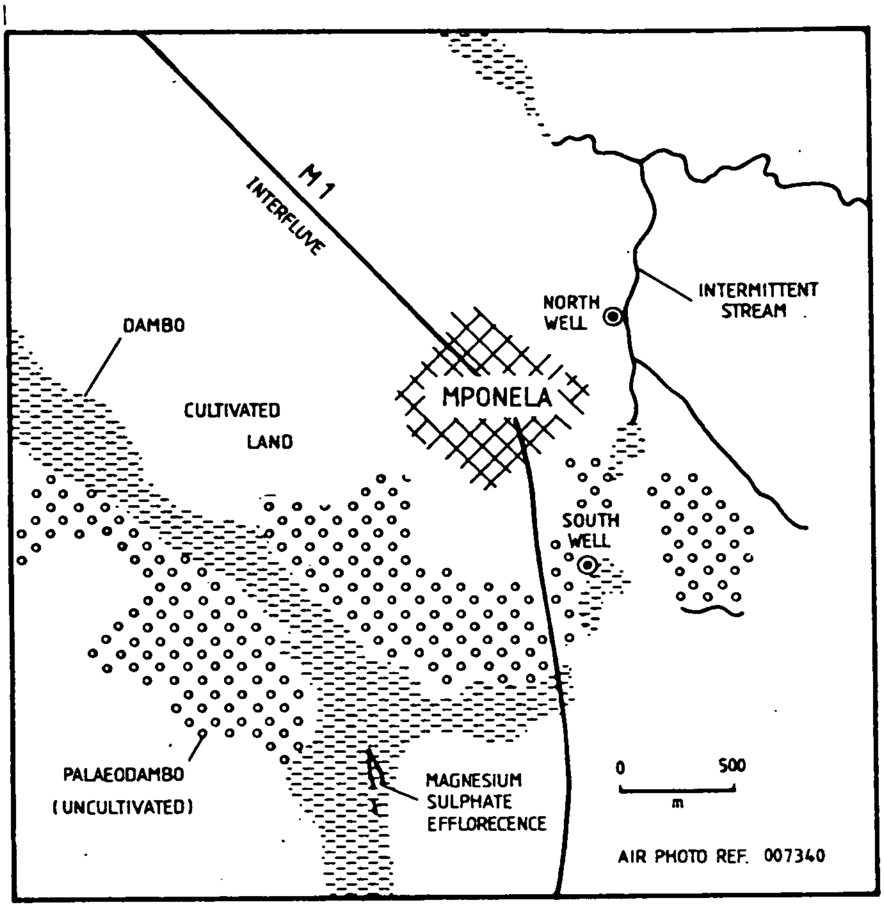


Figure 8.19 The sites of the Mponela collector wells, Malawi. For explanation see text.

sample within an endless list of possible variations, but a sample with limited possibilities, pertaining to its place in the history of erosion surfaces.

For example, in Malawi, it has been established that on the African Surface, weathering is deep and collector well site selection involves finding appropriately shallow bedrock. The post-incision modifications of the surface, dambo insetting and profile thinning, have reduced the site selection options, as shown in Figure 8.17. The dambo profiles themselves have the greatest likelihood of being too thin (though with locally deeper pockets) and there is the problem of access in the wet season. The interfluves have profiles which have the greatest likelihood of being too thick; in addition the water level is likely to be too low. The best options, on geomorphological grounds, are afforded in dambo-peripheral areas, where the depth of weathering is likely to be intermediate and the water-table appropriately high. However, these are the traditional village sites and it is on the interfluves, at the junctions of the roads which follow the interfluves, that new and expanding townships, which require collector wells, occur. Terrain analysis has provided an understanding of how these may be reconciled.

As indicated earlier, it has been established that the African Surface here comprises a flight of small surfaces, surviving as 'steps' on the interfluves. The dambos, although to some extent stepped in response to this, cut across the surfaces (Figure 8.18a). Thus, as illustrated by the schematic cross sections of interfluves and dambos (Figure 8.18b), towards the upper end of each small landsurface facet, the collector well options for interfluve sites improve, as the dambos and interfluves become closer. Thus, a community at A has slope-bottom options, but the water would have to be pumped up to the settlement. At B, the pumping could be reduced by choosing a slope bottom site higher up along the margin of the dambo. At C, a more immediately local site is likely to be found. In many cases the C-class sites have dambos which cross the divides. Mponela is an example of an interfluve site which has the benefit of a C-class location, with a locally high, dambo-associated water-table on the southeast ('upslope') side of the local erosion surface. Thus, preferable sites for Mponela should occur on the southeast side of the township.

More detailed geomorphology, from the air photos and in the field, allows site selection to become more finely tuned. The salient features of the site are sketched in Figure 8.19. On the southwest side, lies a fairly wide dambo, flanked by a pale toned band with darker toned circles. These dark circles are old Macrotermes mounds, now largely dead and flattened. The formerly ubiquitous mounds have been ploughed out and obliterated where the soils are richer and have been long cultivated. Hence the identification of dark circles, former mounds (in some cases still active), indicates low priority cultivation areas, heavily leached palaeodambo sands, poor in nutrients. The valley on the northeast side presents a striking contrast. It is narrow and contains a seasonal stream. The insetting of dambos is accompanied by narrowing and eventually the dambos pinch out, to be replaced by streams. This replacement is associated with shallow bedrock. Hence, these contrasting valleys on the southwest and northeast side of the Mponela interfluve, indicate shallower bedrock on the northeast side than on the southwest (Figure 8.20). Since the height difference is slight, this in turn implies that less readily weathered rocks occur on the northeast side, i.e. basic gneiss facies as opposed to micaceous or fractured quartzo-feldspatic. Thus, with a choice between southwest and northeast, the latter looks distinctly more promising. In addition, saline water occurs in the dambo on the southeast side; magnesium sulphate efflorescences (white) show clearly on the air photos. To the south of the town, the western dambo creeps across the divide; (purists might claim that the short duration of flooding means it is not a 'real' dambo, but the flooding is long enough to ensure that the vegetation is herbaceous). As the feature links with the northeastern valley it becomes 'broken up', strongly suggestive of deeper pockets of regolith separated by shallow bedrock. Some further information can be gleaned from the geomorphology. Research of the Basement Aquifer Project has produced the tentative generalisation that dambos may originally have had a preferred location over areas of fractured quartzo-feldspathic and micaceous rocks and that when insetting occurs, this is favoured over the former rock type, leaving the micaceous in dambo-peripheral sites. The wide expanse of dambo-peripheral sands to the southeast of the township might therefore be taken to indicate micaceous bedrock.

In short, given a framework of the broader geomorphology (erosion surfaces and their relationship with dambos) the local geomorphology can provide the site exploration program with a hypothetical basis of expectations, which can then be examined with geophysics and exploratory drilling. This can either reduce the number of holes to be drilled, or allow them to focus more closely on the better options. It can also assist with interpretation of the results, so that the ultimate choice of site provides optimal yield opportunities, as well as assisting with the choice of directions and angles of laterals.

In the case of the siting of the three collector wells variously associated with the African Surface in Zimbabwe, their location in relation to the local erosion surfaces has already been outlined (Figures 8.15 and 8.16).

The site of Mukumba was previously described (Figure 8.4) in terms of the very difficult configuration of the basal surface of weathering in the area. The geomorphological context, near the periphery of a flat area of the upper component of the African Surface carries clear implications. In interfluve sites, the weathering will be thickest but the water-table low. A hand dug well on an adjacent interfluve, to the south, which found a local pocket of regolith some 30 m deep, was still reported to go dry in a bad year. Significant dambo insetting, associated with the generally thinner regolith, as evidenced by bouldery outcrops, renders slope-bottom (dambo-peripheral) situations also unattractive, with the likelihood that the water level may commonly be below the irregular basal surface of weathering in the dry season (as indeed became evident from inspection of local hand-dug wells). On the dambo floor itself, options deteriorate rapidly in a

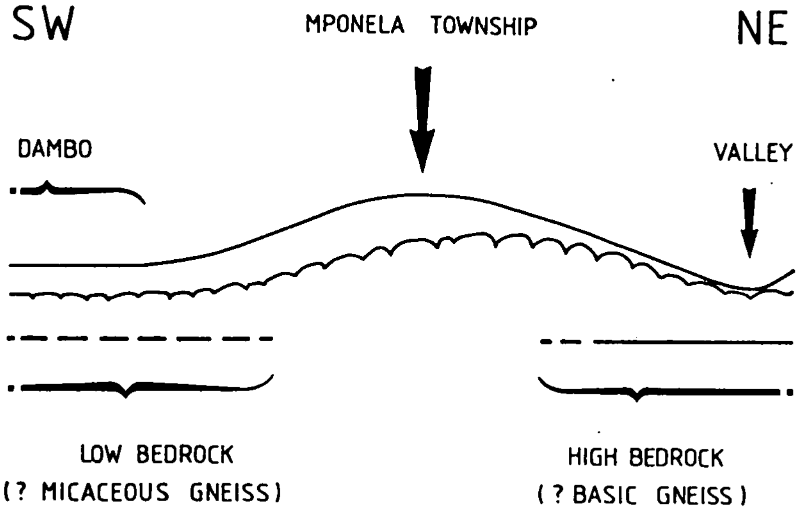


Figure 8.20 Variations in depth to bedrock indicated by the geomorphology in the Mponela area.

downstream direction, as the dambo insetting increases and the regolith thins. In short, the options at Mukumba are poor and reduced to the upper part of the floor of the dambo and possibly the palaeodambo which crosses the divide to the south, where 'msasa', the 'water bush' indicates shallow groundwater. The low water-table in interfluve profiles, frequent slope-bottom outcrops of bedrock and the thinning of regolith in a down-dambo direction, are all closely related to the position of the site, at the lower extremity of an area of erosion surface above a 'break' zone.

St Nicholas lies within the 'break' zone between the upper and lower components of the African Surface (Figures 8.15 and 8.16). In such situations, the relative relief on the basal surface of weathering increases and air photo expression of geological features becomes a likelihood, in contrast with area of well developed African Surface, where air photos can be singularly uninformative as regards geology. Hence, with this knowledge of the location of the site, within the context of the erosion surfaces, it is to be expected that a careful study of the air photos would be informative, as indeed it was, allowing the identification of two lineaments (Wright et al. 1987). An extension of one of them reached the head of the dambo below the school, but had neither on-the-ground nor clear air photo expression there. It was deduced both from the air photos and field reconnaissance, where the feature was well expressed (some kilometres further to the north), to be a granitic 'high' on the basal surface of weathering. From its alignment with the head of the dambo below the school (Figure 8.26) it could be surmised that in the vicinity of the school it constitutes enough of a barrier to encourage deeper weathering on the upslope side, particularly if micaceous rocks occur. A high water-table would be expected.

Although an extensive area, traversing the 'high' and both the upslope and dambo approaches to it, was explored and drilled, the ultimate choice of site lay upslope from the 'high'. Thus, the chosen site was in an area generally indicated by the geomorphology as favourable, and in which both geophysical and borehole exploration gave good indications concerning regolith thickness and water levels. Details of the profile are provided later.

St Liuba was, quite predictably on geomorphological grounds, a very difficult site, situated in the major break zone leading down to the Post African Surface (Figures 8.15 and 8.16). Relative relief on the basal surface of weathering is high, and here expressed as a local horse-shoe shaped lowland, with variable depth of regolith, 'suspended' above actively incising drainage, and set within an amphitheatre of high granitic outcrops (Figure 8.21). The problem of corestones in such aggressively leached sites has already been indicated (Figure 8.8). A further problem relates to the small catchment. Although deep weathering can be found in the footslope area of such outcrops, water-table oscillation may be inappropriately high, the profile filling up rapidly with water shed from the bergs in the wet season and draining out in the dry season, if the bergs themselves have little storage potential which could allow continuous infeed of water to the lowland area in the dry season. In this case the granites are fairly well fractured. A patchy, but quite active seepage zone occurs at their boundary with

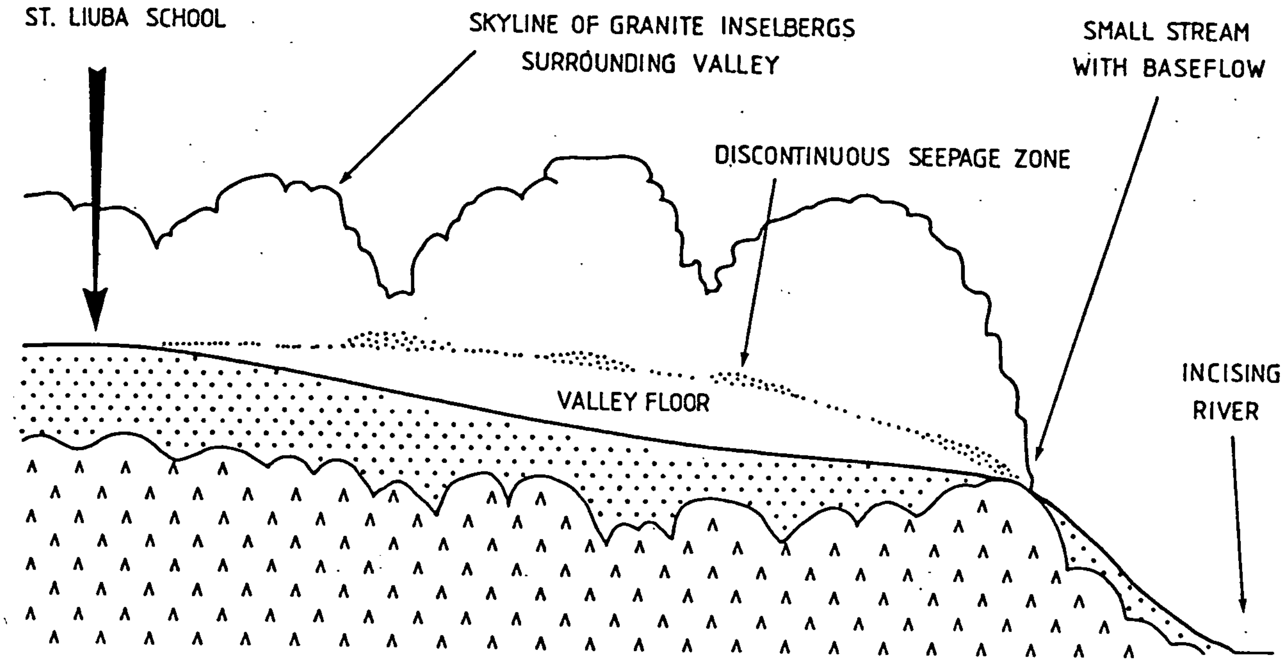


Figure 8.21 The geomorphological context of St Liuba collector well. For explanation see text.

the flat valley floor (irrigating good vegetable gardens even at the end of the dry season). Also, a small stream with modest baseflow occurs at the lip of the valley, baseflow which is maintained through the dry season if the wet season is good, but fails following a bad wet season. In short, although clearly an area with considerable problems, the local situation was not totally without possibilities.

The problems facing site selection become progressively greater in drier areas, where regolith is less well developed and also in Post-African areas where time has been too short for extensive regolith development. In the Post-African area of southern Zimbabwe, these factors combine to make collector well site selection distinctly challenging. At the time of writing, no collector wells had been installed in Post-African areas, but some study of the weathering environment, pertaining to the Regolith Project, has provided preliminary observations relevant to the problems. In extensive, flat areas, basins with appropriate depth of weathering are likely to be saline. This problem is in addition to poor regolith permeability expected in basin contexts as a result of weak weathering of micas (to hydrobiotite) and the innate low permeability of saprolite developed from gneissic facies rich in orientated biotites. The salinity problem is probably best avoided in two geomorphic contents: near zones of incising streams (which improve groundwater circulation) or where the immediate hinterland is high and provides a head for more vigorous flushing of the lowland profiles. The problem with the first of these is that the water-table is likely to be too low. In the latter situation, as already discussed in the case of St Luiba, deeper zones of weathering at the foot of granitic inselbergs are likely to suffer from very great seasonal water-table oscillations. Clearly the nature of the hilly outcrop is important. South of Masvingo these range from very bald, smooth, steep inselbergs of granite with virtually no storage potential, to the much less steep and broken greenstone ridges, likely to offer considerable storage for the adjacent lowland areas. The granitic massif at Chibi introduces another element in this question of upland storage for lowland sites. The massif is sufficiently large for areas of regolith and 'suspended' dambos to survive on the summit. These feed directly to the lowland area via a well defined system of lineaments. The discharge sites in footslope areas have high water levels and are deeply weathered. Similarly in areas close to the margins of surviving areas of African Surface, slope bottom situations are fed from the high level profiles. Two collector wells are planned (German funding), which take advantage of these site factors and it is hoped that study of their profiles will be made, so that understanding of their performance will contribute to providing further guidelines for collector well location in such difficult terrain.

8.4 The Mineralogy of the Collector Well Profiles

The context of the two collector wells at Mponela has already been described (Figure 8.19). The south well (well A) was sited in the palaeodambo area on the north side of the weak dambo which crosses the divide, south of the township. Mineral assemblages of the profiles are shown in Figure 8.22. (The lower part of the south well profile is from an adjacent exploration borehole, MP3.) The contrasts are striking and comply well with the indications from the geomorphology. The south site has a very sandy, kaolinitic surface layer some 2 m deep (palaeodambo sand), with goethitic, slope-bottom laterite. Primary minerals in the saprolite are quartz, plagioclase, K-feldspars and mica, the upper parts of which (3-8 m) are very micaceous, with only doubtful traces of quartz. The mineralogy of the deeper part of the profile, from the borehole, is very informative. Conversion of mica to kaolinite is direct, by-passing hydrobiotite and vermiculite. (The parent mineral of the kaolinite is deduced to be mica rather than plagioclase, as orthoclase and plagioclase co-exist up to about 6 m, above which the more vulnerable plagioclase disappears.) This direct kaolinisation indicates very aggressive leaching of the saprolite below the water-table. As indicated earlier, kaolinisation is normally claimed to be associated with "superior alteration" above the water-table and here it occurs some 30 m below it. This also carries the strong implication that the base of the regolith is a good deal deeper than 34 m; the lower, 2:1 clay mineral zone (hydrobiotite and vermiculite) has not even been reached. Had the mineralogy been made available immediately following the drilling of MP3, it could have contributed to the assessment of the site. The results of the geophysics were rather ambiguous. Although the 34 m hole did not reach bedrock, in combination with the geophysics it was anticipated that steep angle laterals (40 degrees) would intercept the boundary. In the event, they did not; as indicated by the mineralogy, weathering is very deep here.

In the upper part of the saprolite, the extremely micaceous part, there appears to be something of an inversion of the normal weathering progression, with abundant hydrobiotite and vermiculite (which were not identified in deeper horizons). It is difficult, therefore, to avoid the conclusion that this profile is not the result of simple leaching from the surface downwards. A split-level water system is indicated, with shallow interflow leaching the palaeodambo material (and introducing Fe), separated (? by the highly micaceous shallow saprolite and clay beneath the sand) from a deeply circulating system, which in this site is particularly effective because of the head provided by the upland to the south. The weathering inversion strongly suggests that upward movement through the micaceous clayey material is negligible. The clay zone appears, in effect, to be by-passed by the main water movement, which is presumably diverted laterally within the saprolite, towards the western dambo and the eastern valley (Figure 8.23). This mineralogy would be consistent with modest entry of water (iron rich, especially in the dry season) to the well because the base of the well is high above the potentially very tight hydrobiotite-bearing basal zone.

