TECHNICAL REPORT WD/89/15

The Basement Aquifer Research Project 1984-1989: final report to the Overseas Development Administration

British Geological Survey and others

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BRITISH GEOLOGICAL SURVEY
Natural Environment Research Council

TECHNICAL REPORT

Hydrogeology Series

Report WD/89/15

THE BASEMENT AQUIFER RESEARCH PROJECT 1984-1989: Final Report to the Overseas Development Administration

British Geological Survey[1] in association with
Institute of Hydrology[1]
Ministry of Energy, Water Resources and Development[2]
Public Works Department[3]
Water Resources Board[4]

1 Natural Environment Research Council
2 Zimbabwe Government
3 Malawi Government
4 Sri Lanka Government

Keyworth, Nottinghamshire British Geological Survey 1989

Project Leader and Editor: *Dr E P Wright*

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EXECUTIVE SUMMARY

Basement aquifers are of considerable importance in tropical regions because of their widespread extent and accessibility and particularly so in the more arid countries or those with seasonal rainfall because there is commonly no alternative sources of water supply for dispersed rural communities. There is an increasing demand also in more humid regions, mainly in recognition of groundwater's better quality.

The main outcrops of crystalline basement rocks of the tropical regions are in sub-Saharan Africa, Brazil and South Asia. These studies exclude aquifers within sedimentary cover rocks, some of which are also of Precambrian age.

Africa has a more dispersed rural population than South Asia and the current scale of groundwater development is much less. It is estimated that in sub-Saharan Africa, less than 30% of the rural population has access to clean potable supplies of minimum quantity (25 litres per head per day). The bulk of the additional requirement to attain this basic demand will need to be supplied by groundwater from basement aquifers.

Basement aquifers are predominantly low yielding and development is mainly by boreholes and wells fitted with handpumps or small motorised pumps. Drilling costs constrain development and it is estimated that even when basic requirements of Africa's rural communities are satisfied, total abstraction from the basement aquifers will be much less than typical recharge rates. There is therefore a significant potential for additional usage, possibly for minor urban supply or small-scale irrigation, if methods for increased abstraction are feasible and economic. The Collector Well Project has been concerned with one such method. A Final Report on this Project has been submitted to ODA (Wright, 1988).

The programme of Work carried out between 1984-1989 is listed below but reviewed in more detail in the 'Summary and Recommendations' section which follows.

(a) State-of-the-Art Reviews on Hydrochemistry, Geophysical Methods, Remote Sensing and Weathering Processes in relation to Basement Aquifers (1984-5).

(b) Questionnaires on basement aquifer occurrence and development were circulated and replies received from Botswana, Ghana, Kenya, Malawi, Mozambique, Tanzania and Zimbabwe (1984-5).

(c) Field studies were carried out in Malawi, Zimbabwe and Sri Lanka (1985-1988) in order to identify more precisely the main controls to aquifer occurrence with a view to improving the methodology of exploration and development and to gaining a better assessment of groundwater potential. The results have clarified the targets to be identified in borehole and well sites and discussed the most appropriate methodology to resolve them. Recharge rates have been determined more accurately and shown to be in the main range of 8-16% of mean annual rainfall which is very considerably in excess of what is likely to be abstracted using the current methodology.

(d) A Workshop was held in Harare, Zimbabwe, in June 1987 which reviewed the interim results and at which contributions were given by professionals from many countries in Africa and selected countries elsewhere, notably Brazil, Canada, Australia, India and Sri Lanka. The Proceedings have been published.

(e) A meeting was held at the Geological Society on 17/18th April 1989 which reviewed the final results and at which contributions on related research results were given. To assist extrapolation of results, a number of invited speakers were requested to give continental reviews on the geology and geomorphology of the basement areas of Africa.

(f) A special publication of the Geological Society on the hydrogeology of basement aquifers has been given provisional approval.

Although quantitative analyses have been carried out, the degree of correlation, the complexity of controls and the areal variability are such that comprehensive rules for exploration and development are not yet feasible. What is important at the present time is ensuring sufficient flexibility in the procedural programmes to allow for this variability of aquifer occurrence but also to make use of the more local correlations. Flow diagrams and 'intelligent' computer programmes to assist borehole siting should be feasible to produce.

SUMMARY AND RECOMMENDATIONS

1. Duration and General Programme

The BGS/ODA Research Programme on the Hydrogeology of Basement Aquifers commenced in April 1984 and continued through to March 1989. The results of the study were reviewed at a Geological Society meeting in April 1989 at which other speakers were present, both from the UK and elsewhere. A special publication of the Geological Society is planned. As an interim review during the Programme, a Workshop was held in Harare in June 1987 for which Proceedings have now been published.

The first year was mainly devoted to preliminary planning and review studies and the final year to summary reporting, although a number of interim reports have also been produced throughout the programme and are listed in the bibliography. The field studies in Malawi, Zimbabwe and Sri Lanka were carried out in the intervening three years. Although Sri Lanka was among the countries in which field studies were undertaken, the main emphasis of the Project has been on the basement aquifers of Africa, justified because of their particular importance and development needs.

There would have been advantages to be gained had the research programme been integrated or associated with one or more development projects in the countries concerned, since short overseas visits which involved detailed and wide-ranging field studies tend not to be overly cost effective. To offset this limitation, locations of study were selected in which recent development projects with a high standard of data collection had been carried out. These included three integrated projects in Malawi-Livulezi, Dowa West and Lilongwe, and two drought relief projects in Zimbabwe - EEC and Japanese Aid (Midlands/Victoria Province). The BGS team were supported by professional/technical staff of the main national organisations concerned with groundwater. The hydrological studies obtained support from the appropriate hydrological branches of the same Ministries.

2. ACKNOWLEDGEMENTS

In addition to the overseas collaborators whose names are listed in the frontispiece to this report, acknowledgement should also be made to the following people who provided assistance or support to the Project.

Zimbabwe: Ministry of Energy, Water Resources and Development

Mr P Sinnett-Jones, Chief Hydrogeologist
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Malawi: Public Works Department

Mr S de Souza, Water-Engineer in Chief
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3. PROGRAMME RATIONALE

Basement aquifers are of considerable importance in tropical regions because of their widespread extent and accessibility and particularly so in the more arid countries or those with seasonal rainfall because there is commonly no alternative sources of supply for dispersed rural communities. There is an increasing demand also in more humid regions, mainly in recognition of groundwater's better quality.

The main outcrops of crystalline basement rocks of the tropical regions are in sub-Saharan Africa, Brazil and South Asia (Figure S1). These studies exclude aquifers within sedimentary cover rocks, some of which are also of Precambrian age.

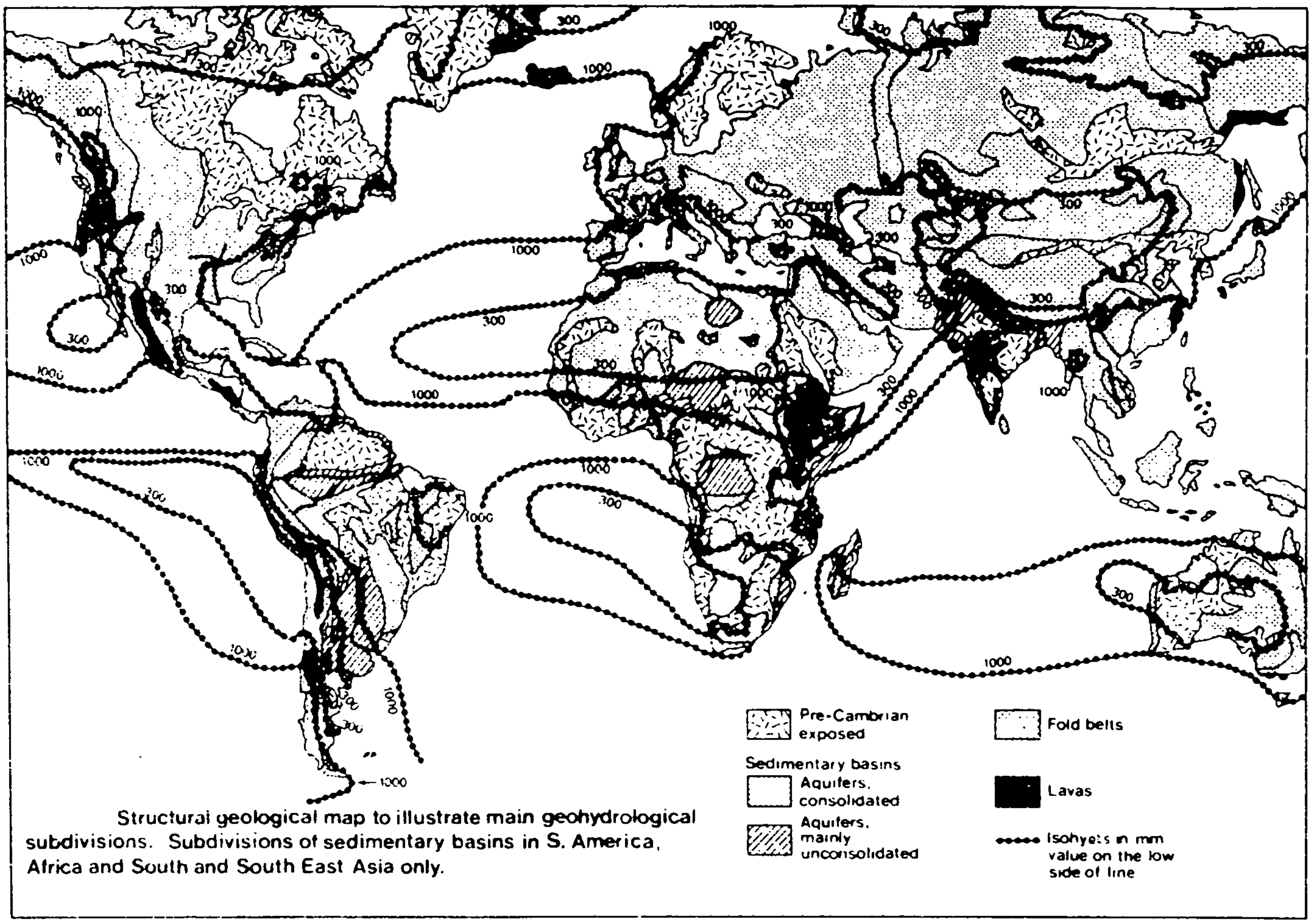
Africa has a more dispersed rural population than South Asia and the current scale of groundwater development is much less. It is estimated that in sub-Saharan Africa, less than 30% of the rural population has access to clean potable supplies of minimum quantity (25 litres per head per day). The bulk of the additional requirement to attain this basic demand will need to be supplied by groundwater from basement aquifers.