At the northern site the parent rock is dominated by amphiboles and plagioclase. At about 5 m, secondary clay (vermiculite) is beginning to be detected. The saprolite layer is indicated to be from 2-5 m, with sandy, kaolinitic colluvium above this. The predominant profile component in the well is, on mineralogical grounds, brecciated saprock (hornblende gneiss). Digging only

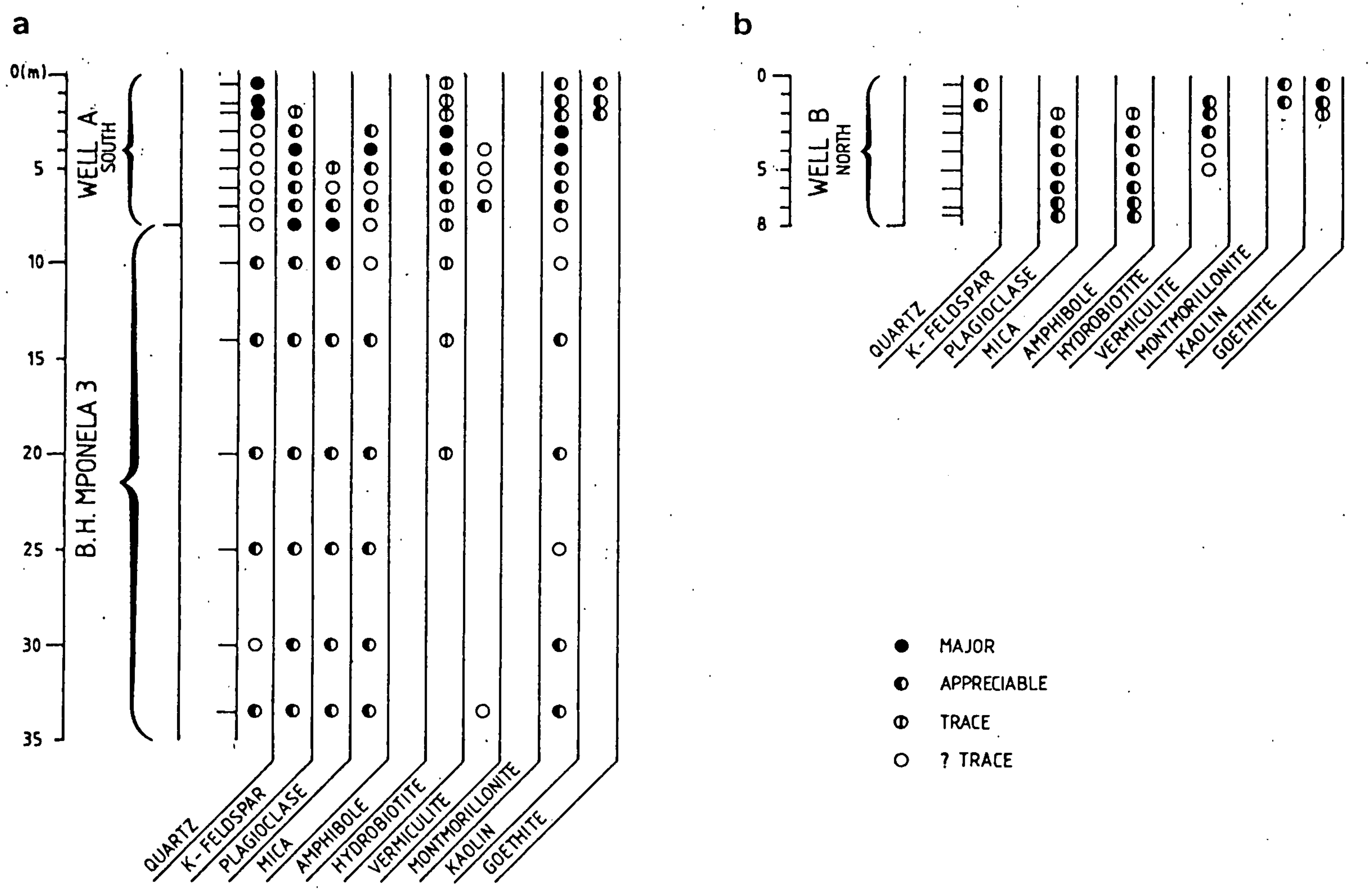


Figure 8.22 The mineralogy of the Mponela collector well profiles. For explanation see text.

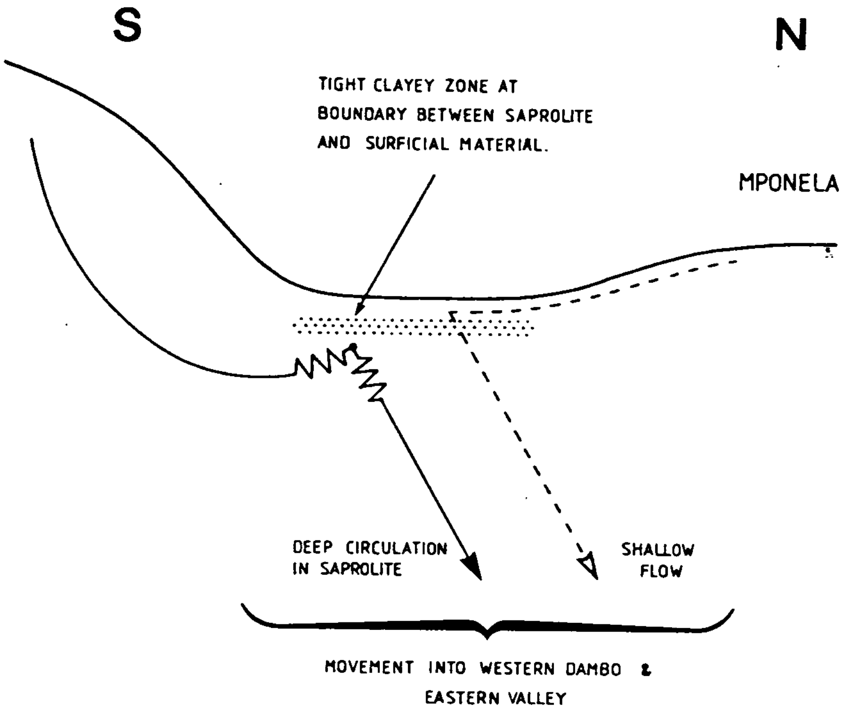


Figure 8.23 Schematic representation of water movements as suggested by the mineralogy of Mponela South collector well. For explanation see text.

became difficult (jack hammer) at about 7 or 8 metres, indicating that the disaggregation to form saprolite can be achieved, as in the 5-7 metre zone, with mineral alteration so slight as to be beyond XRD detection (a thin zone of weathering at the grain contacts, constituting less than about 5% of the material).

Well performance is discussed more fully elsewhere. The south well, beyond question successful, was nevertheless significantly poorer than the north well and from the mineralogy it is very clear why. It is encouraging, for future site exploration, that the contrasts could have been anticipated from the geomorphology. Terrain analyses can therefore contribute to collector well siting, but its cost-effectiveness clearly depends on aspirations. If the lower yield achieved by the south well is sufficient for the local requirements, then such analyses are irrelevant because the south well demonstrates clearly that even in profiles which are far from ideal (particularly in the failure to reach brecciated and saprock zones either by well or laterals) a successful yield can be achieved. If, on the other hand, well yields aspire to the higher end of the range exemplified by these two contrasting sites, then quite clearly site investigation must utilise all the exploration techniques available, including geomorphology and associated study of exploration borehole mineralogy.

The three collector wells, variously associated with the African Surface in Zimbabwe, also exposed informatively contrasting profiles. Fortuitously, they were placed in sites of sufficient geomorphic contrast to allow assessment of the effects of such contrast on profile and mineral assemblage development, and associated well performance.

8.4.1 Mukumba

The regional and local geomorphological contexts of the well site have already been outlined (Figures 8.4 and 8.16), the site being a relative dry shoulder above a pan on the floor of the dambo (Figure 8.24) on, but near the lower limit of, the upper component of the African Surface. Profile characteristics are shown in Figure 8.25. About 1.5 m of sandy clay overlies the saprolite. Green colouration extends up the profile to about 2-4 m below the surface, which is consistent with 'inferior alteration' under saturated conditions. Although the parent rocks are predominantly quartzo-feldspathic granite gneiss, dark zones poor in quartz and rich in amphiboles also occur. In the parent rock, plagioclase exceeds K-feldspars and since the former is more vulnerable to weathering than the latter, as long as plagioclase exceeds K-feldspar it can be deduced that there is little or no feldspar weathering. On this basis, it appears that the feldspars survive throughout the weathering profile, the plagioclase only yielding to leaching very near the surface. Amphiboles, rather more vulnerable, disappear at about 4 m. Hydrobiotite, the first stage of mica weathering, preceding vermiculite formation, survives together with vermiculite right up to about 4 m from the surface. Above that level it no longer occurs and even the vermiculite is rapidly replaced by kaolinite. Clearly, the zone of 'superior alteration' is very narrow indeed, restricted to the saprolite directly below

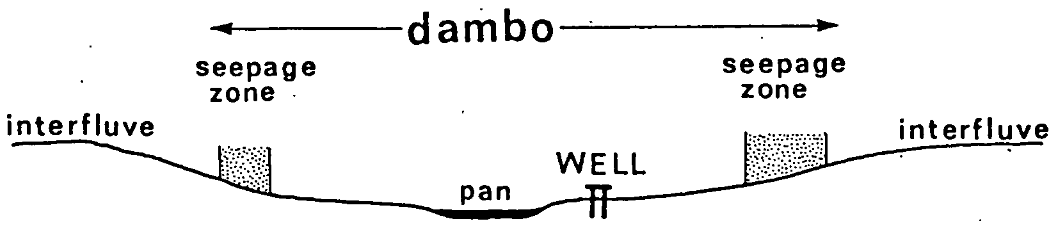


Figure 8.24 Transect of the site of the Mukumba collector well.

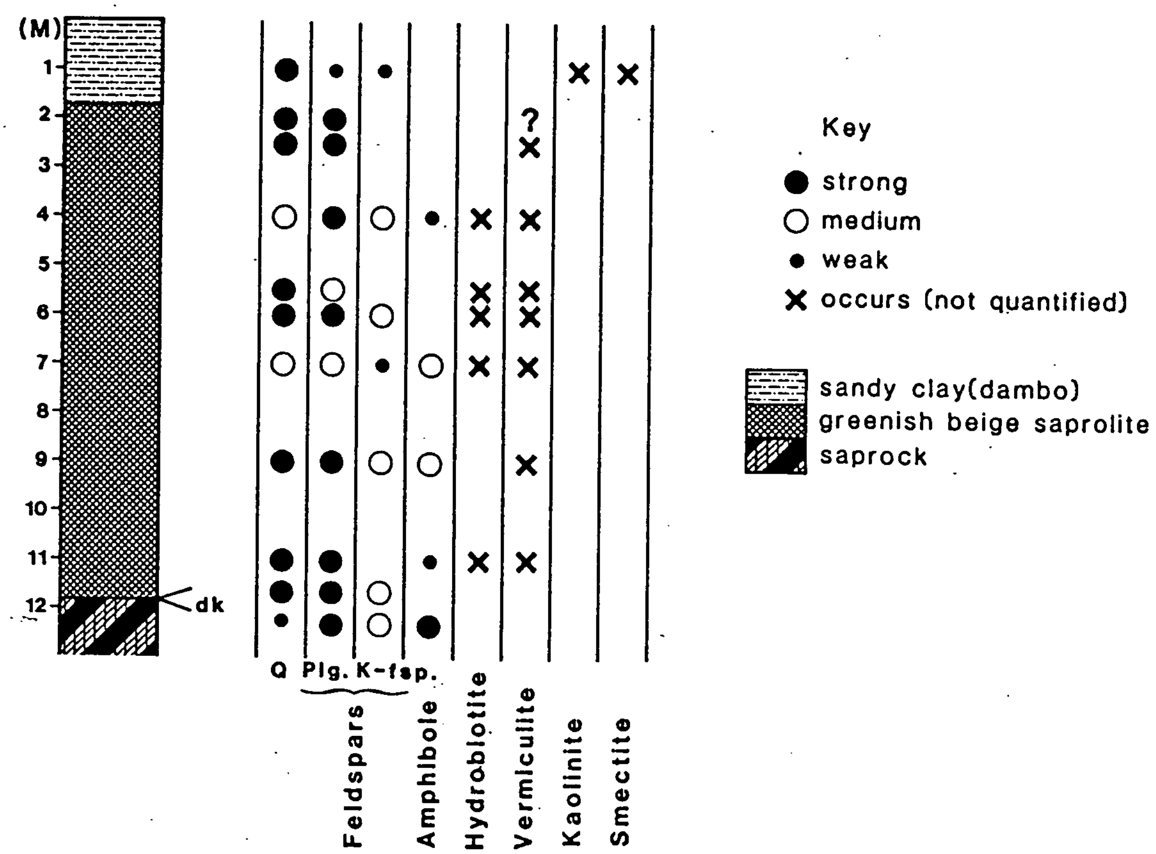


Figure 8.25 Profile characteristics and mineralogy of the Mukumba collector well. For explanation see text.

the surficial dambo clay, with its neoformed smectite. In general, this profile represents quite deep but very poorly advanced weathering. The rock is converted to saprolite essentially by the alteration of only one mineral, the most vulnerable mineral, biotite mica. As such, the proportion of clay is relatively small, much smaller than would be the case were the feldspars also converted to secondary clay minerals. The point has already been made that in the case of saprolite, the generalisation (from sedimentary materials) that permeability is directly related to the proportion of clay need not apply. The nature of the clay is also important. Here seems to be a case in point. Prior to drilling the laterals, the well had a very low yield indeed, because of the swelling habit of hydrobiotite. It says much for collector wells in general that an appropriately high yield was finally achieved, with the laterals.

8.4.2 St Nicholas

The situation of the well, in the small break zone between the upper and lower components of the African Surface, has already been described; salient features of the site are shown in Figure 8.26. The profile characteristics are shown in Figure 8.27. Samples were only available below 5.5 m, all in saprolite. This is predominated by orange/beige colouration. At about 8 m greenish patches begin to occur, but they are heavily invaded by orange/beige bands and even the predominantly green saprolite at the base of the profile has orange/beige bands and patches. This colouration suggests more aggressive leaching than at Mukumba. 'Superior alteration' is actively invading 'inferior'. Oxygen-bearing water is penetrating the former horizons of green saprolite, oxidising the iron minerals. Again, the mineralogy is informative. The lesser quartz signals, as compared with Mukumba, reflects the more micaceous nature of the parent rock, as indeed is evident in saprolite hand specimens. As in most of the Mukumba profile, the feldspars appear not to be affected by weathering. The absence of hydrobiotite, coupled with the co-existence of mica and vermiculite, indicate direct conversion of mica to vermiculite, by-passing the hydrobiotite stage. This is consistent with the more aggressive leaching, already indicated by the colouration of the saprolite, and this accords with the geomorphological context of the well, situated in the break zone between the two African Surface components.

Because the hydrobiotite stage is not there, even though the rock is more micaceous than at Mukumba, better primary permeability of the saprolite could be expected. A modest yield was achieved from the collector well, even before the drilling of the laterals.

Comparison of these two profiles serves to illustrate the point that the leaching history is an important factor in the permeability of the saprolite. In situations in which the leaching history is the same, a rock which is more micaceous and poorer in quartz would yield tighter saprolite than a rock which is richer in quartz. Here the rock which is poorer in quartz yields the more permeable saprolite because it is more aggressively leached, this influencing the nature of the micaceous mineral weathering progression.

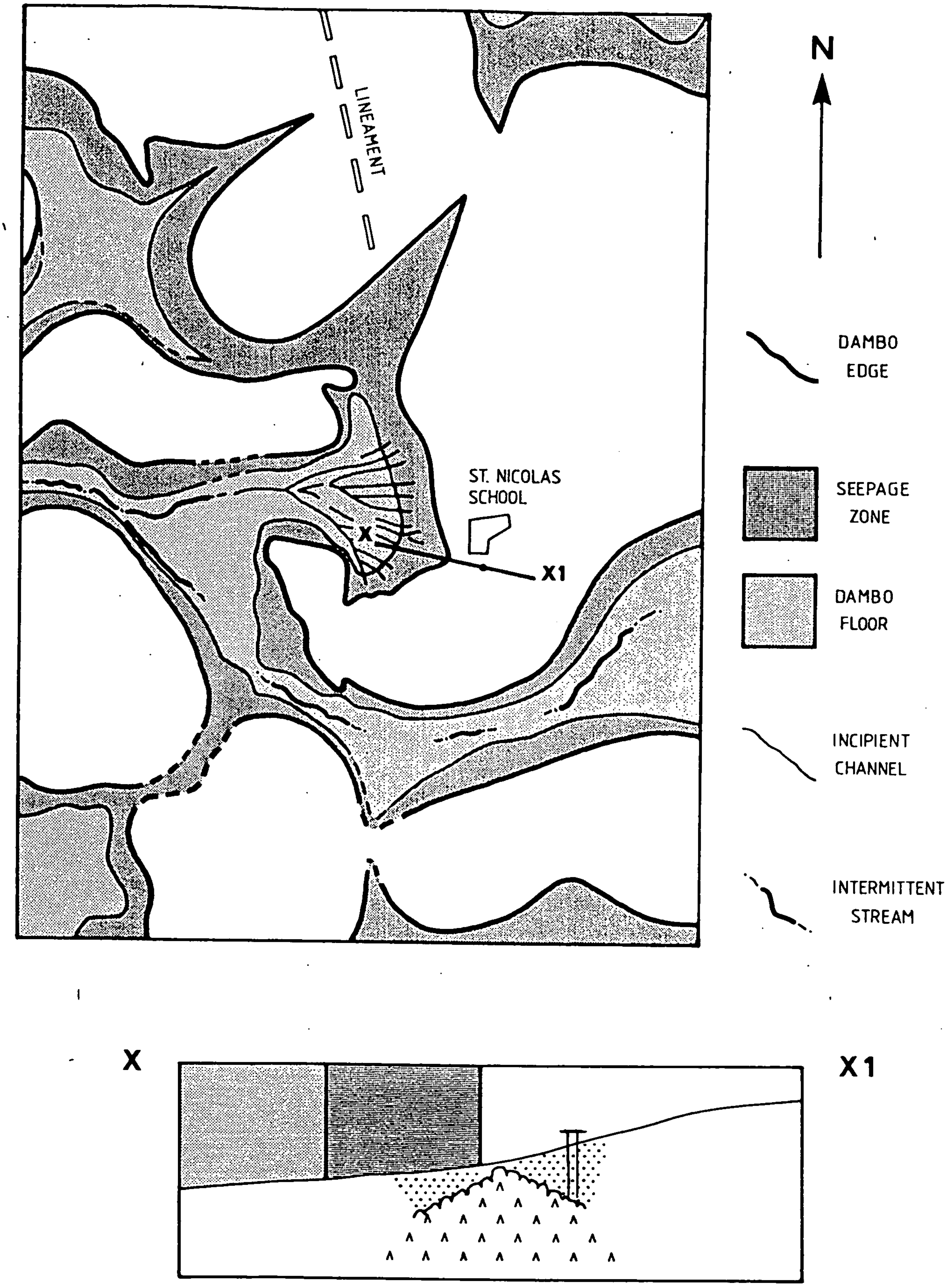


Figure 8.26 The site of the St Nicholas collector well.