Basement aquifers are predominantly low yielding and development is mainly by boreholes and wells fitted with handpumps or small motorised pumps. Drilling costs constrain development and it is estimated that even when basic requirements of Africa's rural communities are satisfied, total abstraction from the basement aquifers will be much less than typical recharge rates. There is therefore a significant potential for additional usage, possibly for minor urban supply or small-scale irrigation, if methods for increased abstraction are feasible and economic. The Collector Well Project has been concerned with one such method. A Final Report on this Project has been submitted to ODA (Wright, 1988).

Basement aquifers are thin and extensive but with considerable variability of occurrence. These circumstances result in a significant borehole failure rate which tends to increase in the drier regions or areas of higher relief. The research programme has been designed with a view to gaining a better understanding of the aquifer systems by studies of the basic controls to occurrence, including geometry, internal structure and recharge rates, and of the appropriate methodology of exploration.

4. PROGRAMME OF WORK

The programme of work and the field studies are set out in Figures S2 and S3. The various categories in Figure S3 are used as a basis for a general discussion of the results obtained during the Project.



Structural geological map to illustrate main geohydrological subdivisions. Subdivisions of sedimentary basins in S. America, Africa and South and South East Asia only.

Figure S1.

PROGRAMME

State of the Art Reviews	Questionnaires	Field Studies	Workshop
Hydrochemistry Geophysics Remote Sensing Weathering Processes	Botswana Ghana Kenya Malawi Mozambique Tanzania Zimbabwe	Recharge/Discharge Aquifer Occurence Exploration Development	Harare/ June 1987

Figure S2.

FIELD STUDIES

Recharge/Discharge	Aquifer Systems	Exploration	Development
Base Flow	Weathering Profiles	Geophysics	Collector Wells
Chloride Balance	Terrain Analysis	Remote Sensing	Drilling Depths
Seepage/Phreatophyte Transpiration: — hydrometeorology — satellite imagery	Structural Analysis	Radon Survey	
	Data Base		
	Borehole Geophysics		
Flow Net [modelling]	Drilling		

Figure S3.

RECHARGE ESTIMATES

[% OF MEAN ANNUAL RAINFALL]

MALAWI

Method	Regions: Livulezi	Regions: Central Plateau	Groundwater Unit 5
Base Flow	8	15	
Chloride Balance			
– Well waters	10		
– Base flow			8
Seepage Loss		(I) 10–16 (II) 33	
Flow Net			10–16
Water Level Changes		1–16 1–4	

ZIMBABWE

Method	Regions: East Central	Regions: South East Central
Base Flow	8–10	(I) 5 (II) [2–9]
Chloride Balance		
– Tunnel drips	10–12	
– Well waters		(I) 3–15 (granites) (I) 1–4 (gneiss)
Water Balance		[1–5]

Figure S4.

To assist extrapolation of the results of the BGS research programme, there were other speakers at the Geological Society meeting who discussed research on basement aquifer hydrogeology in other regions of Africa. Continental review papers were given by invited speakers on Africa's geomorphology and geology with a particular reference to basement rocks. The papers in the Proceedings of the Harare Workshop are also relevant in this respect.

5. RECHARGE ESTIMATES

Figure S4 gives the results of recharge estimates obtained by a variety of methods and expressed as a percentage of mean annual rainfall which is in the main range of 800-1100 mm in two of the study areas - the central plateau of Malawi and the east-central region of Zimbabwe, and rather less (600-900 mm) in the Victoria Province region of S.E. Zimbabwe. The values of recharge may be compared with the maximum abstraction rates of between 1-3 mm/a which will be obtained when the basic minimum requirements to rural communities are eventually provided.

Of the various methods used, baseflow analysis (by hydrograph separation) and chloride balances of rainfall and groundwater are likely to provide the more reliable regional estimates; the former method represents a minimum value since any evaporation from the aquifer system must be added. Flow net and water level changes are constrained in accuracy by the generally high variability of the aquifer parameters, transmissivity and storage. The results indicate an order of recharge in the range 8-16% of mean annual rainfall in the central regions of Malawi and Zimbabwe and a rather lower and more variable range in southeastern Zimbabwe. The variability of the chloride balance estimates in the latter area can be attributed to borehole yields being derived mainly via the fractured bedrock component of the basement aquifers. The deeper circulation systems are likely to include older groundwater resulting in chloride values which are more variable and with a wider range. It is significant to note that in a recent study of recharge into basement aquifers in the Sahelian region of Niger in West Africa (Pointet, 1988)*, recharge estimates based on comprehensive modelling studies are of the order of 20% of mean annual rainfall in the range 600-1200 mm.

6. AQUIFER OCCURRENCE

Crystalline basement rocks are mainly of Archaen and Proterozoic age but to a lesser extent include rocks of younger Phanerozoic age. They exclude the relatively unaltered sedimentary rocks or any recent volcanic cover, even when the former date back to the Precambrian. Basement aquifers occur within a shallow depth range, generally less than 100 m below ground level, and occur within the weathered overburden (regolith) and the weathered and fractured bedrock. There are of course some similarities between basement aquifers and those within volcanic and consolidated sedimentary rocks but there are important differences which distinguish basement aquifers, chiefly in relation to their dual structure.

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* Harare Workshop

Figure S5 shows the distribution of the main hydrogeological units of Africa from which the significance of basement rocks is readily apparent.

Figure S6 gives the sequence of a typical aquifer profile and Figure S7 the catenary variations. Aquifer yields are a function of both storage and transmissivity (Figure S8) and sustained yields are additionally determined by recharge rates.

Recharge is determined mainly by rainfall with added controls by relief, surface soils and subsurface profiles. [Recharge from runoff in basement aquifers is not thought to be a significant factor in the sub-humid to semi-arid regions where the studies have been carried out]. Hydrological studies have demonstrated local correlations with dambo occurrence and soil type but there is no simple process interpretation which can apply to the whole southern Africa region without taking account of the subsurface profile.

Storage occurs mainly in the regolith, which is the disaggregated upper zone consisting of the saprolite and overlying collapsed or colluvial zone. Transmissivity is provided by (i) the transitional zone between the saprolite (disaggregated but with little clay mineral component in the basal section) and the weathered bedrock (saprock) and/or (ii) the fractured bedrock. In Malawi, boreholes derive their yields mainly from the former zone (i) whereas in Zimbabwe and particularly in the drier regions of lower elevations, yields are mainly but not wholly derived from zone (ii). In either case however, there must exist sufficient recharge and sufficient storage in the overlying regolith to sustain abstraction.

Storage is a function of the rest water level (RWL), regolith thickness and regolith mineralogy and fabric. Controls to these features are complex and no simple correlations can be expected although both regional and local controls can be identified. Identifying this component is one of the objectives of exploration, using either ground/remote sensing observations and/or geophysical survey methods.

Rest water levels are dependent on rainfall, relief and hydraulic factors. Precise knowledge of the elevation is less important for borehole exploration when the regolith is thick, such as in the central plateau of Malawi, other than in respect to dug well or collector well siting for which optimum conditions exist over a relatively narrow range only. Rest water levels cannot be identified with a high degree of accuracy by geophysical surveys methods, mainly because the moisture content remains high in the vadose zone of clayey regolith.

Regolith thickness is known to be generally thicker on older erosional surfaces but there are significant regional and local variations to this correlation. The regolith appears to be thicker on the African surface of Malawi than on the surface of the same age in Zimbabwe with mean maximum thicknesses of the order of 70 and 30 m respectively. The difference is tentatively ascribed to the higher latitudinal position of Zimbabwe outside the tropical zone at the time of the formation of the African surface in early Tertiary times.

GROUNDWATER REGIONS IN AFRICA

(After Dijon - Les Eaux Souterraines de L'Afrique)

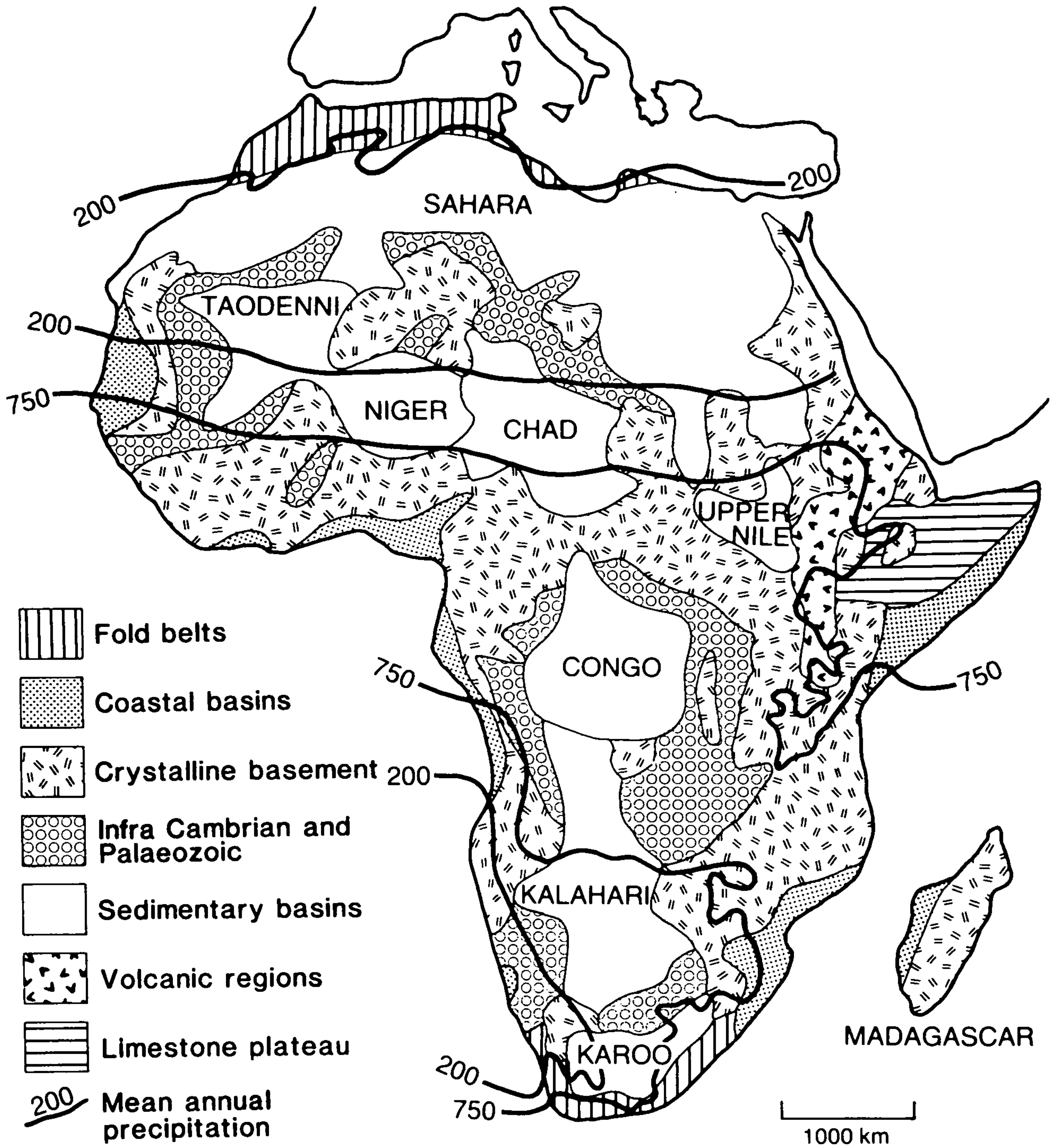


Figure S5.

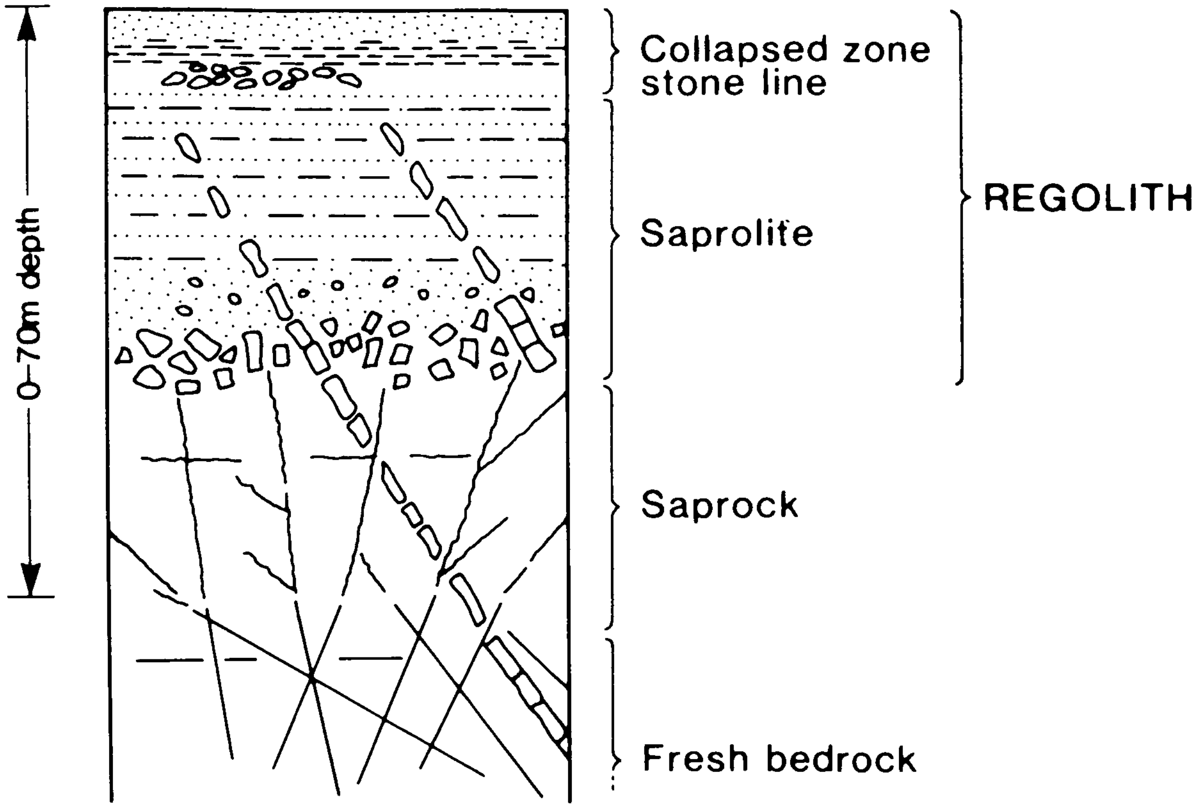


Figure S6. Typical weathered profile above crystalline basement rocks.

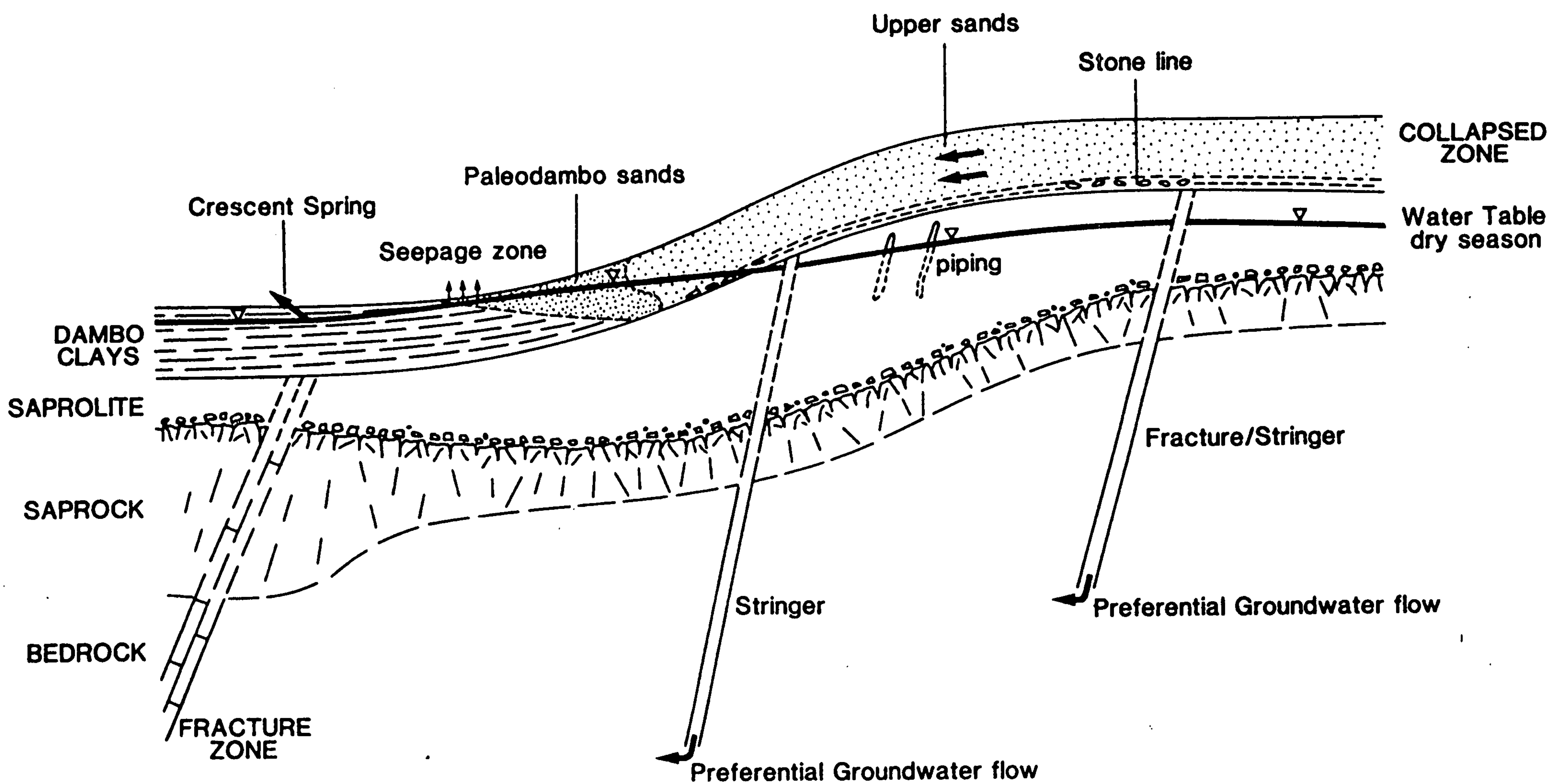
Notes:

(1) Collapsed zone. This may show marked lateral variations being generally sandy on watershed areas with illuviated clay near the base and sometimes a stone line changing to predominantly neoformed clay minerals in valley bottomlands (dambos). Slope bottom laterites may also occur associated with the peripheral dambo clays.

(2) Saprolite is derived by in-situ weathering but is disaggregated. Permeability and effective porosity tend to decrease at higher levels as a consequence of increase in secondary kaolinite minerals.

(3) Saprock is cohesive weathered bedrock.

Figure S7. Schematic basement aquifer cross-section.



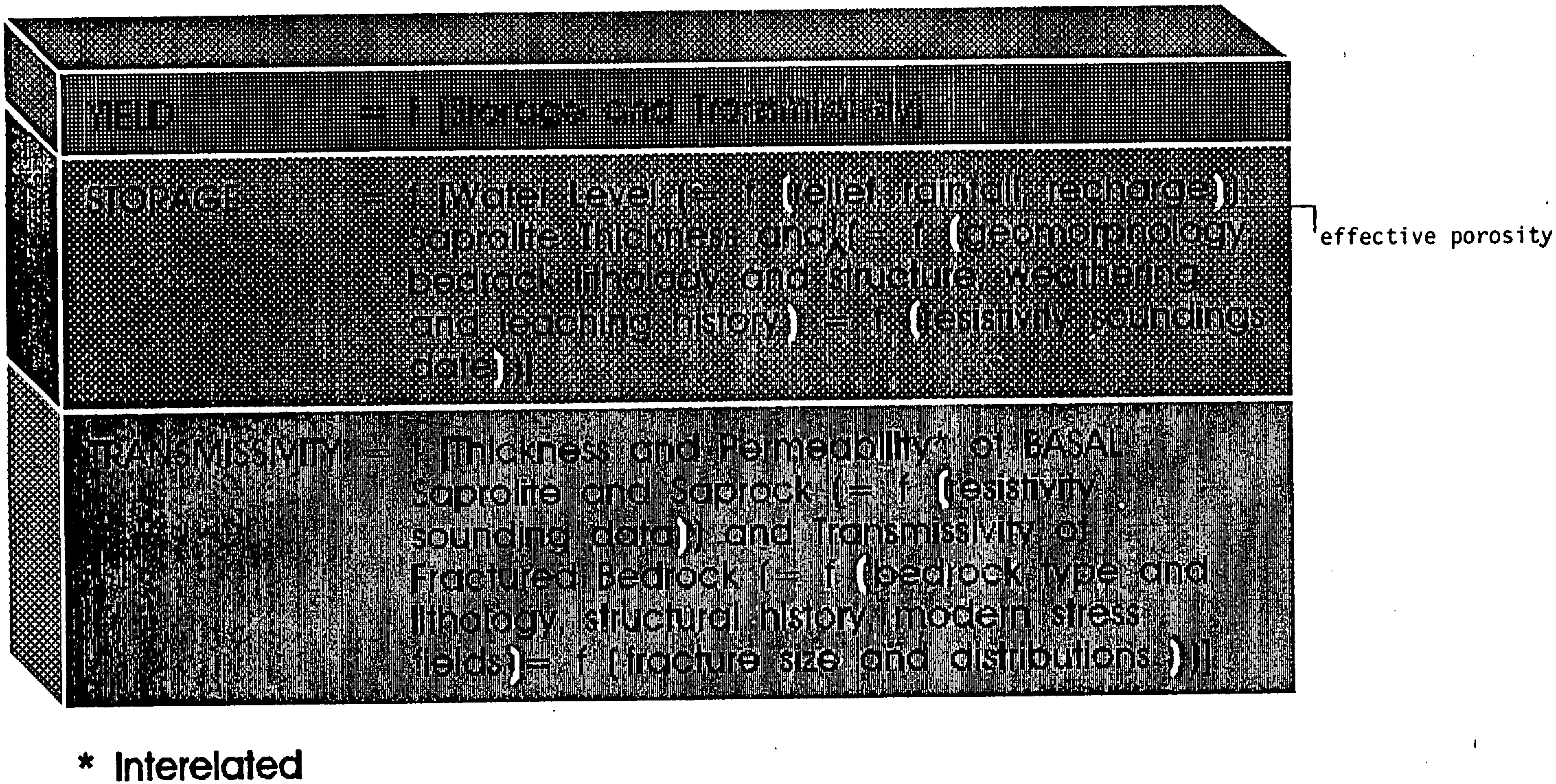

YIELD = f [Storage and Transmissivity]
STORAGE = f [Water Level (= f (relief, rainfall, recharge)), Saprolite Thickness and χ (= f (geomorphology, bedrock lithology and structure, weathering and leaching history) = f (resistivity soundings data))]
effective porosity
TRANSMISSIVITY = f [Thickness and Permeability* of BASAL Saprolite and Saprock (= f (resistivity sounding data)) and Transmissivity of Fractured Bedrock (= f (bedrock type and lithology, structural history, modern stress fields) = f (fracture size and distributions))]
* Interelated

Figure S8.

Regolith thickness controls and features may be summarised as follows:

- no observed correlations with the identified subdivisions of the African surface in central Malawi but a broad correlation with relief being thicker (mean values) in areas of lower relief (although with a wider range),

- thickness is known to increase over individual fracture zones (Figure S9) but in the Livulezi project area no correlation was observed between thickness and lineament density either observed or extrapolated from adjacent areas of thinner regolith. It is assumed that other controls to thickness have predominated,

- thickness increases below inselbergs as a consequence of runoff,

- thickness may reduce below dambo clays due to accelerated leaching of lateral groundwater flow,

- thickness increases over bedrock with greater proportions of the less resistive minerals, e.g. biotite,

- thickness increases on coarser grained rocks,

- thickness is more variable near the contact zone of erosional surfaces (which can be predicted) but significant variability exists below areas of uniform relief for which no reasons can be observed,

- thickness can be identified by geophysical survey techniques including seismic, resistivity and EM but accuracy reduces with increasing variability of the basal surface of weathering or with the occurrence of marked transitions.

Effective porosity is a function of the grade of weathering and the leaching history and the characteristics may be summarised as follows:

- higher when grade of weathering is poorly advanced, i.e. disaggregation with little clay mineralisation. The regolith of the Masvingo project area is of this type,

- lower in the early stages of weathering when biotite is converted to hydrobiotite and increasing in the later stages with development of vermiculite or kaolinite. The latter stage is still of lower effective porosity than that of the disaggregated regolith,

- higher as a result of strong leaching and kaolinite dissolution such as at the base of inselbergs, below dambo clays or at the junction of erosion surfaces.

These correlations between resistivity and clay minerals (and type of clay minerals also) is shown in Figure S10 reproduced from Barker (1982). Effective porosity is also to some degree a measure of permeability and may be critical to even the test yields of a borehole. Effective porosity can be assessed by borehole or surface geophysical surveys (resistivity).