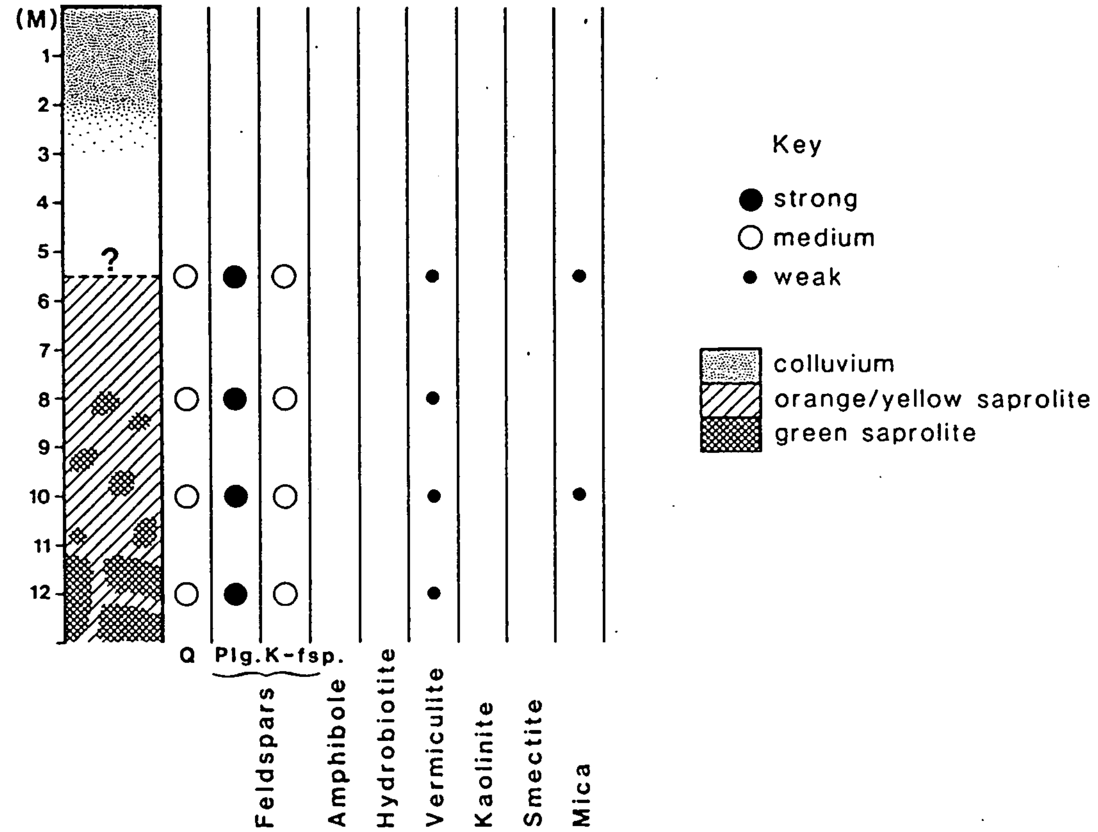


Figure 8.27 Profile characteristics and mineralogy of the St Nicholas collector well. For explanation see text.

8.4.3 St Liuba

The site of the well, within a horseshoe-shaped valley surrounded by rocky outcrops, in the major break zone down to the Post-African, has already been discussed. The profile characteristics are shown in Figure 8.28. Again, the colour of the saprolite is initially informative. Orange/beige colours penetrate right to the bottom of the profile. Green colouration begins at about 7 m depth, taking the form of discrete 'eggs' surrounded by oxidised saprolite. Rather like core-stones of fresh rock which survive in saprolite, these small green cores of 'inferior' saprolite survive within horizons of 'superior' saprolite. Even at the base of the profile, the predominantly green saprolite is heavily invaded by oxidised material. In total, the colouration implies even more aggressive leaching than at St Nicolas and very rapid invasion of the horizons of 'inferior' by 'superior' weathering.

Two sets of mineralogical data are shown below 6.5 m because, although this area is mapped as I-granite, excavation of the well exposed rather different materials on each side, below that depth. At about 4 m the proportion of K-feldspars and plagioclase change such as to indicate the leaching of plagioclase above this level. As at St Nicholas, the absence of hydrobiotite and the co-existence of mica and vermiculite indicate direct alteration, by-passing the hydrobiotite stage. The conversion of vermiculite to kaolinite, 'superior alteration', occurs deep in the profile, at 6 m and possibly even at 10 m, that is, below the dry season water-table (ca. 2-3 m). Thus, the mineralogy reflects the more aggressive leaching of this profile, as already indicated by the geomorphological context and saprolite colouration.

Of the three profiles, it could be expected that this one enjoys the highest permeability. When the well was dug, ingress of water was very rapid, the source being identified as a large hole in the saprolite at the side of the well. Nevertheless, although adequate yield was achieved, the initial very high yield was not maintained and this probably relates to the limited storage in a very aggressive but generally constricted leaching situation.

These three well sites provide a progression, offering insight into the effects of incision and rejuvenated leaching. They range from slow, but sustained yield associated with the flat, upper component of the African Surface, to initially fast, but less well sustained yield in the break zone to the Post-African Surface, where weathering is only locally developed, between major outcrops. The profile colouration, the mineral assemblages and the well performances are consistent with the geomorphological contexts, providing optimism that terrain analysis can provide a useful exploration tool, allowing informative anticipation of the hydrogeological potential of individual sites within the context of the major erosion surfaces.

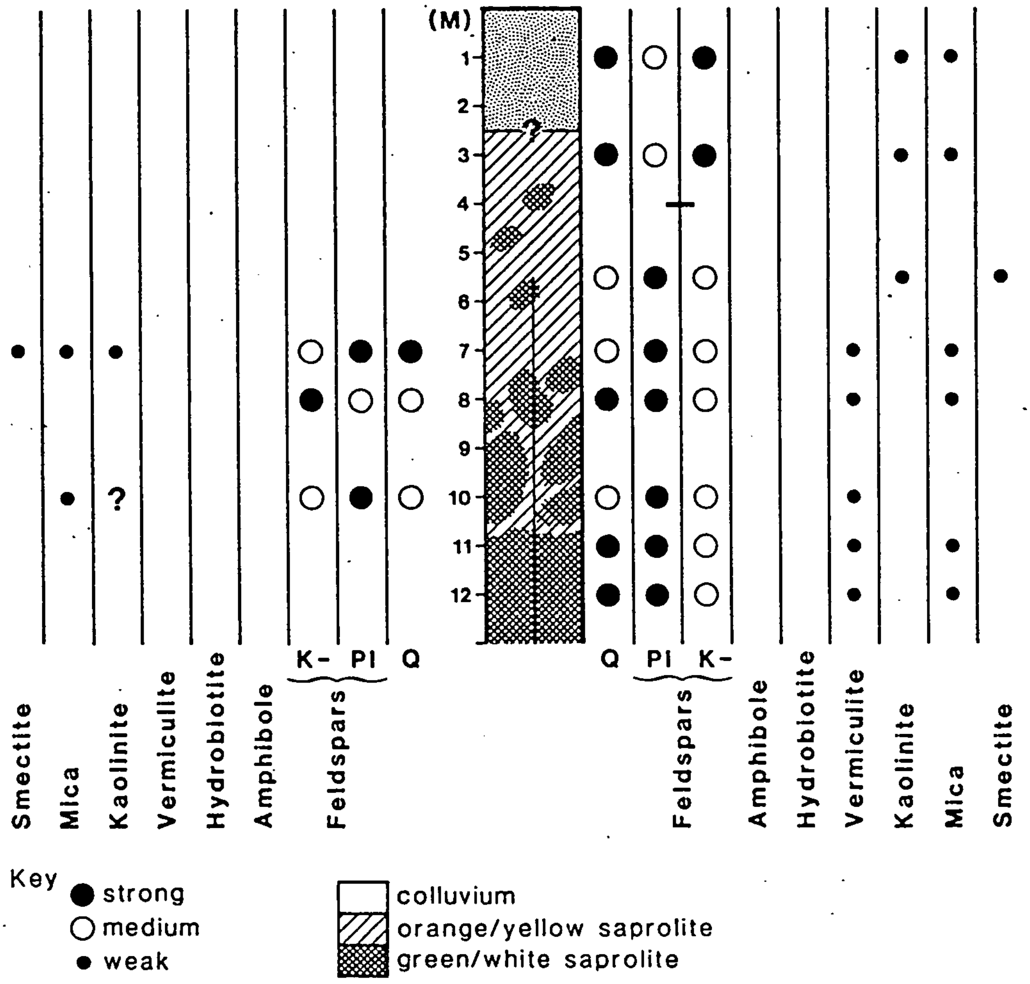


Figure 8.28 Profile characteristics and mineralogy of the St Liuba collector well. For explanation see text.

8.5 Conclusions and Recommendations

This preliminary study of profile characteristics associated with profiles developed from a variety of rock types and in distinctly defined geomorphological contexts has illustrated the way that geology and geomorphology interplay to yield profiles with differing hydrogeological potential. Although the study was limited, it has provided some tentative answers, which are consistent with the principles of weathering, and which can be of value to collector well siting where yield maximisation is important. Nevertheless, it is only a beginning; ongoing research is needed in order to explore further criteria which apply in areas with different geology and leaching history. In any earth science research program, the acquisition of samples is by far the most costly part of the program. Collector well development programs therefore go more than half way to catering for the cost of such research. They provide unprecedented opportunities for regolith research and it would be a sad loss, were these missed.

9. COLLECTOR WELL CONSTRUCTION

9.1 Summary

The first four collector wells in Zimbabwe were of caisson type and constructed with a 3 m diameter central shaft. The radials could be drilled in horizontal positions only. Full details of constructional methods and materials including photographs are given in Wright et al., March 1985 (op. cit.).

The second set of wells (3) in Zimbabwe and one of the wells in Malawi were also of caisson type but with a 2 m central shaft. Material requirements for a 2 m well of caisson type are given in Annex 1 to this section and includes notes on construction.

The collector wells at Wenimbi (Zimbabwe) and the second collector well on Malawi have been constructed with emplaced concrete segments, bolted together (Plates 10.4 and 10.5). Details of the current well constructions in Gutu Province southern Zimbabwe were not available at the time of visiting but it is planned that attempts will be made to drill the central shaft using a large capacity drill rig with reverse circulation water flush. A 2 m drill bit has been fabricated in Zimbabwe. The well, if successful, would be lined with galvanised steel sheeting, bolted together. Material of the desired thickness is not fabricated in Zimbabwe and this could present problems. Fibre glass segments would also be suitable but the costs would be high.

9.2 Caisson Wells

The earliest collector wells were required to have a minimum internal diameter of 3 m in order to accommodate the specially designed drilling rig to operate horizontally at the bottom of the wells.

In manuals on dug well construction it is advised that any work of more than 1.5 m in diameter should not be contemplated without first seeking specialist engineering advice. As a caissoning method of well sinking was considered, using perforated brickwork (i.e. conventional bricks with uncemented gaps between) based on a reinforced cutting ring, the local chief hydrological engineer in the Ministry of Water Resources and Development, Zimbabwe, was consulted and a design produced with all details of concrete shoe reinforcement construction and reinforcement of subsequent brickwork.

The logistics of construction demanded that two caissons be built simultaneously on neighbouring sites utilising only one team of well sinkers. The caissons were to be built up one metre at a time, then undercut and sunk; another metre built, sunk and so on. Thus while the mortar was setting on a newly-completed 1 m rise at the first well, the second caisson could be lowered, by which time the first caisson should be ready for sinking. Hence, schedules were prepared for the building of the wells in pairs.

In practice, the sinking of the caissons proceeded at easily one metre per week per well in the most homogeneous aquifer (weathered epidiorites at Hatcliffe, Harare). Elsewhere, the granite regolith was found to contain random fresh core stones, some of several metres of thickness, where resort had to be made to rock drills. 'Mud rushes' or quicksand conditions occasionally occurred below the water table where liquid mud suddenly poured in under the cutting shoe (usually at one side) because of the pressure differential in the dewatered shaft. While the core stones slowed construction, the mud rushes also necessitated more material being removed from the shaft than the actual volume of the shaft displaced which resulted in a void forming outside the caisson wall and very often the caisson falling askew.

Since it is not easy to continue laying bricks at the angled line of a skewed caisson, there is a tendency to continue upwards vertically with a result that the caisson is difficult to straighten and more inclined to stick.

At Mponela South, however, the bricks made available were comparatively poorly fired and the angular displacement of the caisson resulted in vertical cracks developing in the brickwork. Generally the problems were resolved by contriving to land such skewed caissons on weathered rock when the well could safely be completed by digging open hole to total depth. In the Malawi case referred to earlier; the caisson was lodged by steel H-girders being driven radially under the cutting shoe, then emplacing a concrete 'foot' to stabilise before completing down to hard rock by means of concrete segments of the type already being used in Zimbabwe.

9.3 Emplaced Concrete Segments

An emplaced method of construction was devised whereby a ring of 8 curved reinforced concrete segments, 0.5 m high, and bolted together, are used as well lining. The planned procedure of using these moulds was to stack successive rings in layers with joint-over-centre alternating construction in the manner of conventional brickbuilding. On initial use it was found after the blocks had been cast that the bolt holes in the upper and lower edges would not register to allow this configuration so that the rings had to be laid with the blocks vertically in line. The completed lining would still be amply secure as each ring of blocks was butted and bolted together below the water table.

Well construction with these blocks was started by digging out a shaft of the requisite diameter to within half a metre of the water table. A ring of blocks was laid at the bottom, bolted together and grouted, the next layer built on top of this, and so on until the ground surface was reached and a reinforced concrete well apron built and tied into the topmost blocks. The next stage was to excavate and emplace one block at a time beneath the existing structure. The advantages of this method are that a vertical shaft results and any mud rush problems are more than easily controlled than when caissoning. Moreover, once the blocks have been prefabricated well-sinking is a more rapid and continuous process.

To date, two concrete block wells have been completed successfully in Zimbabwe to depths hitherto inaccessible by the caissoning method.

9.4 Annex 1

SCHEDULE OF MATERIALS FOR CONSTRUCTION OF TWO 2-METRE DIAMETER WELLS OF 16 m DEPTH

20-gauge steel strip	0.60 m wide, 8.30 m long	
20-gauge steel strip	0.30 m wide, 6.50 m long	
8 mm round steel reinforcing rod (20 x 1.45 m) (x2)		58 m
12 mm round steel reinforcing rod totalling 120 m (4 x 8.2 m; 4 x 7.0 m = 60.8 m for cage, 32 x 1.2 m long stakes 38.4 32 x 0.6 m short stakes 19.2 + mould tool rod)		120 m
16 mm round steel reinforcing rod - 96 steps @ 1 m each		96 m
16-gauge galvanised iron wire - 1 roll		
8-gauge galvanised iron wire - 4544 m		
6 mm square twist high tensile steel reinforcing rod (8 x 0.7 m; 6 x 1.1 m; 6 x 1.6 m; remainder 20 m)		totalling 352 m
21,700 common building bricks		
Cement:	Cutting rings 30 sacks 34 m brickwork 5.5/m 187 Apron say 83 totalling	300 sacks
Sand:	Cutting ring say 0.8 m^3 x2 = 1.6 m^3 34 m brickwork 0.2 m^3/m 6.9 m^3 Aprons say 8.6 m^3 totalling	17 m^3
Stone	Cutting rings: 2.0 m^3 Gravel pack and bottom: 6 m^3 Aprons: 16.0 m^3 (Note stone grade $\frac{1}{4}$-$\frac{1}{2}$-inch size, not less than $\frac{1}{4}$-inch)	24 m^3
Timber	6 scaffold planks 4 m long per well if dug simultaneously. 30 mm wide timber lathe to make up frame for moulding mortar blocks length of timber according to thickness thereof. 1 straight-edge plank more than 2.5 m long Sufficient timber 0.2 and 0.25 m wide to make two boxes (bottomless gauge boxes) of capacity = 3:4, the smaller for cement, the larger for sand and stone. Lifting rails, parallel along the top and protruding like wheelbarrow handles helpful.	
8 m hessian, about 1.0 m wide		
5 kg multi-purpose grease		
1 litre black paint		

PREFABRICATIONS:

Make up re-rod case for cutting ring
* Make up windlass, mould tool, wooden mortar block mould, gauge boxes
Mould molier blocks with tying wire inserts

Cut and bend 6 mm square twist re-rod
Cut long and short. 12 mm re-rod stakes
Cut 16 mm re-rod into 1.0 m letting bend and hot dip galvanised step hoops.

* Remember OD of shoe, may be in excess of 3 m if rainwash erodes sides.

Schedule of implements required for construction of 2 m diameter wells

1	slump cone for concrete mix
2	picks - long handle
2	picks - short handle
2	spades
2	shovels
2	mason's chisels 9-in
2	mason's hammers
2	iron floats
2	wooden floats
2	trowels
1	48-inch spirit level
1	36-inch spirit level
1	heavy-duty wire cutter (?bolt cutter)
1	25 mm paintbrush
3	builder's buckets
1	pliers for 16-gauge wire
	Wheelbarrow

Made-up items: Windlass with large bucket OR gantry with builder's buckets
Mould-shaping tool for bevel on cutting ring
Wooden mould box for mortar blocks
Wooden gauge boxes for sand, cement and stone

Below-water-table work: 1 Ingersoll-Rand p.35 sump pump operated through air hoses (1 delivery, 1 exhaust, 1 discharge) powered by 100 psi 250 cfm air compressor. It is found that pump impeller and bowl wear out quite rapidly when operating in quartzose sands hence advisable to have these spare items on hand.

At depth, operation of a single large bucket by windlass/winch is considerably more efficient than hauling two builder's buckets over pulley sheaves on a gantry.

9.4 Annex 2

NOTES ON WELL CONSTRUCTION

Cutting ring:

Have ground levelled.
Mark outer and inner circumferences with mould tool.
Insert 32 outer longer stakes each 300 mm into the ground around outer periphery, making sure that mould tool can rotate inside them.
Dig out bevel mould from inside using mould tool as template.
Dampen bevel surface.
Insert 32 inner periphery stakes each opposite an outer stake.
Grease one side of narrower steel strip and lay along outside of inner stakes with greased side facing greased side of wider strip.
Attach some mortar blocks at intervals along underside of bottom edge of re-rod cage.
Install cage between greased steel strips and use mortar blocks where required to prevent contact of cage with strips. Add sq. twist.
Mix sand, stone and cement in proportions 4:4:3 using wooden gauge boxes and add water until slump cone 'fall' is between 1 and 4 inches, noting amount of water used for reference in later mixes.
Place concrete mix into mould (a wheelbarrow is useful) tamping thoroughly. Continue until mould is full or top of re-rod cage is covered. Smooth and level off with wooden float and spirit level.
Cover with hessian, poking the vertical reinforcements through holes made in the material.
Wet the hessian morning, noon and night for 3 to 4 days.
Allow the concrete to cure for at least one week before attempting further work on the well.

Building the caisson:

Once the cutting ring has cured, remove hessian, steel stakes and inner and outer steel strip, clean up and store these materials ready for use at next site.
Have available on site water, sand, cement, bricks, 8-gauge and 16-gauge wire, bolt cutters and pliers, plus some hoop steps which will have been hot-dip galvanised to prevent rusting.
Lay the bricks in alternate rows of radial and circumferential disposition placing two parallel 'rails' of 8-gauge fence wire between each course, positioning the fencewire by occasionally tying to adjacent vertical re-rods with 16-gauge wire. This will take a considerable amount of cement between each course. However, no cement is to be placed between each brick vertically, except where the vertical reinforcements go through. While it is realised that cement will slip down between bricks from the mortar courses, where the bricks are radially laid with inner edges touching the interstices can be cleaned out by means of a 'poker' of 16-gauge wire so that daylight can be seen between the bricks (except, of course, where vertical reinforcements pass through). The galvanised step hoops should be inserted one at each fourth course. Build up to 1 metre in height, finishing with a course of radially-lying bricks.

The top 3 m of caisson below ground level should be cemented solid, with the outside rendered, in order to provide a sanitary seal.

10. PROGRAMME OF EXPERIMENTAL WORK

10.1 Planning

Initial calculations using Hantush-Papadopulos (1962) were applied to the basement aquifer with reasonable assumptions of values for the transmissivity of the regolith aquifer and likely rates of recharge (Wright, 1981). On the basis of these calculations, a project was proposed and subsequently approved. The operational requirements of a collector well drilling rig were drawn up and a contract let.

10.2 Drilling Rig

A motorised drilling rig was constructed for the Project (Photographs, Back Cover) by Drilling and Geoservices Ltd. of Nuneaton, Warwickshire, at a cost of £20,000. The rig is hydraulically operated and capable of drilling in all formations from unconsolidated material to hard rock. Drilling methods available include rotary and air hammer with either air, foam, water or mud as the circulating medium. For drilling through unconsolidated formations, the duplex system is available and screen can be inserted before withdrawal of the duplex casing. The drill rods are 0.75 metres in length and the dimensions of the radial collectors in the current programme have been 30-40 m in length and 120 mm outside diameter.