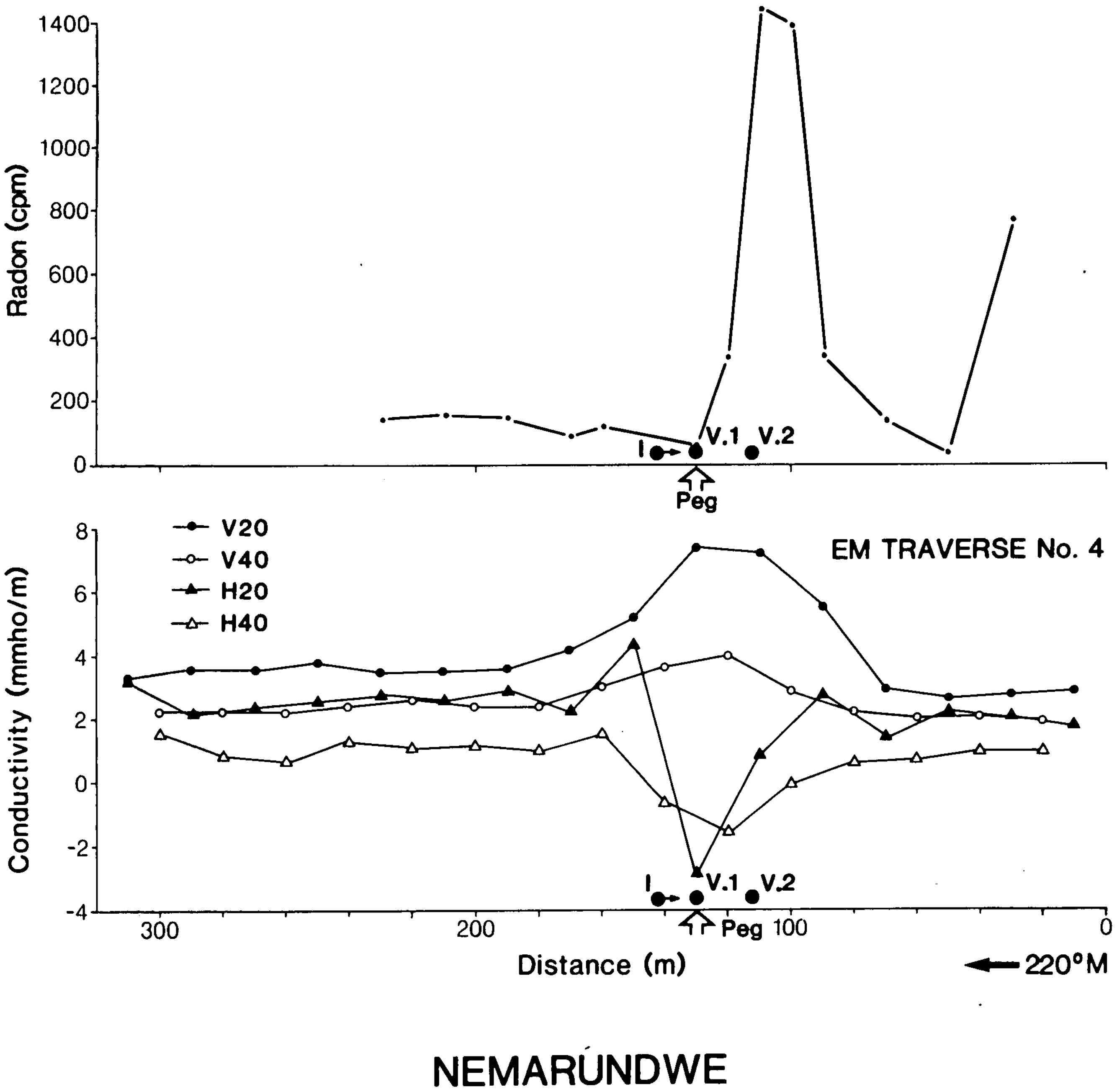


Figure S9. EM and Radon profile across lineament demonstrating localised increase in regolith thickness.

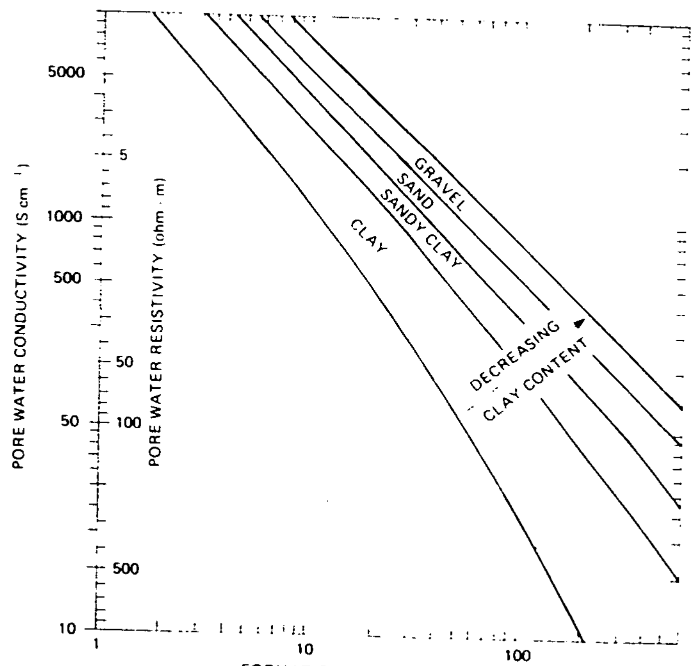


Fig. S10. Relationship between formation resistivity and pore water resistivity for different rock materials (after Barker)

Yields relate both to accessible storage and transmissivity. The main levels of inflow appear to occur in the transitional zone from saprolite to saprock (or occasionally at the intersection of rapid throughflow channels such as quartz veins) and from productive fractures in the bedrock. The occurrence of these zones of inflow are known from drillers logs, statistical correlations and, during the BGS drilling, by direct observations (Figure S11).

The transition zone can sometimes by resolved by VES surveys and has an intermediate resistivity between the regolith and fresh bedrock. Thickness of this transitional zone might reasonably be expected to correlate with regolith thickness but there is not necessarily a corollary with yield. Figure S12 shows the wide range of regolith thickness associated with dry/low yielding boreholes although statistical summaries in the Malawi Strip have demonstrated a broad correlation of yields with regolith thickness. What seems likely to be required is an optimum combination of adequate transmissivity (reflected in both the thickness of the transition zone and the thickness of the regolith) and a high effective porosity which, as discussed earlier, will relate to grade of weathering. The proposed combination may correlate generally with the criteria laid down in the UN Master Plan for Zimbabwe which requires an adequate thickness of saturated regolith of an intermediate resistivity range although this data relates only to the main regolith.

The bedrock fracture zones cannot be resolved directly by geophysical surveys other than by an association with thicker weathering and EM/radon anomalies (Figure S13). The emphasis in this context is on relative changes in regolith thickness; controls other than structure are likely to be reflected in the degree of thickness. In the results of the drilling programme, the larger yields did not occur in the boreholes with the thickest regolith, even when the resistivity is taken into account.

7. EXPLORATION AND DEVELOPMENT

Basic separation of the basement aquifer into regolith and bedrock components is a useful terminology but must not disguise the situation that the systems essentially co-exist and the preferential development is a consequence of local conditions of aquifer occurrence, convenience and economic factors. In recent years in Malawi, the emphasis has been on development of the regolith system other than where the regolith is thin, as in areas of higher relief; in the future, yield and reduction-in-maintenance criteria might require fuller consideration of the deeper bedrock profile. In Zimbabwe and particularly below the Post African erosion surface, which covers the greater part of the country, development of the bedrock aquifer predominates although substantial numbers of boreholes are completed in the regolith. However, since larger rigs have to be used to cope with the likelihood of hard rock drilling, there is less need to limit drilling to restricted locations of thicker regolith.

8. REGOLITH AQUIFERS

Where the regolith is relatively thick and uniform, development can be largely restricted to this aquifer component, thus allowing the use of lighter rigs, including cable tool. Geophysical surveys may be restricted to minimal use in integrated type projects employing several rigs, other

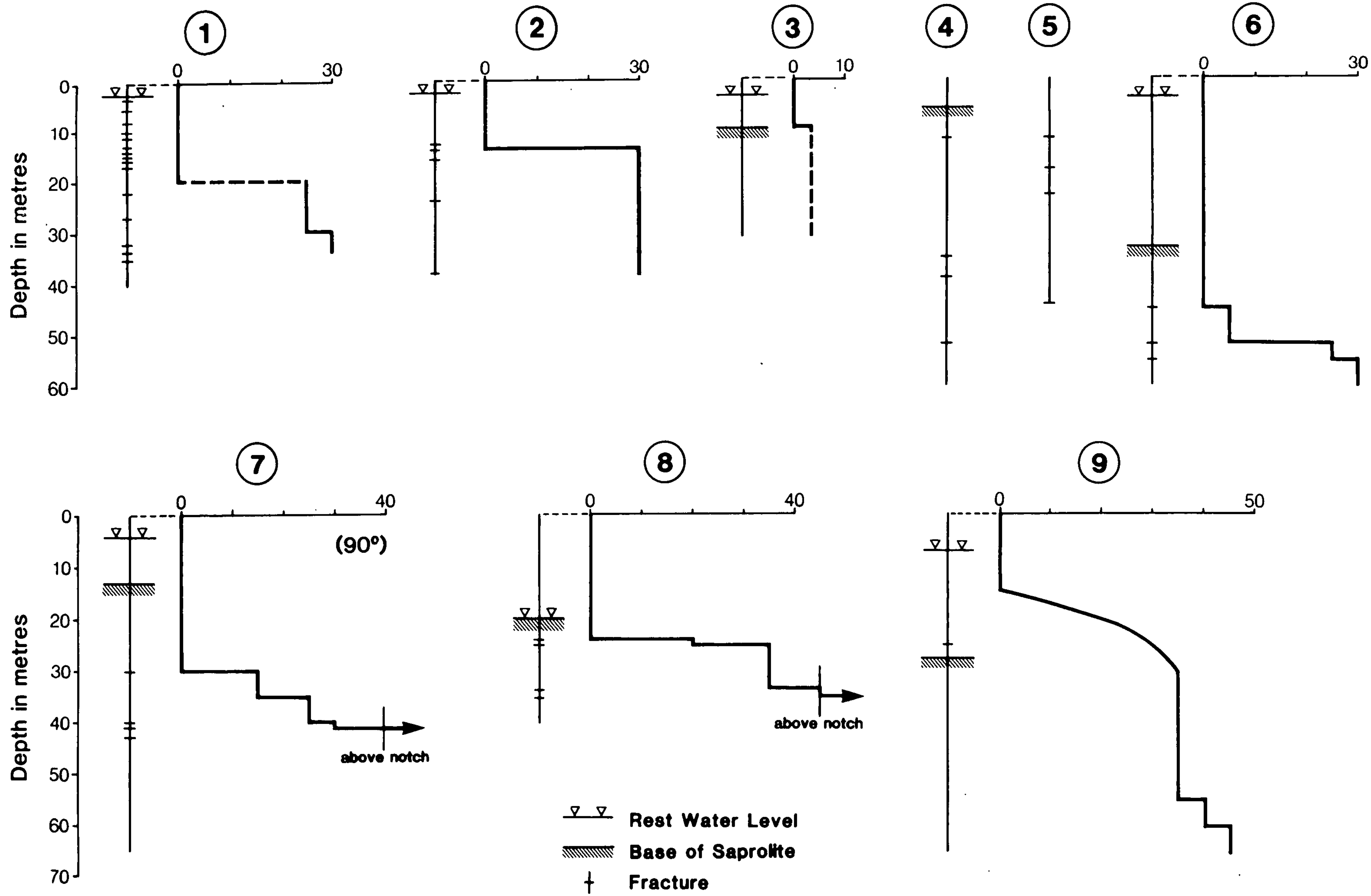


Figure S11. **Drilling Discharge in mm over V Notch (45° or 90°, when shown)**
(Data from BGS test drilling programme)

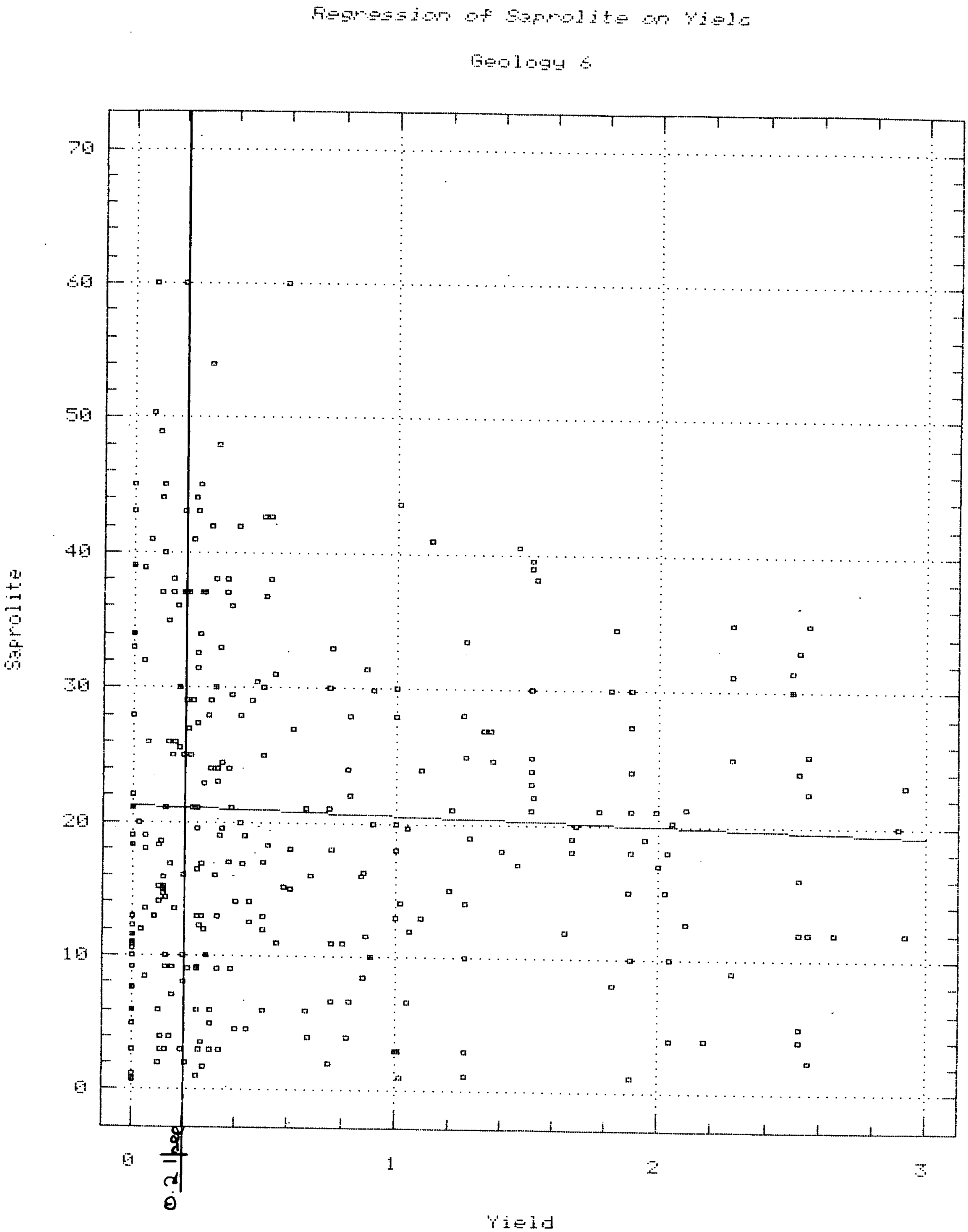


Figure S12. Plot of yields versus regolith thickness (base of saprolite) for Older Gneiss group in southern Zimbabwe.

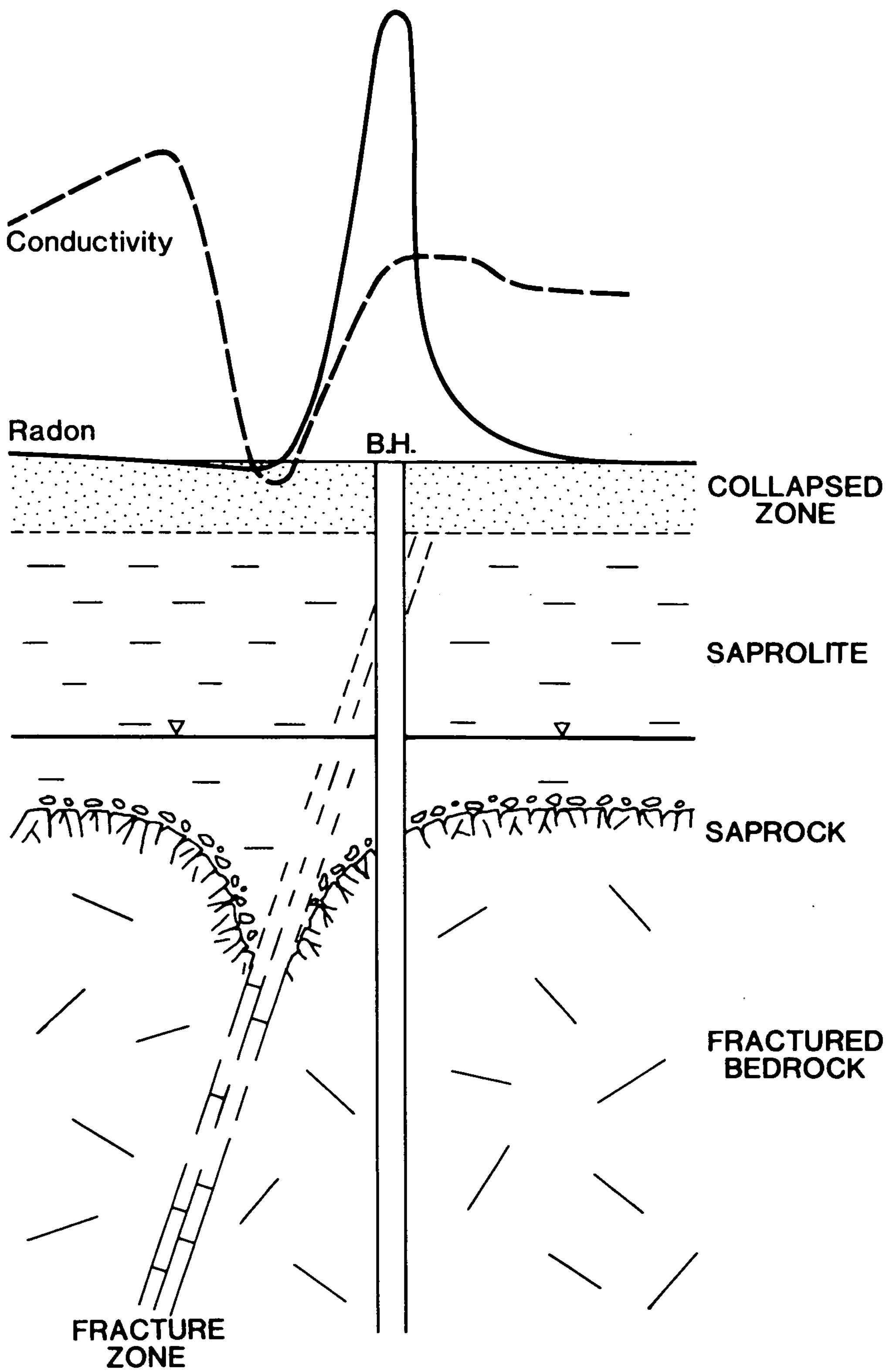


Figure S13. Suggested correlation of EM and Radon profiles across a dipping fracture zone.

than for rapid surveys (e.g. by EM) to identify shallow bedrock. If yields tend to be low or marginal, increased use of geophysical survey techniques, mainly VE Soundings, are merited.