The first drill rig constructed was designed to operate in a 3 m diameter shaft to a maximum depth of 20 m below ground level. The depth was constrained in the present instance by the length of hydraulic hose supplied. The radial collectors could only be drilled horizontally.

The drill rig was sent to Zimbabwe by sea to Durban and road to Harare. After drilling the first four collector wells in Zimbabwe, the rig was sent to Sri Lanka. After successfully converting three existing large diameter wells into collector wells the rig was modified to allow it to operate within a 2 m diameter hole. Following a somewhat unsuccessful visit to Malaysia, the drill rig returned to Sri Lanka and is currently being used on the 50 well conversion programme.

A second rig was constructed for the second phase of well construction in Africa. The rig incorporated a number of improvements in addition to a '2 m' operating size. The rig was supplied with a Bedford 5 ton reconditioned ex-Army lorry equipped with a crane (Plate 10.1). Radial collectors could be drilled at any angle with the new rig from vertical to horizontal.

The drilling of the radial boreholes has in the main been carried out with consummate ease and few problems. Duplex casing has been required at only one site - Karonga in northern Malawi - where drilling occurred in alluvial sands and gravels. The first four wells were completed with Demco mesh-wrapped slotted PVC casing/screen but all other wells have used cheaper PVC slotted pipe, locally manufactured as drainage pipe. Significant drilling problems which occurred at Karonga included sand locking of the duplex casing and the inserted well screen in one hole which required both to be extracted together, thereby losing the hole. Periodic locking of coarse gravel of the drill rods against the duplex casing occurred but this could be surmounted although it reduced the drilling rate.

10.3 Country Programmes

10.3.1 Zimbabwe (I)

The first four collector wells were constructed in Zimbabwe between September 1983-December 1984. The results of this work are described in the BGS Internal Report (Wright et al., 1985) which has been widely circulated. The constructions were carried out in association with the Ministry of Water Resources and Development (MWRD) which carried out much of the geophysical survey, the test drilling, and provided labour, constructional materials and equipment. Senior supervision of the construction and the radial drilling were carried out by BGS staff.

The general locations of the collector wells were designated on the basis of demand and inadequacies of existing supply. Two of the first 4 sites were at schools (Murape and Marikopo) and the other two at the College of Agricultural Engineering on the outskirts of Harare. One of the latter wells is fitted with a solar pump (Plate 10.7) and the second is planned to be used with an animal powered pump. Both wells are to be used for irrigation. The site at Marikopo would now be rejected if similar circumstances should arise, because of the shallow and poorly permeable regolith occurring at the site. Having said this, the well is used to the maximum extent possible by the school who have no other convenient source of supply.

10.3.2 Zimbabwe (II)

The second series (3) of collector wells were constructed between September 1985 and June 1986, although long term well testing was not completed until November 1986. The results of this series of collector wells are described in the BGS Internal Report (Wright et al., 1987). Angle drilling of the radials was carried out for the first time in this series of wells but did not prove particularly productive, probably because all the central well shafts had reached the base of the saprolite and the initial set of horizontal collectors provided the main inflows. It had been demonstrated by analysis (Hantush and Papadopulos, op.cit) that numbers of radials beyond four spaced regularly provided little additional improvement in yield. Angle drilling will be mainly of use where the collector well has been unable to be completed to the base of the regolith.

A fourth site, Maruta, was investigated but rejected owing to the low yield of the test boreholes, although the regolith had an apparent thickness of some 17-18 m. The sequence shown in the test boreholes showed about 4 metres of clayey regolith underlain by weathered granite with periodic hard bands. Apart from the low yields of the test borehole, it is possible that the excavation might have proved difficult in the weathered granite; the thin clay regolith overlying would have contained little storage. A somewhat surprising feature was the initial high yield of a test borehole which produced 1.0 litres/sec at the end of the rainy season but only 0.02 litres/sec at the end of the dry season. It is unclear where the water was derived for the initial high yield but it is a situation worth bearing in mind in future exploration work. A flow log would have been informative in this respect.

10.3.3 Zimbabwe (III) [Appendices 4 and 5]

As part of a development programme initiated by the Zimbabwe Government, collector wells are in course of construction at four sites, a resettlement area at Wenimbi (2 wells - see Appendix Zimbabwe 8.1 and Zimbabwe 8.2, this report), a second resettlement area at Soti Source in Gutu Province and a site for hospital supply at Chinyika, also in Gutu Province. The construction costs of the latter two wells are being met by German Aid. The work programme is being mainly supervised by Mr L L Hindson of the MWRD although there has been some BGS involvement in the selection of the well sites in Gutu Province. The same drill rig will be used and Mr P Rastall is now on an ODA/TC appointment to the Zimbabwe Government to carry out the drilling.

10.3.4 Malawi [Appendices 1, 2, 3]

The two collector wells at Mponela were finally completed and tested in September 1987. The siting and construction of these wells has had a long and checkered history, aggravated by lengthy delays throughout the programme. The cost of the work was shared between the Public Works Department and the BGS/ODA Collector Well Project Fund. The original geophysical surveys by BGS were carried out in June-July 1985 and exploration test holes were drilled in November-December 1985, one at each proposed site. Sites for the wells were selectedly fairly close to the existing test boreholes. Mponela North was a reasonable choice; the selection of the Mponela South site is unaccountable at neither the drilling data nor the pump testing of the test borehole met the established criteria. No samples were collected from the test hole at MP2 and three months after construction had commenced a second test hole was drilled and on this occasion lithologically logged.

Work commenced in March 1986 but construction was not completed until July 1987, partly a consequence of delays due to equipment failure or unavailability and partly a consequence of structural problems, notably at Mponela South. The latter was eventually excavated to 15 m using emplaced concrete segments below a caisson stabilised by driven steel rods at about 8 metres. Since the base of the saprolite is below 35 m, the radials had to be angled steeply downwards. Although the yield is not high, as compared with Mponela North, it is moderate.

A third collector well was constructed at Karonga in northern Malawi at the request of the Water-Engineer-in-Chief of the Public Works Department. A caisson had been previously constructed close to a river from which a pipe lead directly to the caisson. The caisson is then pumped for distributed water supply. Two problems existed, one caused by pollution of the surface water and the second, the effect of siltation in the caisson. For both problems, a treatment plant was under consideration at a very considerable estimated cost. The collector well conversion was regarded as an attempt to rectify the problems at minor cost. Three radials have been drilled from the caisson, each between 10 and 12 m in length and completed in saturated sand/gravel in hydraulic continuity with the river. The water inflow into the caisson has been most satisfactory and it is hoped that filtration will effect a cure for both the siltation and pollution problems. If it proves to be so, the collector well will have effected a major cost saving.

10.3.5 Sri Lanka (I)

The situation in Sri Lanka differs from that found in Africa in that there are many large-diameter wells in existence which can be used for conversion to collector wells. The regolith also appears to be generally less thick and the aquifer occurs mainly in the weathered bedrock (saprock), at least in the areas examined in the present investigation. Penetration of the wells into the aquifer is generally quite small, a few metres only.

Three existing wells were converted into collector wells during March/April 1985. The results were reported upon in the BGS Internal Report of June 1985 by R Herbert et al. The yields of the wells were increase 2-3 times as a result of the conversion and justified a follow-up development project.

10.3.6 Sri Lanka (II)

In mid-1987, an ODA-funded Technical Co-operation Project commenced to convert 50 existing large diameter wells to collector wells. Criteria applied to the selection of suitable wells included a minimum well diameter of 2.5 m, minimum depth of water at end of dry season of 1.5 m and adequate access/structural condition. By the end of the year 10 wells had been completed and of the 9 tested, all were successful and improved performance in the same proportion as in the initial study.

Table 10.1

Collector Well Summary of Data: Zimbabwe and Malawi

Location	Total Depth (m)	Static Water Level (time of LT test) (m)	Regolith Thickness for site (m) [1]	T [2] Local (m^2/d)	T [3] Regional (m^2/d)	LD Well Recovery time over given interval (min) [4]	Collector Well Recovery time over same interval (mm)	Ratio [5]	Actual Pumping Rate at LT test (litres/second)	Daily Pumping Drawdown Amplitude (m)	Estimated Safe Yield (litres/second) (pumped 2+2+2 hrs daily) [6]	Estimated Safe Yield (litres/second) with continuous pumping	Specific Capacity for continuous rate (litres/sec/metre)	Specific Electrical Conductance of Collector Well Discharge at end of LT test (microsiemens/cm/23°C)
ZIMBABWE														
Murape, Seki	14.3	2.6	20	-	7.0	500	61.5	8.1	1.5	1.85	1.7*	0.4	0.804	1330
Hatcliffe Windpump	10.0	3.3	26+	12.0	27.0	525	291	1.8	2.6	2.7	3.4*	1.3	0.963	105
Hatcliffe Willowtree	10.8	5.9	14 max.	40.0	50.0	40	22	1.8	3.6	2.6	3.5*	1.5	1.364	Low
St Nicholas Chiota	12.0	4.3	12 max.	1.4	5.0	57	19	3.0	1.5	3.5	1.4†	0.5	0.459	73
Mukumba Chiota	11.0	2.9	11+	0.2	3.0	92	8	11.5	1.5	2.8	1.4†	0.45	0.536	340
St Lioba's Wedza	11.3	3.8	17	1.5	2.8	20	15	1.3	1.0	2.3	1.1†	0.3	0.434	110
MALAWI														
Mponela North	12.0	3.4	20+	26.0	57.0	18	10	1.8	4.0	3.5	6.63†	4.0	1.159	545
Mponela South	12.0	2.8	35+	negl.	4.8	50	26	1.9	0.84	2.1	2.2 †	0.85	0.41	538

Notes:

[1] In the majority of the collector wells, the large diameter well reached the base of the regolith. Values shown are of maximum thickness in the general area.

[2] T local: transmissivity in immediate vicinity of large diameter well from LD well tests.

[3] T regional: transmissivity from long term collector well test based on a Jacob analysis of a semi-log plot of the observed drawdowns at the beginning of the first daily pumping cycle.

[4] Recovery times over equivalent intervals for each well but intervals not the same for all wells.

[5] Ratio of LD recovery to CW recovery over same interval.

[6] Safe yield based on the extrapolation of drawdowns and adjusted values of drawdown and pumping amplitudes for the corresponding pumping rate. Original tests carried out at the end of dry season with water levels at seasonal lowest. * 100 days; † 180 days.

Table 10.2
Collector Well Summary of Data: Sri Lanka

Location	Total Depth (m)	Static Water Level (time of LT test) (m)	Regolith Thickness for site (m) [1]	T [2] Local (m^2/d)	T [3] Regional (m^2/d)	LD Well Recovery time over given interval (min) [4]	Collector Well Recovery time over same interval (mm)	Ratio [5]	Actual Pumping Rate at LT test (litres/ second)	Daily Pumping Drawdown Amplitude (m)	Estimated Safe Yield (litres/ second) (pumped 2+2+2 hrs daily) [6]
SRI LANKA INITIAL PROJECT											
Anuradhapura Korakahawewa	5.4	1.6	4	20.0	80.0	15	4.5	3.3	5.0	2.0	1.1*
Puttalam Anamaduwa Tattewa	7.0	2.5	7	2.0	13.0	299	120	2.5	5.6	3.7	1.1*
Kurunegala Kumbukwewa	4.9	3.4	4	33.0	29.0	29	6.5	4.5	2.0	0.5	1.7*
SRI LANKA 50 WELL PROJECT											
SLAH Anuradhapura	5.1	3.90	4.9	17.0	96.0	158	80	2.0	1.0	0.5	2.0 †
Ulukkulama	9.7	5.14	7.0	<1	-	120	15	8.0	-	-	-
Maha Balankulama School	7.3	6.8	7.3	43	25.0	24	15	1.6	0.8	0.7	1.0 †
Helambawa	6.8	5.3	6.8	1	2.5	40	26	1.5	0.8	0.35	0.3 †
Karuwalagasheena Temple	10.1	-	4.3	<1	------------------- Well cave-in 2 months after drilling -------------------						
Wellagala Temple	5.6	0.60	5.5	25	68	168	60	2.8	6.5	3.6	5.0 †
Police Camp Kurunegala	8.5	3.04	8.5+	3	4	140	75	1.9	2.3	1.0	2.0 †
Kumbulwana Oya	7.1	3.60	6.0	<1	11	155	65	2.4	1.62	1.1	0.8 †
Nikaweratiya CTB Depot	9.0		9.0+	2.6	) no details available						
Yauwanagama	6.7		6.7+	<1	)						

Notes:

[1] In the majority of the collector wells, the large diameter well reached the base of the regolith. Values shown are of maximum thickness in the general area.

[2] T local: transmissivity in immediate vicinity of large diameter well from LD well tests.

[3] T regional: transmissivity from long term collector well test based on a Jacob analysis of a semi-log plot of the observed drawdowns at the beginning of the first daily pumping cycle.

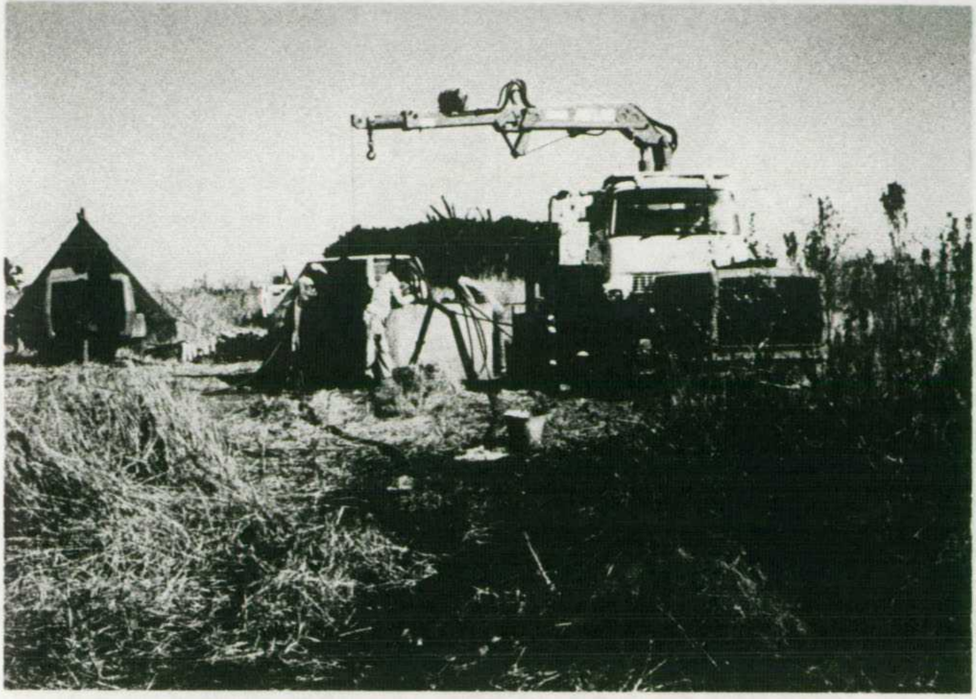
[4] Recovery times over equivalent intervals for each well but intervals not the same for all wells.

[5] Ratio of LD recovery to CW recovery over same interval.

[6] Safe yield based on the extrapolation of drawdowns and adjusted values of drawdown and pumping amplitudes for the corresponding pumping rate. Original tests carried out at the end of dry season with water levels at seasonal lowest. * 100 days; † 180 days.

Plate 10.1 Bedford truck with crane lowering drill rig down large diameter well. Note dewatering in progress.

Plate 10.2 Interior of caisson showing step hoops and hydraulic hose.



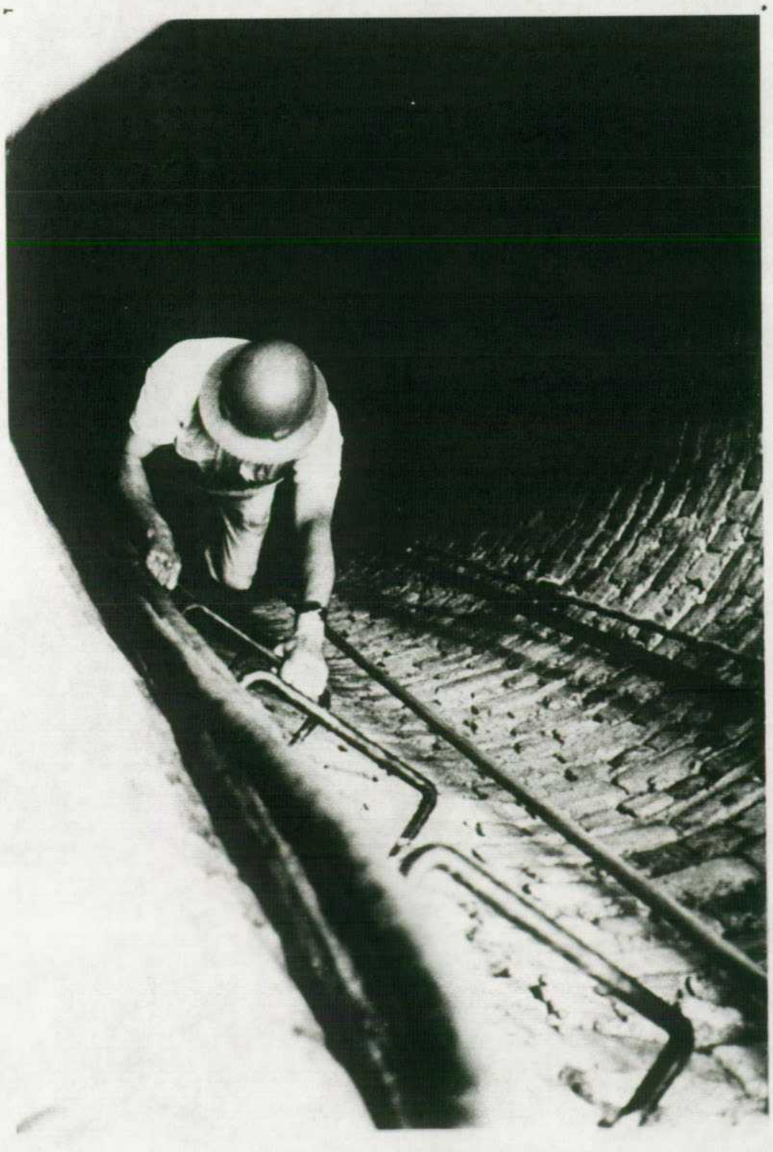
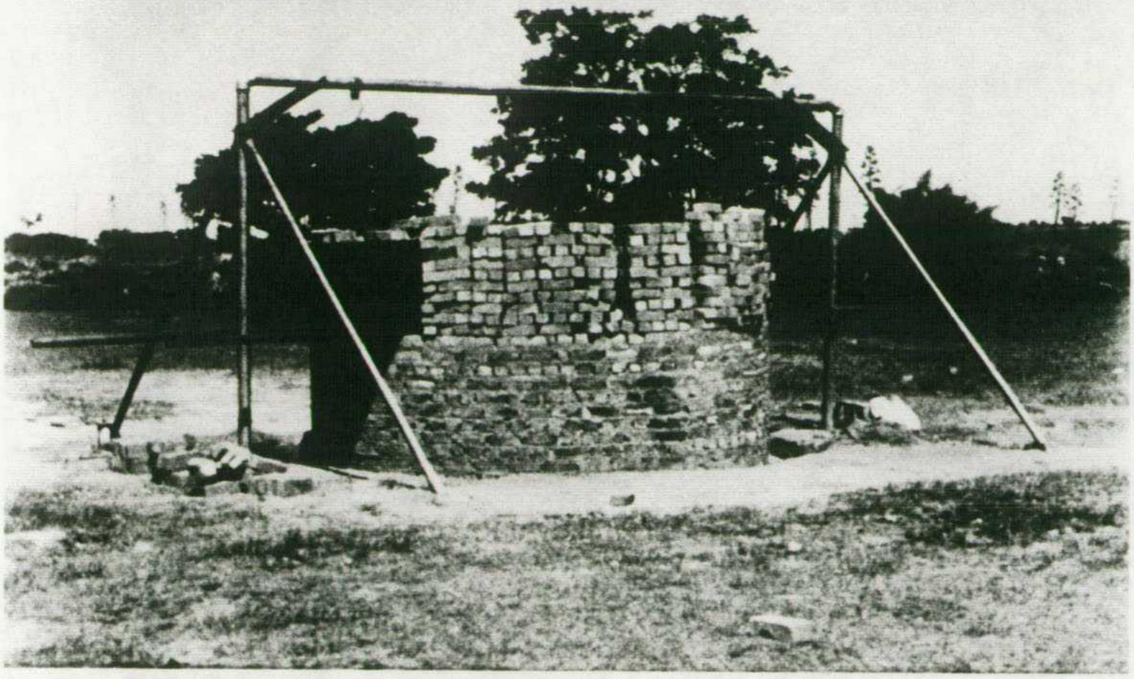


Plate 10.3 Loading bricks onto a sticking caisson.

Plate 10.4 Concrete segments for second series of collector wells.



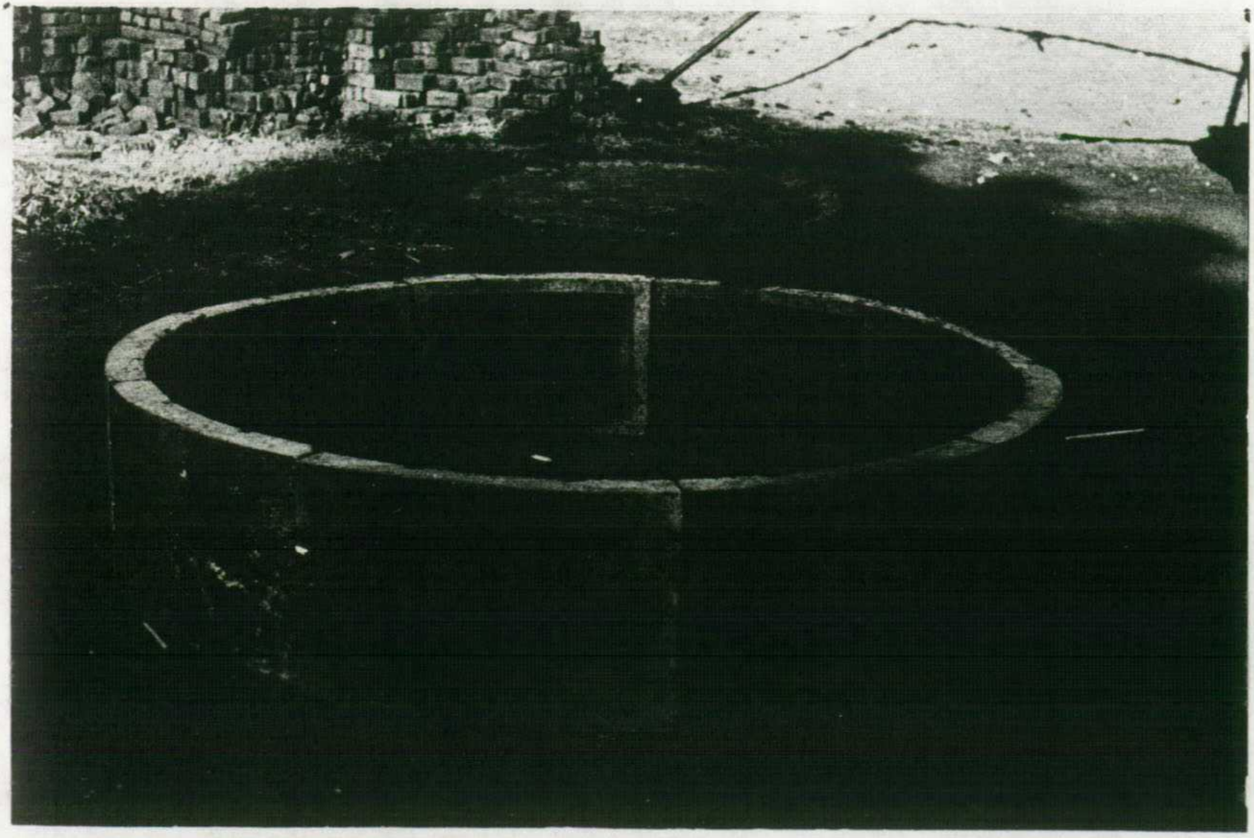


Plate 10.5 Wenimbi: removing spoil by drum and winch. Note interior of concrete blocks.

Plate 10.6 Completed well at Murape fitted with handpump. Note water level recorder.

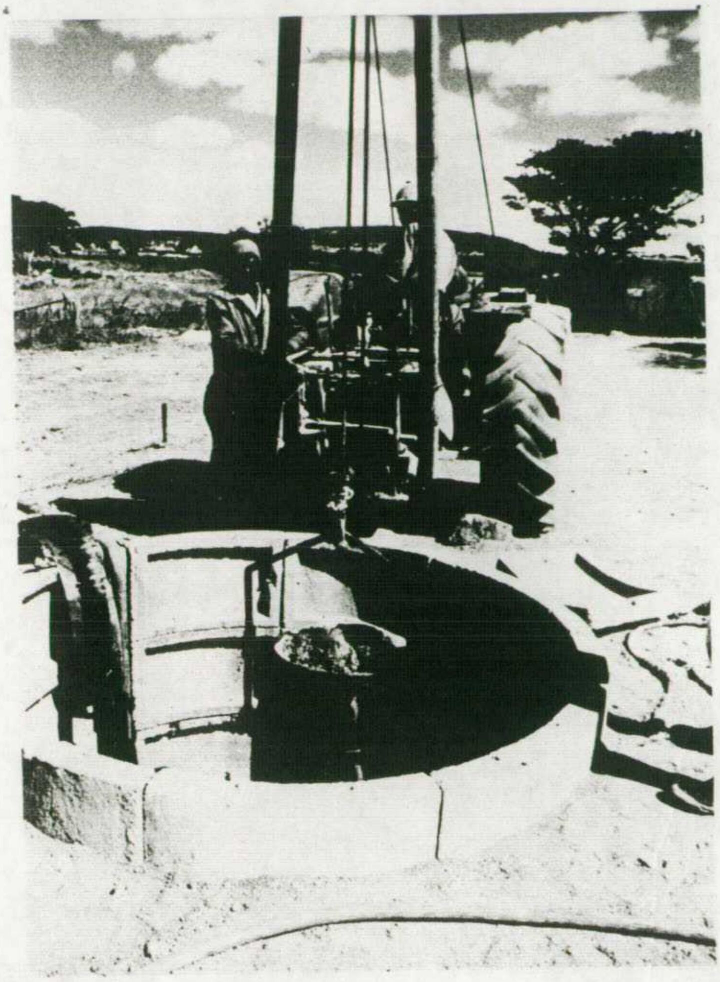


Plate 10.7 Hatcliffe Willowtree fitted with solar pump.

Plate 10.8 Trials of manual horizontal drilling rig at Wallingford.

11. LARGE DIAMETER AND COLLECTOR WELL PUMPING TESTS AND ANALYSIS

Pumping tests have been developed for both large diameter wells tapping the regolith aquifers and for collector wells, created from large diameter dug wells. The tests developed were as follows:

11.1 A Recovery Test for Large Diameter Dug Wells and Collector Wells

This test is fully described in Barker and Herbert (in preparation), see Appendix 6. The test requires that a well is pumped for about one hour, the well drawdown is noted and times taken to achieve 25%, 50% and 75% recovery are monitored. Special nomographs have been developed, which allow estimates of Transmissibility and Storage Coefficient to be made simply in the field from a knowledge of the rate of pumping, maximum drawdown, well dimensions and times of recovery.

11.1.1 Use of Test in Large Diameter Wells.

(i) If the aquifer is confined, i.e. the clayey regolith is virtually impermeable when compared to the saprock, and homogeneous, the test will give exact values for Transmissibility and Storage Coefficient of the lower confined layer. On the other hand if the clayey layer can transmit a significant amount of water relative to that transmitted by the lower, faster, layers the response in the early stages of the recovery will be something like the response of a leaky aquifer. Also, an homogeneous non-layered, unconfined aquifer can be considered as an extreme case of this 'leaky' condition. Mathematical modelling has been carried out to examine the effects of this layering and Table 11.1 summarises the results found.

Table 11.1
Effect of Layering on Results of Recovery Test

	Derived						Notes
T_l modelled (m^2/d)	T (m^2/d)			S (-)			
	25	50	75	25	50	75*	
3	10^{-6}	2	7	10^6	.2	.02	Water Table Aquifer
7.5	10^{-3}	2	6	10^3	.1	.01	Layered - Leaky
9 and 9.5	.05	2	8	6	.02	.003	Layered - Leaky/Confined

NB. The aquifer simulated had a Transmissibility of 10 m^2/day and T_l is the value of T in the lower 3 m of a 10 m thick aquifer. Sy was .05 and S_c (the sum of both layers) was .001.

* Percentage Recovery

If results for T and S are obtained in the field having the same pattern as those in Table 11.1, a 'leaky' situation is indicated and only the 75% recovery results are indicative of the true aquifer situation. In fact, to date, about half of all the results on dug wells carried out display the kind of behaviour noted above.

(ii) In addition to the above the test is repeated after complete recovery using much longer discharges such that a large drawdown occurs in the well. Once more the recovery is closely monitored. This test is then repeated after the well has been transformed into a collector well and the recovery rates of inflow over a similar well drawdown range for both cases can be compared to give a direct measurement of the improvement in rates of inflow for the extreme drawdown condition. This is the most direct way of assessing the value of the horizontal drilling in improving dug well yield.

11.2 A Long Term Test for Collector Wells

This test was devised primarily to give an estimate of the long term yield of a collector well during normal irrigation use. The well is pumped for three 2-hour periods each day for about 10 days. The discharge is arranged so that the well will not run dry during this period. The drawdowns of well water level are monitored at the start and end of each pumping period. Experience shows the drawdown is in two parts. There is a constant daily change in drawdown from the start to end of pumping each day, this is s_{0E}. Also, there is a gradual fall in the background level of drawdown, s_0, which is recorded just before start of pumping every day. Most importantly, if s_0 is plotted against the log of time passed since start of the test, the plot is linear. This plot can therefore be extrapolated to predict the background drawdown that would occur after a complete summer, dry, season. Drawdowns are roughly proportional to discharge and therefore knowing the head in the well available for drawdown it is possible by simple proportion to predict the safe discharge of the well that can be maintained over one dry season.

Thus, if the background drawdown at the pumping test rate, Q_0, after 100 days' is s_{0100} and the extra drawdown, which occurs at the end of every third pumping period, is s_{0E} (a constant) and if the allowable drawdown in the well is s_A, the safe discharge Q_S is given by:

$$Q_S = Q_0 \cdot s_A/(s_{0100} + s_{0E}) \qquad \ldots\ldots (1)$$

This value is of course only approximate. If nearby hydrogeological boundaries occur the figure can be altered significantly.

In addition to the above, the standard Jacob method is applied to the test using the straight line portion of the semi-log plot in the usual way and a value of 'regional' transmissibility is obtained. Experience shows that often this value is significantly different from that obtained from the dug well tests. This is probably due to the varied nature of the regolith and it is likely that the long term collector well test gives a better idea for the 'regional' T than the short time tests.

Alternatively, if the aquifer is 'leaky', then just like pumping tests on slim wells, the transmissibility deduced from the Jacob plot will be exactly twice the real value. Thus, wherever the recovery and long term tests are run together it should be apparent whether the aquifer is 'leaky' or not and just what the best estimates of aquifer hydraulic coefficients are.

11.2.1 A Long Term Test at Kumbulwana, Sri Lanka.

This collector well test was run for 5 days and as usual comprised 3 daily periods of pumping of 2 hours duration each separated by 2 hour recovery periods. The initial discharge rate was 2.2 l/sec which was reduced to 1.6 l/sec because of the excessive drawdown observed. Fig. 11.1 shows the effects of cyclic pumping on the water level in the well. By plotting this drawdown data on semi-log paper a 'regional' value for T of ca. 11 m^2/day was obtained. Using the notation above, after 100 days pumping s_{O100} would be about 1.3 m, s_{OE} is about 1.2 m and the available drawdown s_A was noted from dipping the well to be about 3 m, therefore the safe discharge is given by:

$$Q_S = 1.6 \times 3/(2.5) \triangleq 2.0 \text{ l/sec (cyclically)}$$

Also, as described above a plot of s_O v. log time analysed using Jacobs method leads to an apparent transmissibility value of about 15 m^2/day.

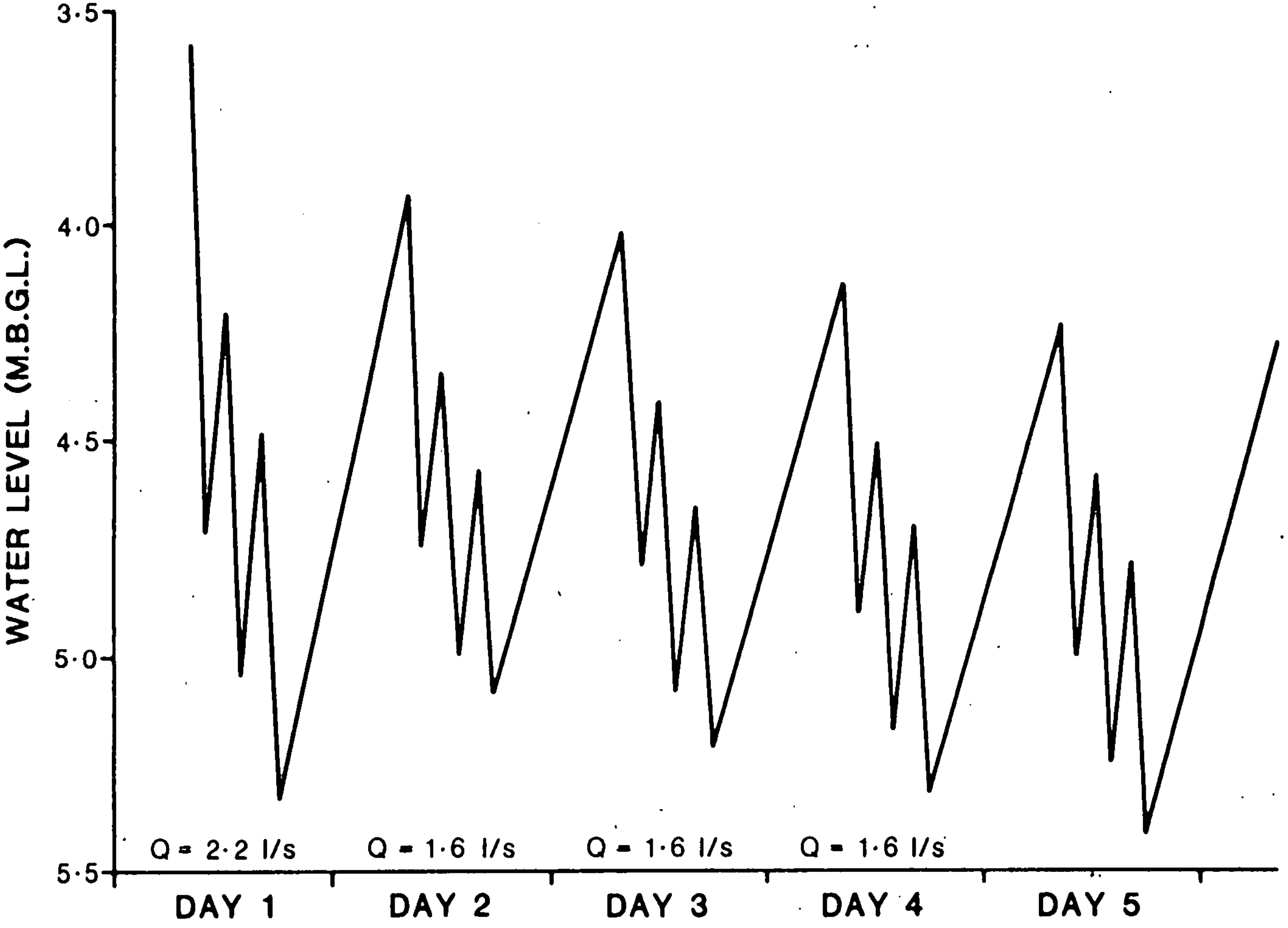

3·5
4·0
4·5
5·0
5·5
WATER LEVEL (M.B.G.L.)
Q = 2·2 l/s
Q = 1·6 l/s
Q = 1·6 l/s
Q = 1·6 l/s
DAY 1
DAY 2
DAY 3
DAY 4
DAY 5

Figure 11.1

12. COLLECTOR WELL COSTS

12.1 General Comments

Full details of individual well costs are contained in the Appendices attached to this and previous reports and a summary of selected information is set out in Tables 12.1 and 12.2. The actual costs of the experimental constructions, including siting procedures, cannot be simply extrapolated for a projected development programme. The degree of geophysical survey and test drilling carried out has been in most cases far in excess of what would be considered necessary for normal development projects. During the constructional work, there have been substantial delays, mainly due to equipment malfunction which have significantly increased labour costs - the main component of construction costs. As compared with a slim borehole of overall cost c. 10,000Z$ or 8,000 Malawi Kwacha, the experimental well constructions have varied from a similar order of cost to more than double. These exclude costs of site investigation work which exceeded the requirements for a normal development programme.

There is little doubt the large diameter well constructed of emplaced concrete segments is more cost effective than a brick caisson. It is estimated that including basic geophysical survey and efficient construction with adequate logistical back-up, the costs of a 15 m deep, 2 m diameter collector well should be of the order of one and a half times a borehole cost. Taking into account the increased yield, the cost benefit ratio should strongly favour the collector well. What is required now is to demonstrate this in a carefully planned and monitored development programme in Africa along the lines of the 50 well project in Sri Lanka. If it should prove feasible to drill the large diameter well and line it with galvanised steel sheet, this would represent a major breakthrough in construction methodology. The results of the planned experimental drilling are awaited with interest.

12.2 Zimbabwe Three Metre Wells

The first four wells in Zimbabwe were of 3 m diameter. A summary of costs is set out in Table 12.1. The figures do not include the costs of BGS professional staff inputs.

Table 12.1
Summary of Well Costs in Zimbabwe Dollars for the first four Collector Wells in Zimbabwe (3 metre diameter)

Site	Murape	Marikopo	Hatcliffe Willowtree	Hatcliffe Windpump
Total Depth	(14.3 m)	(11.7 m)	(10.8 m)	(10.0 m)
Geophysical Survey	6,755	5,489	3,080	1,540
Test Drilling	7,781[2]	18,746[3]	8,328[4]	2,080[5]
Well Construction	19,889	15,536	6,399	5,445
Local Costs[1]	1,120	1,472	1,485	2,645
Totals	35,543	41,243	19,292	11,710

[1] Radial drilling, fuel, crane hire, staff costs for well tests.
[2] 22 test holes drilled.
[3] 53 test holes drilled.
[4] 29 test holes drilled.
[5] 6 test holes drilled.

The costs set out above were all met by the Zimbabwe Government. It is worthwhile to note the variability of the construction costs. The lower costs occurred at sites where a good logistic back-up was provided and no serious technical 'ground' problems were encountered during construction.

12.3 Zimbabwe Two Metre Wells

Table 12.2 shows the similar summary of costs for the second set of caisson wells but with two metre diameter. The construction costs still proved to be disappointingly high and a substantial component can be attributed to delays due to equipment failure, most notably the compressor. It has been concluded however that although actual costs to date have generally been inflated by poor logistical back-up, the caisson type of construction will inevitably prove costly unless the 'ground' conditions are favourable as they were at Hatcliffe. This situation is more likely to occur in countries such as Malawi where the regolith is generally thicker and more consistent in nature than in Zimbabwe. The method of emplaced concrete segments promises to be more cost effective but figures from the Wenimbi construction are not available.