Terrain/geomorphological analysis using maps and air photographs is likely to be of more value in areas of thick regolith, rather than an emphasis on structural features. The results will provide only general guidelines but the accumulation of data may indicate more consistent patterns and correlations.

When bedrock (saprock) penetration is essential to produce the desired yield, the emphasis of exploration should be to identify the thickest regolith of the most appropriate resistivity (highest effective porosity) which is also likely to overlie a thick transitional zone. It is unlikely that rapid throughflow channels or fractured bedrock systems can be identified from surface features, other than where the regolith is exceptionally thin.

9. BEDROCK AQUIFERS

The development of bedrock aquifers is required where the regolith is thin or recharge more localised.

Remote sensing (air photographs mainly) and geophysical surveys are generally justified. EM or seismic surveys are likely to be more appropriate than VES soundings, and should be designed to identify the precise location and if possible the dip of a fracture system associated with a lineament.

The regolith tends to have adequate effective porosity other than overlying basic rocks, and the thickness is generally much less critical than the success in intersecting the productive fracture zone. Where this is thin, the dip becomes more critical. The more successful boreholes in the BGS drilling programme were not located on the thickest regolith. Radon surveys could assist in assessing permeability and dip of the fracture system.

Azimuth and length of fracture traces and even general lineament density distributions appear to have no correlation with yield and the effect of current stress fields may be an overriding factor influencing all older fracture systems.

The use of inclined drilling is worth consideration when access for a vertical hole is constrained or also to enable improved intersection of parallel sets of vertical fractures. Hydraulic fracturing to improve intercommunication is also recommended for boreholes with marginal yields although the methodology was not tried on the project, as had been intended. The more simple borehole designs are thought to be most effective with open hole completion where possible in the fractured bedrock.

Data base analysis will assist determination of optimum drilling depths until better factual knowledge becomes available on fracture distribution with depth. A simple exponential relation of fracture frequency with depth is more likely to occur with flat lying fracture systems related to pressure release but the intersections where the fractures are vertical or steeply dipping will be more affected by the precise borehole site.

10. RECOMMENDATIONS FOR FURTHER WORK

(1) More detailed correlative studies are recommended of regolith thickness and regolith resistivity values with borehole yields and with thickness/permeability of the transitional zone at base of regolith. Fuller assessments should be made of existing data bases and some field studies may be merited.

(2) Extended terrain analysis studies are recommended with a view to improved correlations with weathering profiles and regolith thickness and of weathering grade and effective porosity.

(3) Detailed studies are recommended of fracture occurrence and frequency in bedrock aquifers in relation to yields, borehole depths and bedrock types. Studies would require additional drilling, including core drilling and extended borehole geophysical surveys of both new and existing boreholes, if possible including the use of downhole radar and telemeter surveys as well as standard logs. Surface geophysical surveys should be assessed to identify how accurately they can define a fracture zone's configuration (width/dip).

(4) Experimental studies on hydraulic fracturing.

(5) Repeat of studies to evaluate dambo seepage by satellite (thermal) imagery. The previous study confirmed the feasibility and relative variations in rates across the dambos but were handicapped by poor ground control of both surface temperatures and evaporation rates.

1. JUSTIFICATION OF RESEARCH PROGRAMME

Basement aquifers are of importance in tropical regions because of their widespread extent and accessibility. In the arid to sub-humid climate zones underlain by crystalline rocks, there is often no alternative source of water supply for rural communities and even in humid regions, quality considerations promote the use of these aquifers.

Crystalline basement rocks are of intrusive and/or metamorphic origin and mainly of Pre-Cambrian age. Aquifers occur in the weathered overburden and fractured bedrock (see Figure S.6).

Main developments of basement aquifers occur in sub-Saharan Africa, Brazil, South Asia (India and Sri Lanka mainly) and Australia (Figure 1.1.). Africa is distinctive in this grouping because of the very dispersed rural populations and the relatively small scale of current development (as compared for example with South Asia).

Development in Africa is almost wholly for domestic supply and livestock use and it is estimated that at present only about 30% of the rural population has access to clean potable supplies of minimum quantity (25 litres per head per day). The bulk of the additional requirement will need to be supplied from groundwater in basement aquifers.

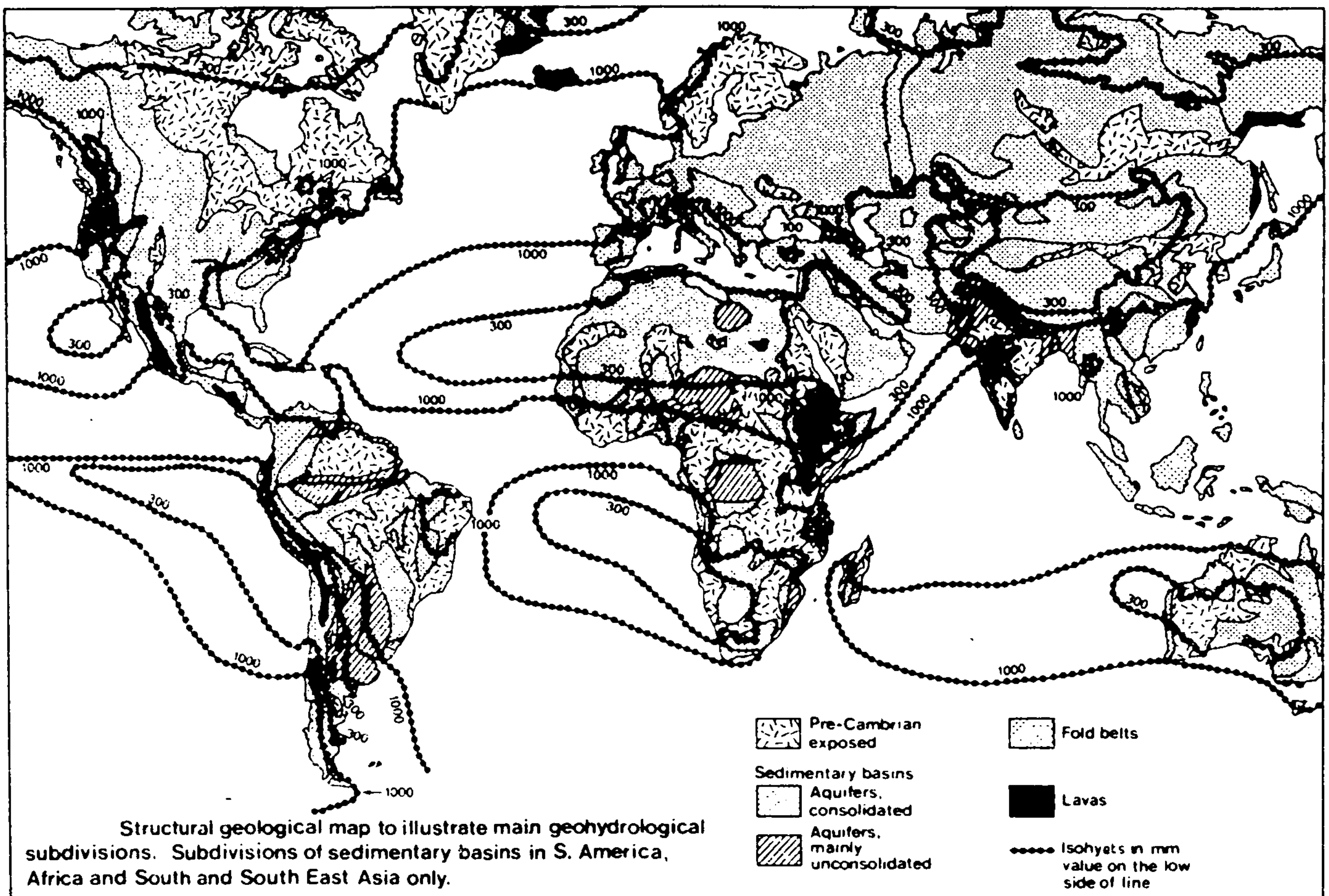
Because of the typically low productivity of basement aquifers, development is mainly from point sources utilising hand pumps or buckets/windlass. Because of economic constraints on borehole numbers, and in accordance with typical population densities, development for the rural communities will eventually abstract the equivalent of between 1 and 3 mm/annum recharge over the catchment areas. Present evidence indicates substantially higher orders of actual recharge, possibly in the range 30-150 mm/a where mean annual rainfall is in the range 500-1000 mm. There is therefore potential for additional usage, if methods of increased abstraction can be developed which are both feasible and economic. The Collector Well Study which has been an ancillary Project, has been concerned with a method to increase abstraction rates from basement aquifers with the added advantage of low drawdowns. The abstractions achieved in the experimental programmes make it feasible to use such wells for small urban supply or small-scale irrigation.