Table 12.2
Zimbabwe 2 Metre Caisson Well Costs

Site	St Nicholas	Makumba	St Liobas
Depth	(12.0 m)	(11.0 m)	(11.3 m)
Geophysical Survey	911	2,638	3,378
Test Drilling	3,300[2]	5,372[3]	5,317[4]
Well Construction	21,593	15,205	15,287
Radial Drilling[1]	1,678	1,266	2,385
Well Testing[1]	378	125	444
Totals	27,860	24,606	26,811

[1] Local costs including fuel, some staff, etc.
[2] 7 test holes
[3] 12 test holes
[4] 10 test holes

12.4 Malawi Collector Well Costs

Table 12.3
Malawi 2 Metre Caisson[1] Well Costs [Malawi Kwacha]

Site	Mponela North	Mponela South
Depth	(12.0 m)	(15.2 m)
Geophysical Survey	Carried out by BGS staff	
Test Drilling	1,476[2]	5,212[3]
Well Construction	11,622	20,042
Radial Drilling and Test Pumping	6,510	7,150
Totals	19,608	32,404

[1] One well had to be completed with concrete segments.
[2] 1 test borehole
[3] 2 test boreholes

12.5 Sri Lanka: Collector Well Conversions

The collector well conversions for the three wells averaged about 18,000 Rps per well and provided 2-3 times increase in yield. This can be compared with the construction cost in Sri Lanka of a 2 metre diameter well to 10 metres of between 30,000-40,000 Rps.

13. MODELLING

13.1 Model Construction

The model used for all the simulations is a 2-dimensional radial/depth model developed at BGS Wallingford. It is a finite difference model with solution by a successive overrelaxation technique incorporating a predictor subroutine. The typical nodal network was 16 vertical by 26 radial. The vertical node spacings could be varied according to the aquifer layering present. The radial node spacings increased with the radius so that improved resolution was obtained in the region near the well where greatest variation took place. The distant radial boundary condition was no flow and the radial nodes were arranged so that this boundary was sufficiently far from the well for no significant drawdown to occur. Horizontal and vertical permeabilities could be varied independently of each other over all nodes. It was necessary to specify the specific yield at the water table and the storativity of the whole profile. A typical initial time step was 5 minutes increasing throughout a stress period. A change of pumping rate (e.g. cessation) required a new stress period and reversion to the initial time step. The model was run on a Cray 1S computer at University of London Computer Centre.

It is not practicable to reproduce all the modelling results in this report, but all are available on open-file at BGS and a summary listing is included with appropriate identification coding.

13.2 Preliminary Modelling

The preliminary models were constructed to confirm the theoretical analyses of large diameter and collector well responses in homogeneous aquifers, and to reproduce drawdown and recovery curves for typical basic parameters of basement aquifers. The collector well was simulated by means of a thin disk of very high permeability but with radius rather less than that of the relevant collector wells. With this construction, the model provided good correlations with theoretical analyses.

13.3 Sensitivity Analysis

The large diameter and collector well models were operated to ascertain sensitivity or degree of correlation with basic parameters which include storage coefficient, specific yield, transmissivity, discharge rates, discharge durations, discharge regimes, well diameter, and layering (higher permeability near the base). The values for the various aquifer parameters used include the typical range for basement aquifers.

	Parameter	Variations Used
(i)	Diameter (D)	3 m and 2 m
(ii)	Transmissivity (T)	5, 40 and 100 m^2/day
(iii)	Discharge (Q)	2 and 4 litres/sec

(iv)	Pumping Regimes	Constant rate pumping and intermittent pumping (6 hours a day at variably spaced intervals)
(v)	Specific Yield (Su)	0.005 and 0.1
(vi)	Storage Coefficient	0.0001 and 0.001
(vii)	Adits (A, NA)	With or without (length)
(viii)	Duration of Discharge	1 - 10 days
(ix)	Bias (layered system)	75% T in basal 25% of aquifer and isotropic

13.3.1 Test Series I

These were mainly concerned to evaluate the effects of discharge rates and well diameter in relation to collector wells or large diameter wells. The transmissivity value used was 40 m^2/day which is fairly high for a basement aquifer. The results of the series are listed in Table 13.1 below. The main features to note are as follows:

(i) 3 m large diameter wells are only marginally better than 2 m collector wells.

(ii) Drawdown is more sensitive to diameter in the large diameter than collector wells.

(iii) Layered conditions showed no apparent change with the parameters used.

Table 13.1
Results of Test Series I

(a) Preliminary Notes

1. Aquifer unconfined and isotropic except in Case G.
2. Pumping at 2 and 4 litres/sec and at two different regimes, A and B. The long term tests are all at Regime B which simulates normal pumping regime with emphasis on day-time operation.
3. Drawdowns quoted at s(max) and s(min), the maximum or minimum drawdowns during any of the cyclic periods referred to, either 1 or 10 days.
4. Su - unconfined storage; Sc - confined storage.
5. Transmissivity relatively high: 40 m^2/day.
6. Regime A: 2 hours pumping with 4 hours recovery, 3 times a day.
7. Regime B: 3 x 2 hours pumping with 2 hour recovery intervals.

(b) Test Results

(A) 3 m well, no adits, Su = 0.1, Sc = 0.001; in Regime B, T = 40 m^2/day

	2 ls^{-1}		4 ls^{-1}		% change at 10 days for 2 pumping rates
Days	1	10	1	10	
s(max)	1.8	1.85	3.75	3.85	+108%
s(min)	0.145	0.195	0.20	0.22	+ 12%

Comments:
- (i) Little change in s(max) between 1 and 10 days
- (ii) s(max) change proportional to change in Q
- (iii) s(min) change much less; presumably relates to well storage, significance not clear.

(B) 3 m well, no adits, Su and Sc as before, Q is 2 ls^{-1} in Regime B. (3 x 2 spaced hours in working day, then recovery)

	1. T100	1. T40	col 2:1 % change	3. T5	col 3:1 % change
s(max)	0.985	1.85	+83%	5.0	407%
s(min)	0.085	0.145	+71%	3.9	4488%

Comments:
- (i) Rapid increase of s(max) with reduced T
- (ii) Even more rapid increase of s(min) with reduced T

(C) 2 m wells with adits; other conditions as in A

	2 ls^{-1}		4 ls^{-1}		% change at 10 days for 2 pumping rates
Days	1	10	1	10	
s(max)	1.55	1.6	3.15	3.145	+97%
s(min)	0.053	0.13	0.045	0.12	- 8%

Comments:
- (i) s(max) increases proportionally with Q
- (ii) s(min) anomalous but change very small and negative

(D) Comparison of 3 m well without adits and 2 m well with adits

	2 ls^{-1}		4 ls^{-1}	
Days	1	10	1	10
s(max) % change of 3 m → 2 m + adits	-14%	-14%	-16%	-18%
s(min)	-63%	-33%	-78%	-45%

Comments:
- (i) 2 m with adits marginally improved and drawdown decreasing from 14-18% in 1-10 days, presumably will continue.
- (ii) s(min) also improves but changes more irregular
- (iii) Sensitivity to changes in T will be important

(E) 1 day pumping, Regime A, 2 ls^{-1} and same other parameters

	3 m			2m		
s(hours)	No adits	Adits	% change	No adits	Adits	% change
s(2)	1.3	1.03		2.15	1.45	
s(8)	0.285	0.16		0.18	0.10	
s(10)	1.5	1.13		2.20	1.50	
s(16)	0.335	0.19		0.22	0.13	
s(18)	1.55	1.15	-26%	2.30	1.50	-35%
s(24)	0.35	0.185	-47%	0.225	0.13	-42%

Comments: (i) s(18) improved with adits by 26 to 35%
(ii) s(24) also improved but by larger amounts

(F) Comparisons of 3 m and 2 m wells with and without adits

	No Adits			Adits		
	3 m	2 m	% change	3 m	2 m	% change
s(18)	1.55	2.3	+48%	1.15	1.50	+30%
s(24)	0.35	0.225	-36%	0.185	0.13	-30%

Comments: (i) Without adits 2 m increases by 48% and with adits by 30%
(ii) Residual drawdowns are anomalous

(G) Comparisons of 2 m well without adits and homogeneous or biased (75% T in basal 25%) of aquifer.

	No Adits		Adits	
	Homogeneous	Biased	Homogeneous	Biased
s(2)	2.15	2.15	1.45	1.5
s(8)	0.18	0.18	0.10	0.10

Comments: No significant change at one day with these conditions.

13.3.2 Test Series II

These tests were mainly concerned to evaluate the differences between large diameter wells and collector well responses for significant variations in diameter, transmissivity and specific yield. The results are listed in Table 13.2 and the following features are apparent.

(i) The effect on specific yield changes appears to be negligible within individual groups and in some cases the results are the reverse of what might be expected in the case of the residual drawdowns. However the differences in value are very small and it may be assumed that the background error could be of the order of .03 m.

(ii) Storage coefficient. The results are as might be anticipated with drawdowns slightly greater for the lower storage coefficient.

(iii) Adits and no adits. The effect is not very marked with high transmissivity but is very significant with low transmissivity affecting the drawdowns. Without adits, wells in low transmissive formations will run dry very quickly. The reason for this rapid recovery with adits seems unlikely to be a simple function of the well radius increase.

(iv) 2 m and 3 m wells. 3 m and 2 m with adits: performance not very different with low transmissivity but appreciably better performance of latter when T is low. The same marked improvement on residual drawdown also occurs. Figure 13.1 and Figure 13.2 show this relationship.

Table 13.2
Results of Test Series II

(a) Preliminary Notes

1. Aquifer unconfined and isotropic.
2. Pumping at 2 litres/sec between 0-120, 240-360 and 480-600 minutes and with recovery to 1440 minutes (one day).
3. Drawdowns quoted at 600 minutes s(max) and residual drawdown at 1200 minutes.
4. Su : unconfined storage coefficient
   Sc : confined storage coefficient
5. A : (as shown)
   B : (as shown)

(b) Test Results

	Adits		No Adits	
Su	0.005	0.1	0.005	0.1
A. 3 m Diameter				
s(mins) (i) T_H = 100 m^2/day; Sc = 0.001				
s (600)	0.835	0.81	0.94	0.81
s(1200)	0.055	0.03	0.05	0.05
(ii) T_H = 100 m^2/day; Sc = 0.0001				
s (600)				
s(1200)				

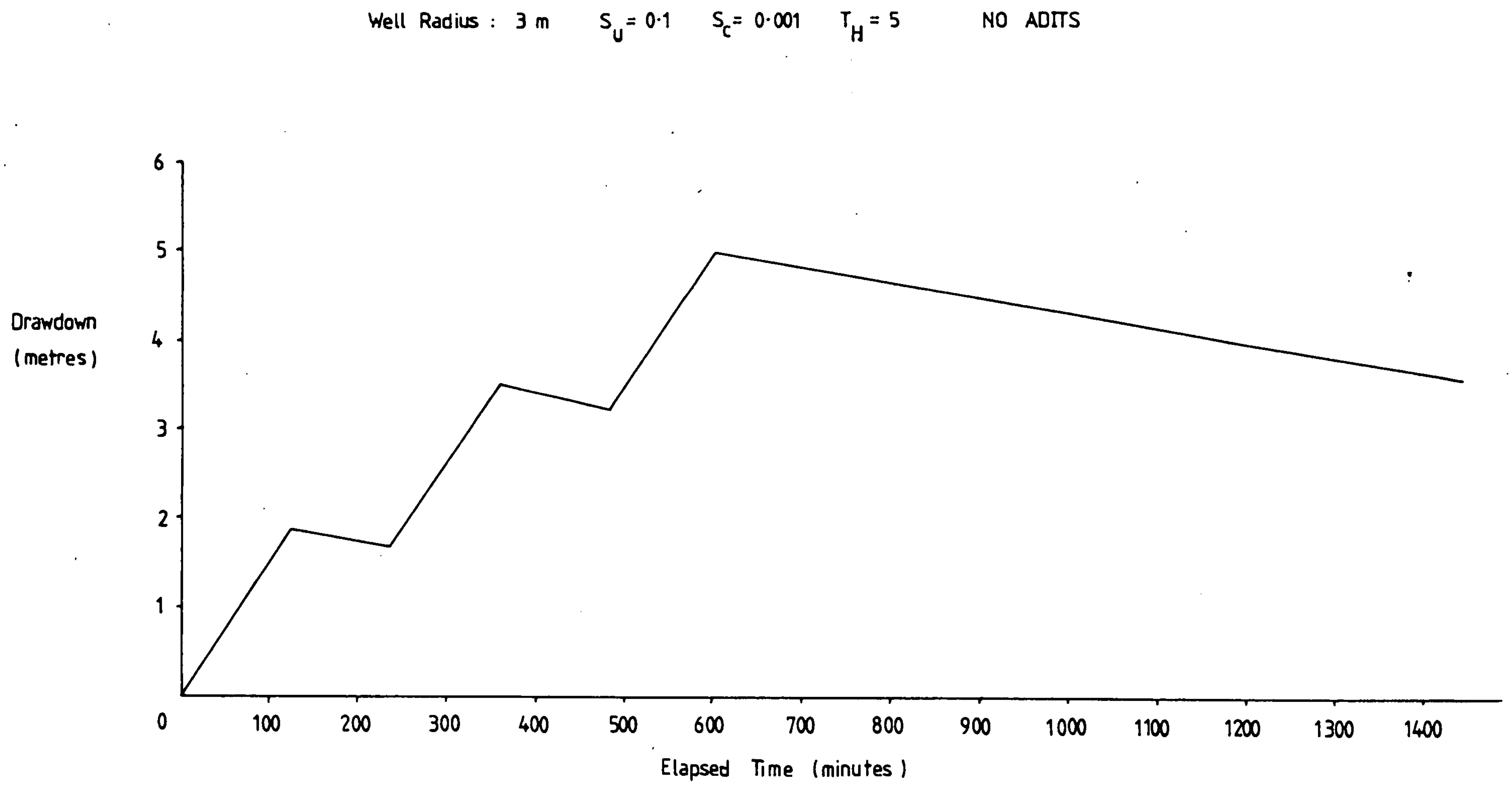

Well Radius : 3 m $S_u = 0{\cdot}1$ $S_c = 0{\cdot}001$ $T_H = 5$ NO ADITS
Drawdown (metres)
0
1
2
3
4
5
6
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
Elapsed Time (minutes)

Figure 13.1

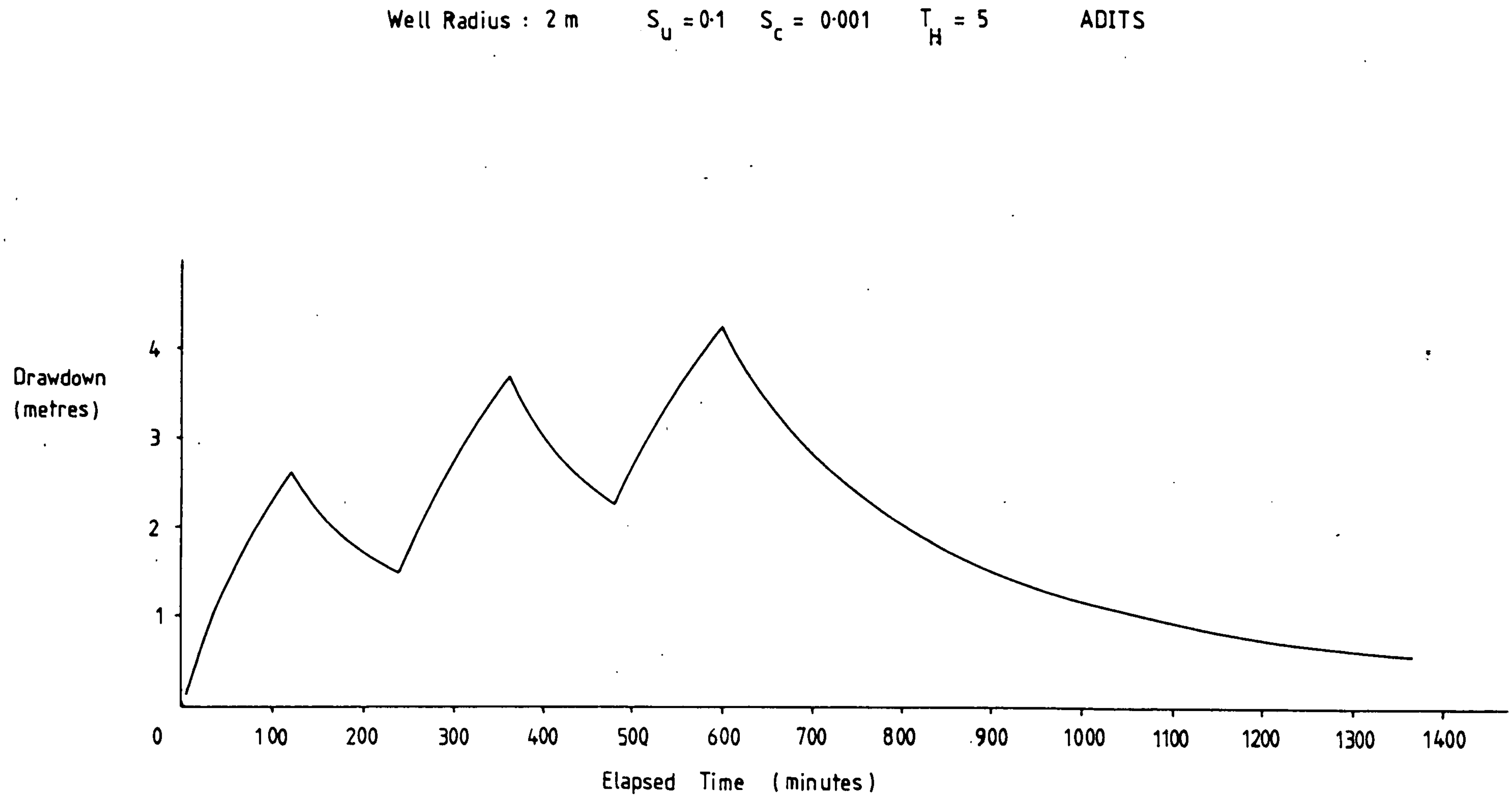

Well Radius : 2 m $S_u = 0{\cdot}1$ $S_c = 0{\cdot}001$ $T_H = 5$ ADITS
Drawdown (metres)
4
3
2
1
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
Elapsed Time (minutes)

Figure 13.2

(iii) $T_H = 5\ m^2/day$; Sc = 0.001

s (600)	2.45	2.40	5.1	5.0
s(1200)	0.55	0.57	3.7	3.9

(iv) $T_H = 5\ m^2/day$; Sc = 0.0001

s (600)	2.7	2.48	5.17	5.15
s(1200)	0.67	0.40	3.80	4.00

B. 2 m Diameter

(i) $T_H = 100\ m^2/day$; Sc = 0.001

s (600)	0.97	0.99	1.18	1.05
s(1200)	0.035	0.025	0.035	0.06

(ii) $T_H = 100\ m^2/day$; Sc = 0.0001

s (600)				
s(1200)				

(iii) $T_H = 5\ m^2/day$; Sc = 0.001

s (600)	4.2	4.2	Dry	Dry
s(1200)	0.065	0.075	Dry	Dry

(iv) $T_H = 5\ m^2/day$; Sc = 0.001

s (600)	-	4.75	-	-
s(1200)	-	0.057	-	-

The explanation for the marked sensitivity to transmissivity is not immediately apparent but can be better understood by reference to the behaviour of dug wells as described by Papadopulos and Cooper, 1967. Figures 13.3 and 13.4 describe 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. The characteristics of the recovery can be deduced using the principle of superposition:

Curve (1) in Figure 13.3 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 13.3 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

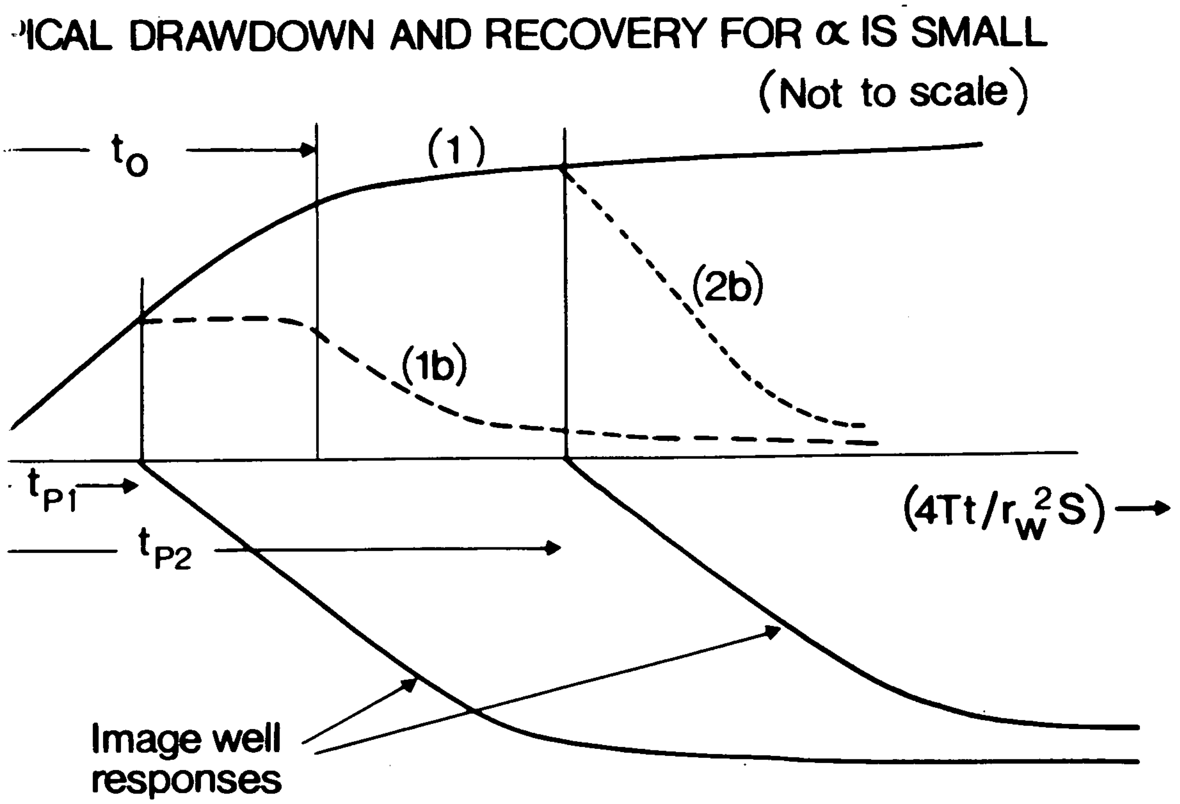
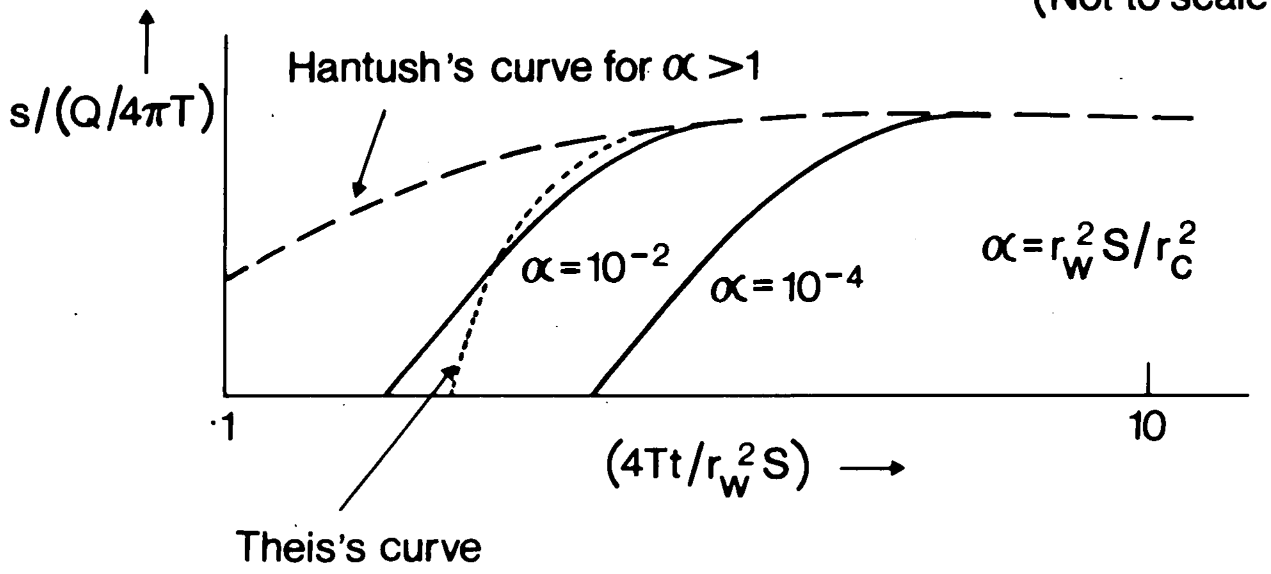

ICAL DRAWDOWN AND RECOVERY FOR α IS SMALL
(Not to scale)
t_o
(1)
(2b)
(1b)
t_P1
t_P2
(4Tt/r_w^2 S)
Image well responses

Figure 13.3



DRAWDOWN CURVES FOR LARGE DIAMETER WELLS
(Not to scale)

Figure 13.4

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 13.4, 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.

13.4 Test Series III: Modelling of Actual Pumping Tests

The final series of model runs have been concerned with actual well test data and the results are shown in Table 13.3. The tests at two sites have been modelled, Mponela North in Malawi and St Nicholas in Zimbabwe. It was ascertained during modelling that the better correlations were obtained when the model was layered and the results listed are based on a model in which 75% of the transmissivity occurs in the basal 3 metres. The specific yield was taken as 0.5 and the storage coefficient was 0.001.

Table 13.3
Results of Test Series III

	Transmissivity (m^2/day)	
	Model	Analytical Calculations
Mponela North		
Large Diameter Well, small drawdown		26
LD Well, deep drawdown	24-30	21
Collector Well, deep drawdown	28	90
CW long term test	28	58
St Nicholas		
LD Well, small drawdown	10	3.4
LD Well, deep drawdown	3-4	1.4
CW, deep drawdown	4	2.3
CW, long term test	not modelled	5.0

The various runs in relation to the deep drawdown test for the collector well at St Nicholas is shown in Figure 13.5. Although run $T = 4$ m^2/day gives the best correspondence with the maximum observed drawdown the recovery rate of the model is faster than for the actual well test. A suggested reason for this is the presence of a large cavity behind the well which developed as a result of 'sand' inflows during construction. The cavity would have the effect of damping the responses.

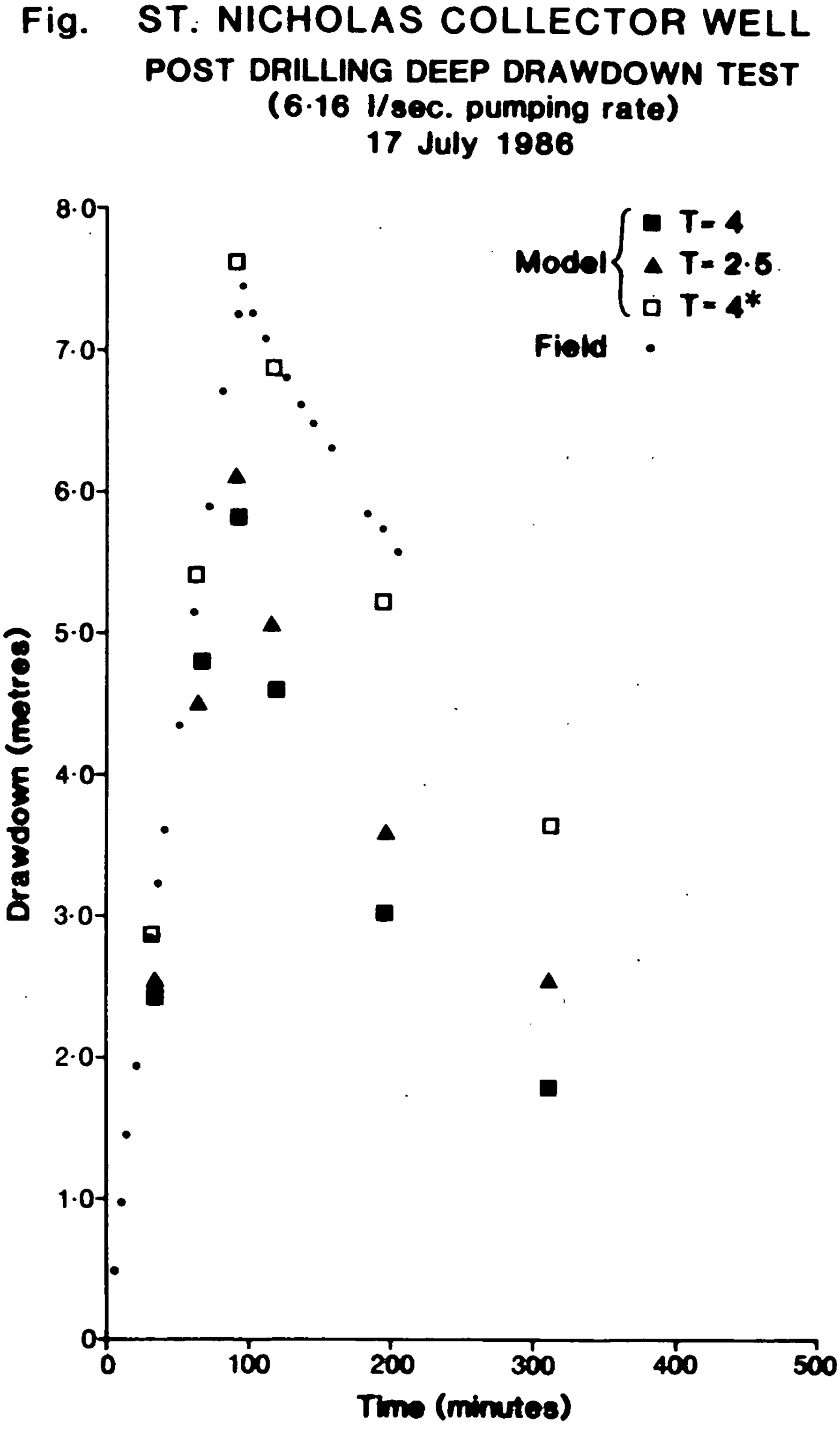


Fig. ST. NICHOLAS COLLECTOR WELL
POST DRILLING DEEP DRAWDOWN TEST
(6·16 l/sec. pumping rate)
17 July 1986

Figure 13.5

Two of the collector well modelling runs, the deep drawdown and the long term tests, at Mponela North, are shown in Figures 13.6 and 13.7. The correlation of modelled with observed measurements is good in both cases and gives credence to the modelled transmissivity of 28 m^2/day. The discrepancy with the analytical results appears anomalous but possible explanations of the anomalous high value for the long term test analysis are apparent. One relates to the validity of the Jacob approximation which occurs when $u(=\frac{r^2S}{4Tt})<0.01$. Depending on the value of S, the time could be either 0.4 or 21 days. The second and perhaps more likely explanation is that the aquifer is behaving in leaky artesian fashion for which the plot resembles a recharge boundary and effectively doubles the apparent transmissivity.

Listing of Model Plots held at BGS Wallingford

Figures

J	Effect of well diameter and adits.
K_1-K_4	3 x 2 hours pumping; 2 m and 3 m diameter.
L	Effect of different pumping regimes
MA-MZ	Sensitivity to well diameter, storage, specific yield, adits and transmissivity.
NA-NF	Layered simulations.
A-I	Simulation of pumping tests at St Nicholas and Mponela North.

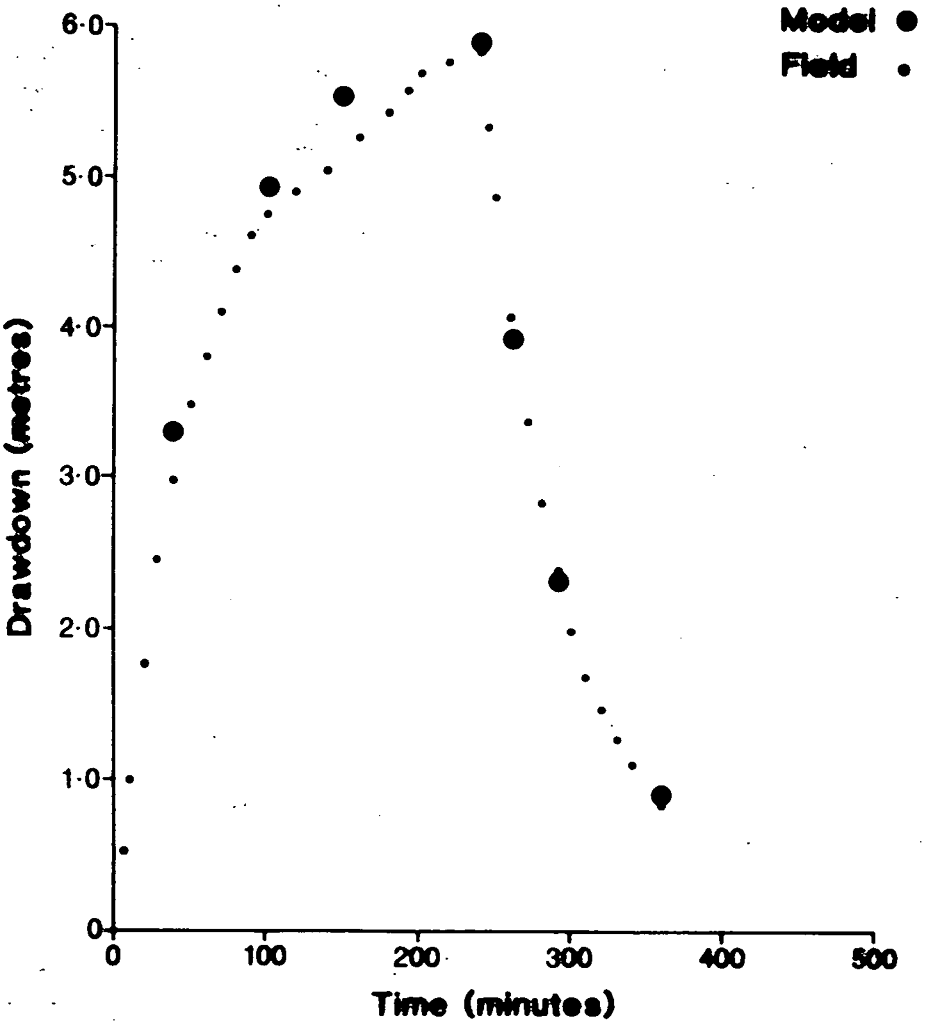


Fig. MPONELA NORTH COLLECTOR WELL
POST DRILLING DEEP DRAWDOWN TEST
22 July 1987

Figure 13.6

Fig. MPONELA NORTH COLLECTOR WELL

LONG TERM TEST
30 August to 7 September 1987
Q : 4 l/sec

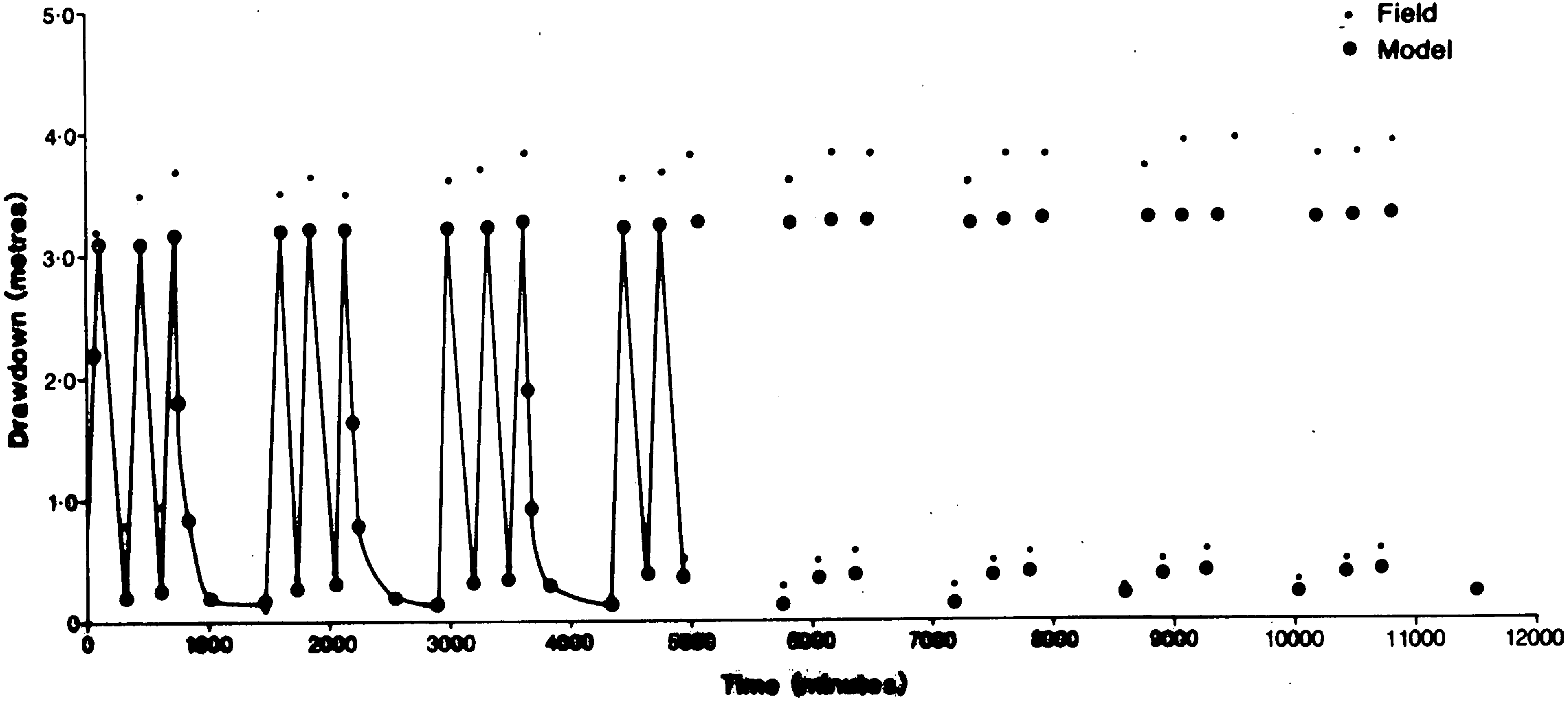


Figure 13.7

14. DEVELOPMENT POTENTIAL

14.1 General Consideration of Water Usage and Demand in Africa

The main current requirements are for domestic supply including livestock, and irrigation, with significantly lesser amounts for industry, including mining. Both domestic and livestock supply require small amounts of water, more particularly in the former case for rural populations, and in the main from widely dispersed sources. Cost factors of development are the main constraint rather than overall water availability. Irrigation requires large volumes of water from more localised sources.

14.1.1 Domestic Supply.

More than 75% of Africa's population of around 350 million live in rural areas and some 75% of the total population live south of the Sahara. Table 1 shows figures for recent (1983) service cover. The most notable feature is the low service cover for the rural population, most particularly for Sub-Saharan Africa. It is important to notice that both the current usage and total demand of the existing population is quite small compared to the amount of renewable resources. On the assumption of an urban usage of 100 litres per head per day and a rural usage of 30 litres per head per day, the current service and total service cover would be equivalent to 3.2 and 6.4 km^3 per year respectively compared to a mean total runoff of 4,225 km^3 per year. Overall availability is therefore not the problem in Africa which relates more to capital and recurrent costs of providing supply to a dispersed population without ready access to easy sources of development.

Table 14.1
Population Cover: Domestic Water Supply.

	Urban Population Millions	Cover in Millions	%	Rural Population Millions	Cover in Millions	%
North of Sahara	40.1	34.3	86	47.5	15.3	32
South of Sahara	57.6	32.8	57	209.2	51.2	24
Total	97.6	67.2	69	256.7	66.5	26

	Millions		
Combined	Population	Cover	%
	354	134	38

[1] Urban supply 100-200 lcpd
[2] Rural supply 20 - 30 lcpd

At the recent rate of progress and assuming a population growth of 3% per annum, it will take between 10 and 15 years to provide a full service cover and perhaps longer since the rate of development is likely to decrease in the more remote areas.

14.1.2 Irrigation.

Africa is the only continent where per capita food production is decreasing and yet, as this recent drought has shown, the importation of food cannot be regarded as a long term solution. Irrigation could provide some assistance, perhaps of most value in times of extreme drought. The practice is labour intensive and requires large applications of water of which an obvious deficiency exists in marginal lands. With regard to the first issue, the comments of a recent FAO report (1984) are pertinent.

"....that in most of Africa labour is a scarcer resource than land and the farming system is more likely to be based on optimising productivity per unit of labour than on unit of land. Rainfed farming has considerable advantages under these conditions; with smaller involvement and less need for inputs the extensive rainfed systems are more flexible than irrigated systems in terms of labour" , "It is well to note that the first step in improvement of production by a traditional farming community may well be in the rainfed areas and that irrigation may be introduced initially as a supplementary activity with certain benefits (such as greater insurance against drought) to offset the inevitable reduction it will cause in labour availability for other activities".

Small scale irrigation has been carried out in Africa from time immemorial. More formal irrigation with full water control has developed in Sub-Saharan Africa only since the colonial period and the record of achievement is not good (Mather, 1983). It is more costly than in any other continent, mainly reflecting the inexperience of the domestic construction industry and the consequent dependence on imported materials (Table 14.2). At the present time, some 2% of the total arable land is irrigated.

Table 14.2

Typical Costs of Irrigation Development, 1980 prices, US$ per hectare (FAO, 1982 and quoted in Mather, 1983).

	Gravity Schemes		Pump and Tubewells	All Schemes Weighted Average
	$/ha	Share in Total %	$/ha	Cost $/ha
Latin America	6,000	50	3,000	4,000
Near East	7,000	70	4,000	6,100
Africa (excl. Sudan)	11,000	70	6,000	9,500
Sudan	5,000	50	4,000	4,500
Asia and Far East (excl. South Asia)	4,000	60	2,000	3,200
South Asia (Bangladesh, India, Pakistan)	2,500	40	1,000	1,600

Rehabilitation in all regions except South Asia - $1,760/ha
Rehabilitation in South Asia - $ 800/ha

Most large scale irrigation is for cash crops and other than in the arid regions, surface water constitutes the main supply source. Water requirements are high, 1-2 litres/sec per hectare, and water costs are critical. Some recent figures relating to Zimbabwe demonstrate this. At the present time, irrigation farming cannot tolerate costs of water more than 15-20 Zimbabwe $ per 1,000 m^3 (ver. comm.) whereas new schemes other than from very large dams are unlikely to be able to produce water at a cost lower than 50 $ per 1,000 m^3. The only way for further development along these lines is to subsidise new developments at the expense of older schemes which have long since paid their way. Recent assessment of large dams for irrigation purposes have been very critical (Goldsmith, 1984). A major component of irrigation costs using surface supplies relate to maintenance - siltation, soil salination, drainage, flooding, etc., all of which tend to increase with land use deterioration.

Present thinking (FAO, op.cit.) favours small scale, even one farmer type irrigation, which may initially be supplementary and therefore more easily integrated with existing farming systems. Such small scale systems are particularly suited to groundwater development if availability of water is sufficient and capital and recurrent costs can be kept within acceptable limits. This constraint favours supplies from near surface aquifers with shallow water level.

14.2 Basement Aquifer Potential

Collector wells are not exclusively designed for the basement aquifers but do have a particular applicability, as perhaps the best means identified to date to exploit their potential more fully. The following features of basement aquifers should be stressed in this context.

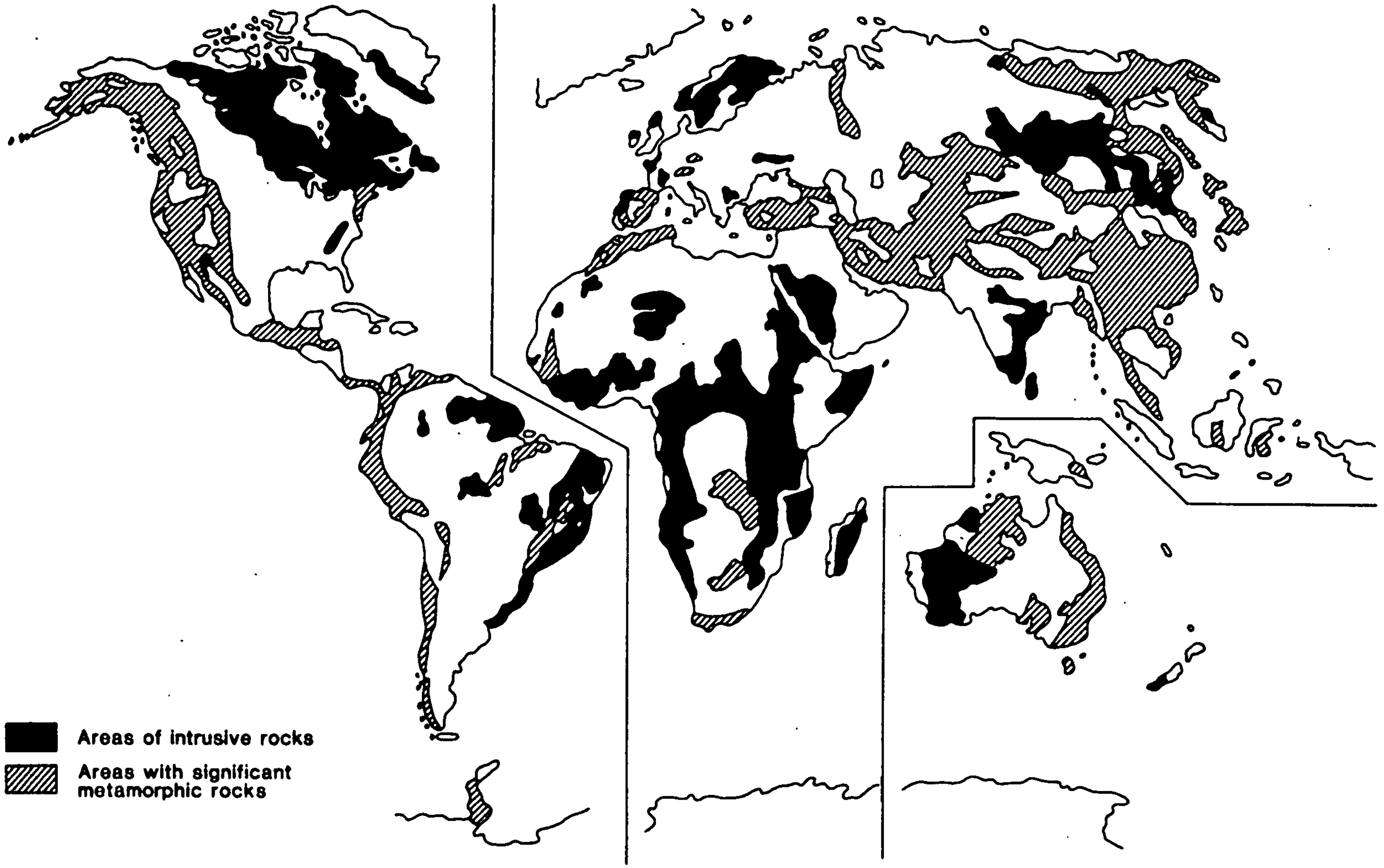
(i) The widespread occurrence of crystalline basement outcrops in Africa and tropical regions worldwide (Figure 14.1).

(ii) The constraints to development by standard boreholes and wells, occasioned by the low transmissivity of the regolith aquifer and the variable distribution of the more transmissive fracture dominated aquifers in the saprock and bedrock.

(iii) The limitations on alternative sources of supply in the great plains of Africa underlain by crystalline basement rocks. Ephemeral flow is typical of rivers where the mean annual rainfall is less than 700 mm. Base flow is reduced in consequence of low hydraulic gradients in the shallow aquifers and much of the aquifer recharge is lost through evapotranspiration. Sites for surface storage are rare in these plainlands and development schemes utilising this approach are expensive both for construction and for operation (water treatment, siltation of reservoirs, etc).

(iv) The economics of development by standard boreholes/wells must limit the degree of development which is feasible. Despite the evidence of quite high orders of recharge on an areal basis, development of only a small proportion is likely to be feasible because of high capital, operation and maintenance costs in relation to yields.

Figure14.1- WORLD-WIDE DISTRIBUTION OF BASEMENT ROCKS
(after Uhl and Atobrah, 1987)



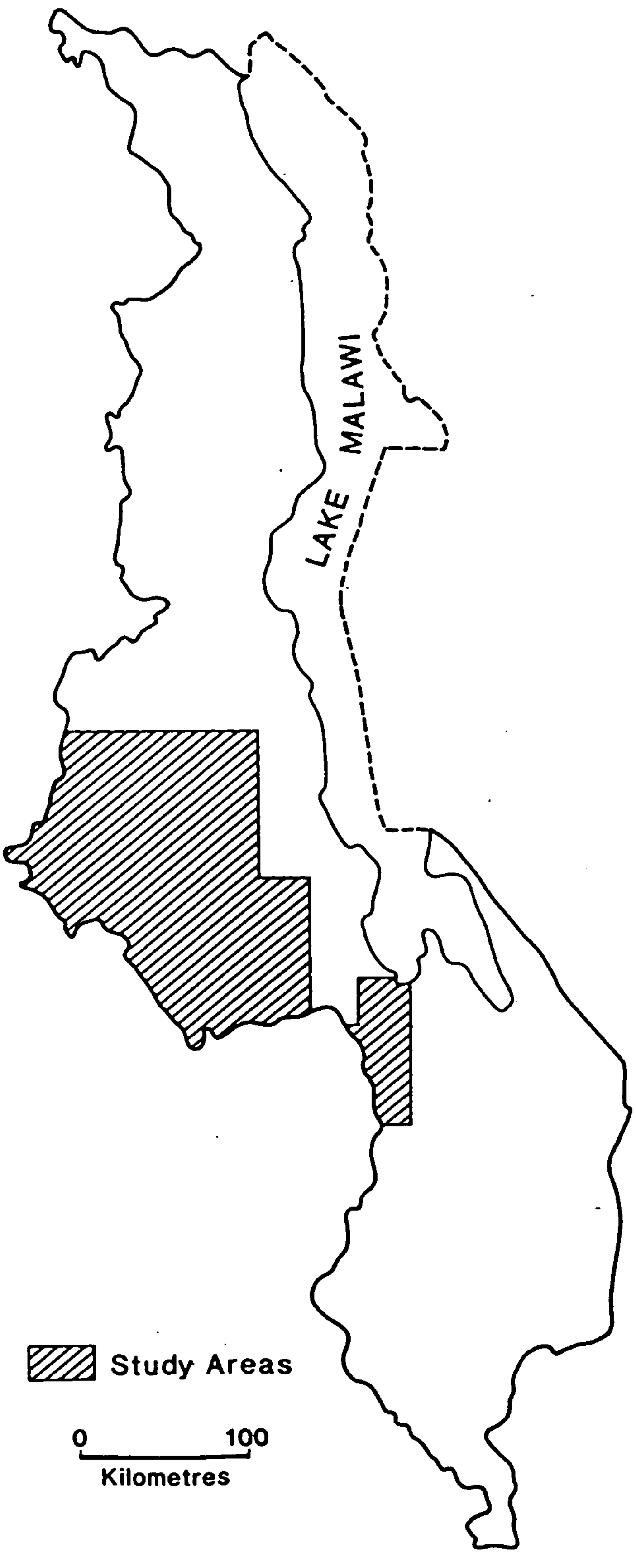


Figure 14.2 Map of Malawi indicating areas for which borehole data has been collected.

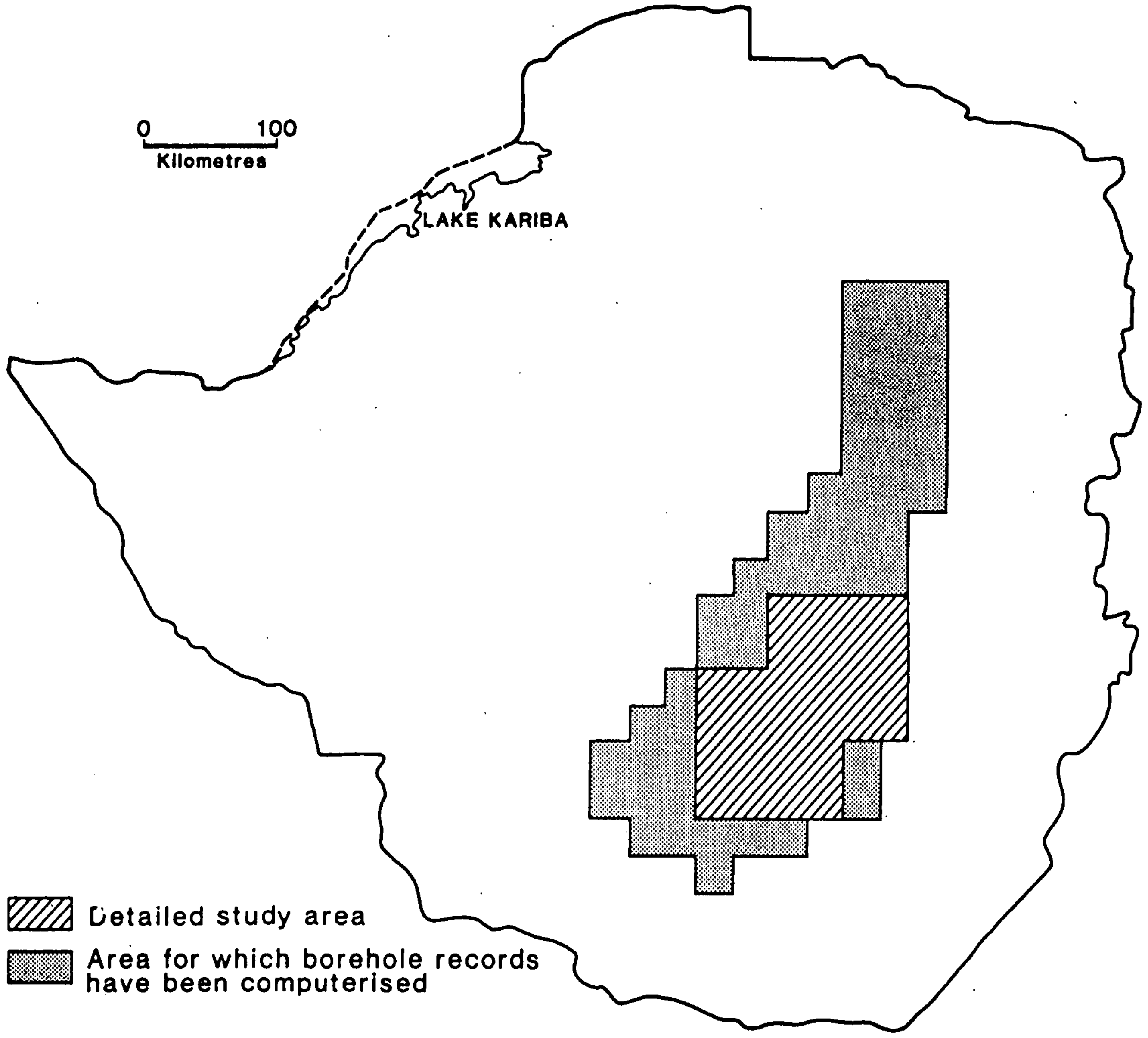


Figure 14.3 Map of Zimbabwe indicating areas studied by BGS.

(v) Drought and desertification have greater impacts on surface water resources (river flow, surface storage) than on groundwater resources.

14.3 Collector Wells for Urban Supply and Irrigation

14.3.1 'Urban Supply'

Urban supply requires substantial volumes of water of the order of 100-150 litres per capita per day as compared with rural demands of 25 litres percapita per day. Much new development, e.g. business centres, as well as the growth of existing urban centres is constrained by water supply. In a recent study of 40 towns in Malawi, it was concluded that groundwater from basement aquifers would need to provide the main source of supply for the majority of these towns; in a few cases due to the apparent difficulty in borehole siting, surface water storage is to be provided but at a considerable expense. Development of groundwater will require significant exploration in order to locate sites with sufficiently high yields to justify the use of motor pumps. The town of Mponela is one of the 40 and future requirements propose the drilling of substantial numbers of boreholes. Some existing boreholes fitted with motor pumps have yields c. 1 l/sec, probably with drawdowns of 20-30 metres (figures not available). The more successful of the two collector wells has a predicted safe yield of 6.63 l/sec for 6 hours daily pumping or 4 l/sec continuously with 3.5 metres pumping drawdowns. Comparisons clearly favour the collector well.

14.3.2 'Small-Scale Irrigation'

Collector wells in basement aquifers have provided yields in the range 1-6.5 l/sec for a 6 hour pumping day. Such yields are feasible for combinations of domestic supply and small-scale irrigation. The small pumping drawdowns make abstraction feasible by low energy sources such as solar, wind and animal powered pumps. The relatively low yields as compared with typical irrigation wells for larger scale irrigation favour the use of such supplies for more intensive practices including drip or pitcher methods or supplementary applications for predominantly rainfed crops. The present study in Sri Lanka which is experimenting with low head tanks and large diameter tubing for efficient drip distribution is a type of usage which favours the collector well. Collector wells in rural locations could have the advantage of providing domestic supplies combined with irrigation usage. The production of high value crops for local markets as well as 'home' use could assist in meeting any maintenance or operational costs associated with the collector well.

14.4 Collector Well Distribution and Spacing

For a recharge rate of 100 mm per annum and transmissivity values of 30 m^2/day, the radius of influence of a 3 l/sec well discharging continuously would be of the order of 380 metres which gives some indication of spacing feasibility.

For a more random assessment, use has been made of the computerised data of boreholes in certain studied areas in Malawi and Zimbabwe (Figures 14.2 and 14.3). The data system was interrogated in order to identify the proportion of boreholes with rest water levels less than

5 m or less than 10 m and the mean regolith thickness in each case. The results are summarised in the two tabulations below.

Table 14.3

Selected Borehole Data from the Computerised Data Base for the Malawi Strip (Figure 14.2).

(A) Total Boreholes in Data Base.

No. of boreholes with a depth given:	1453
Mean depth (m):	43.1
No. of boreholes with RWL data:	1425
Mean RWL (mbgl):	9.8
No. of boreholes with data on regolith thickness:	435
Mean thickness of regolith (m):	31.8

(B) Selected Boreholes.

No. of boreholes with RWL < 5 m:	473
Mean regolith thickness (m) when RWL < 5 m:	29.4[1]
No. of boreholes with RWL < 10 m:	1073
Mean regolith thickness (m) when RWL < 10 m:	31.2[2]

[1] 131 boreholes

[2] 306 boreholes

Table 14.4

Selected Borehole Data from the Computerised Data Base for the Zimbabwe Strip (Figure 14.3).

(A) Total Boreholes in Data Base.

No. of boreholes with a depth given:	1610
Mean depth (m):	42.6
No. of boreholes with RWL data:	1190
Mean RWL (mbgl):	11.1
No. of boreholes with data on regolith thickness:	680
Mean thickness of regolith (m):	18.2

(B) Selected Boreholes.

No. of boreholes with RWL < 5 m:	388
Mean regolith thickness (m) when RWL < 5 m:	15.8[1]
No. of boreholes with RWL < 10 m:	873
Mean regolith thickness (m) when RWL < 10 m:	16.2[2]

[1] 152 boreholes

[2] 282 boreholes

The results of these analyses show that substantial numbers of boreholes have RWL < 5 m in both Malawi and Zimbabwe (33% of data base in both cases). The mean regolith thickness is of the right order for a successful collector well, possibly somewhat excessive in Malawi. The figures give an indication of the feasibility of locating collector wells and indeed of converting existing boreholes to collector wells.

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