There are a number of important constraints to development which need to be recognised both from the viewpoint of general planning but also in the formulation of research studies. These include:-

(i) The typically high failure rate of boreholes in basement aquifers, commonly in a range from 10-50% with the higher percentage values in drier regions or where the weathered overburden is thinner.

(ii) Shallow occurrence and fissure dependent permeability makes basement aquifers susceptible to surface pollutants, most notably of biological origin.

(iii) The basement aquifers have small storage which may deplete significantly during sustained drought periods. Basement aquifers are therefore also sensitive to the effects of 'desertification' which can reduce recharge.



Structural geological map to illustrate main geohydrological subdivisions. Subdivisions of sedimentary basins in S. America, Africa and South and South East Asia only.

Figure 1.1

(iv) The need to maintain large numbers of dispersed boreholes and wells imposes an administrative and economic burden on both local and central governments. It is not unusual to find up to 50% of boreholes inoperative at any one period of time as a consequence of pump or borehole failure.

(v) The difficulties of constructing successful boreholes in basement aquifers has had two important consequences: (a) boreholes with marginal yields, e.g. <0.1/0.15 litres/sec are commonly equipped for production but frequently fail during future use, particularly during the dry season, and (b) because the village has been provided with a 'supply', it now loses any priority for further development.

A situation also arises as a result of a fairly rigid interpretation of Master Plan criteria. A particular area can be excluded for consideration of a borehole supply by reason of rejection of all sites examined in the course of a standard survey programme.

(vi) High pumping drawdowns will cause greater stress on the production pump and probably an increased maintenance requirement. There are therefore potential advantages by the construction of boreholes with higher specific capacities, either in better locations or by deeper drilling.

2. RESEARCH NEEDS

These include:-

(i) Development of methodology to reduce borehole failure rates and maintenance requirements. In this latter context, apart from the problem associated with sand pumping which can be counteracted by improvement in borehole design, an increase of specific capacity could reduce maintenance requirements on hand pumps.

(ii) Develop methodology to allow increased abstraction from basement aquifers. Where successful, particular needs could include piped supplies to large villages and small towns and small-scale irrigation projects.

(iii) Evaluate the resources and resource occurrence more precisely in the context both of development efficiency and with a view to preventing deterioration either by surface pollution or the effects of desertification.

3. BGS RESEARCH PROGRAMME

This programme has included:-

- state-of-the-art reviews on four key topics - geophysical studies, weathering processes, hydrochemistry and remote sensing.

- circulation of a detailed questionnaire to all countries in Africa with a significant basement outcrop area.

- the holding of a Workshop on Basement Aquifer Hydrogeology in Harare, Zimbabwe in July 1987. The proceedings have now been published. [see Bibliography for list of papers]

- detailed studies on selected topics carried out in Malawi, Zimbabwe and Sri Lanka. These studies were co-operative programmes carried out in conjunction with staff of national organisations of the three countries. The objectives were in general accordance with the research needs listed earlier and included limited but systematic studies. It had been hoped to associate these studies with development projects which would have allowed longer term staff inputs and facilitated field investigations but in the event this did not prove possible.

3.1 Malawi Programme

Background. Basement aquifers cover the greater part of the country other than the extreme south and the Lake Malawi immediate littoral area (Figure 3.1). The main 'Central Plateau', (Figure 3.2), is an 'African' surface of early Cainozoic age and the bedrock is overlain by an extensive cover of thick (up to 70 m), weathered overburden (regolith as defined later), except on rocky inselbergs, in the vicinity of the Rift scarp and of major incising streams, rejuvenated by the rifting.

Boreholes on the central plateau are generally completed within the regolith because it is cheaper to do so and success rates* are generally high, other than where affected by quality constraints, e.g. high sulphate in the Dowa area. In integrated development projects employing substantial numbers of small rigs, surface geophysical techniques may not always be utilised. Geophysical survey techniques are generally used on dispersed programmes and in the more difficult areas.

A second important factor has been identified but requires confirmation by statistical analysis. Although a high success rate is common, particularly in the recent integrated projects, the specific capacities of boreholes are often quite low. This may be a consequence of drilling being stopped when bailer tests show an apparently sufficient yield for hand pump supply.

3.1.1 Summary of research studies.

The programme included studies into the following aspects:-

(i) Problems of water quality (sulphate, fluoride, iron) in basement groundwaters.

(ii) Since boreholes in Malawi are mainly completed in the regolith, any information on the thickness or lithological characteristics of the regolith which can be derived by indirect means could be of value. Correlations have been attempted with the following features:

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* Defined usually as a test yield of 0.25 litres/sec.

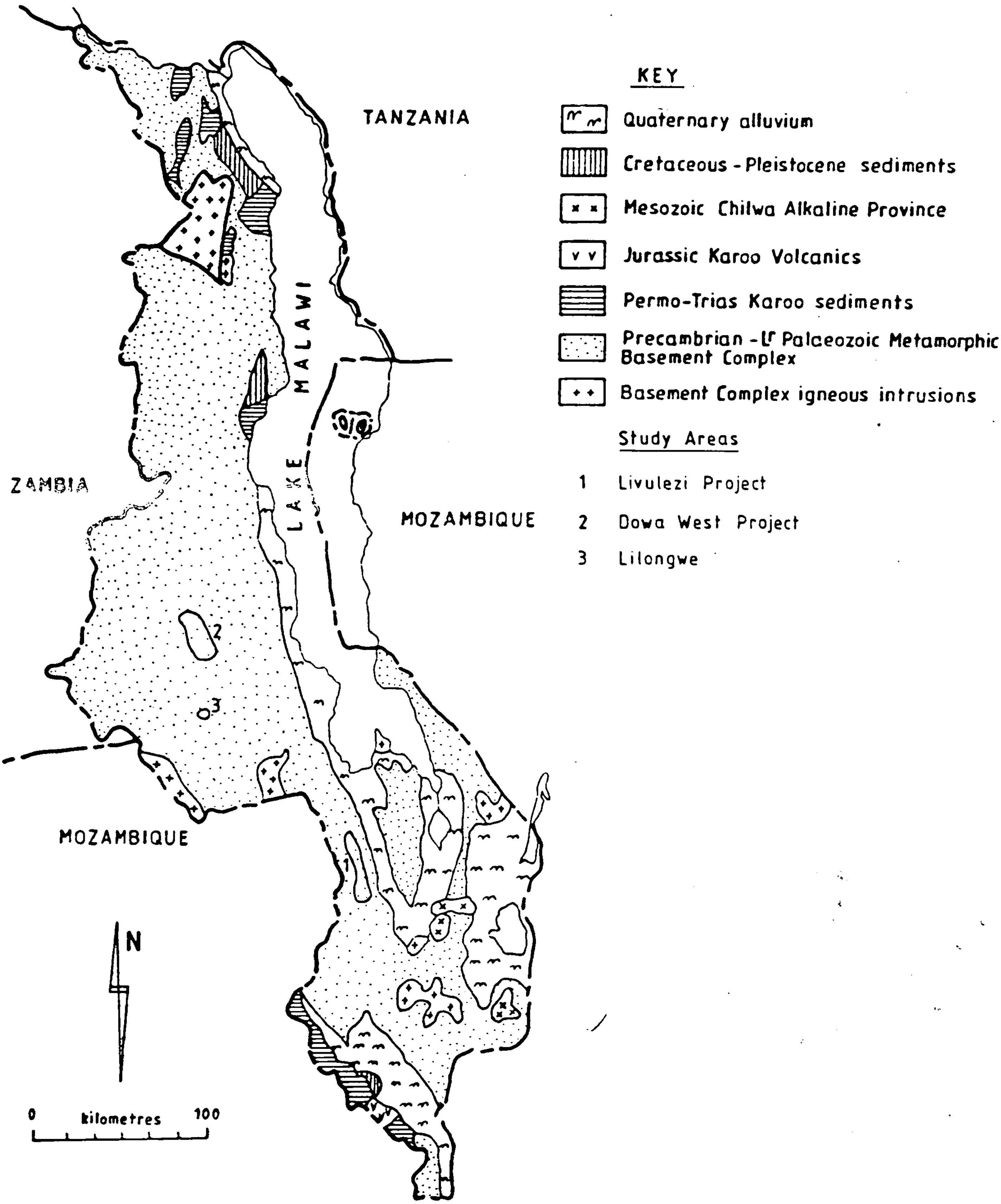


Figure 3.1 Summary Geological Map of Malawi.

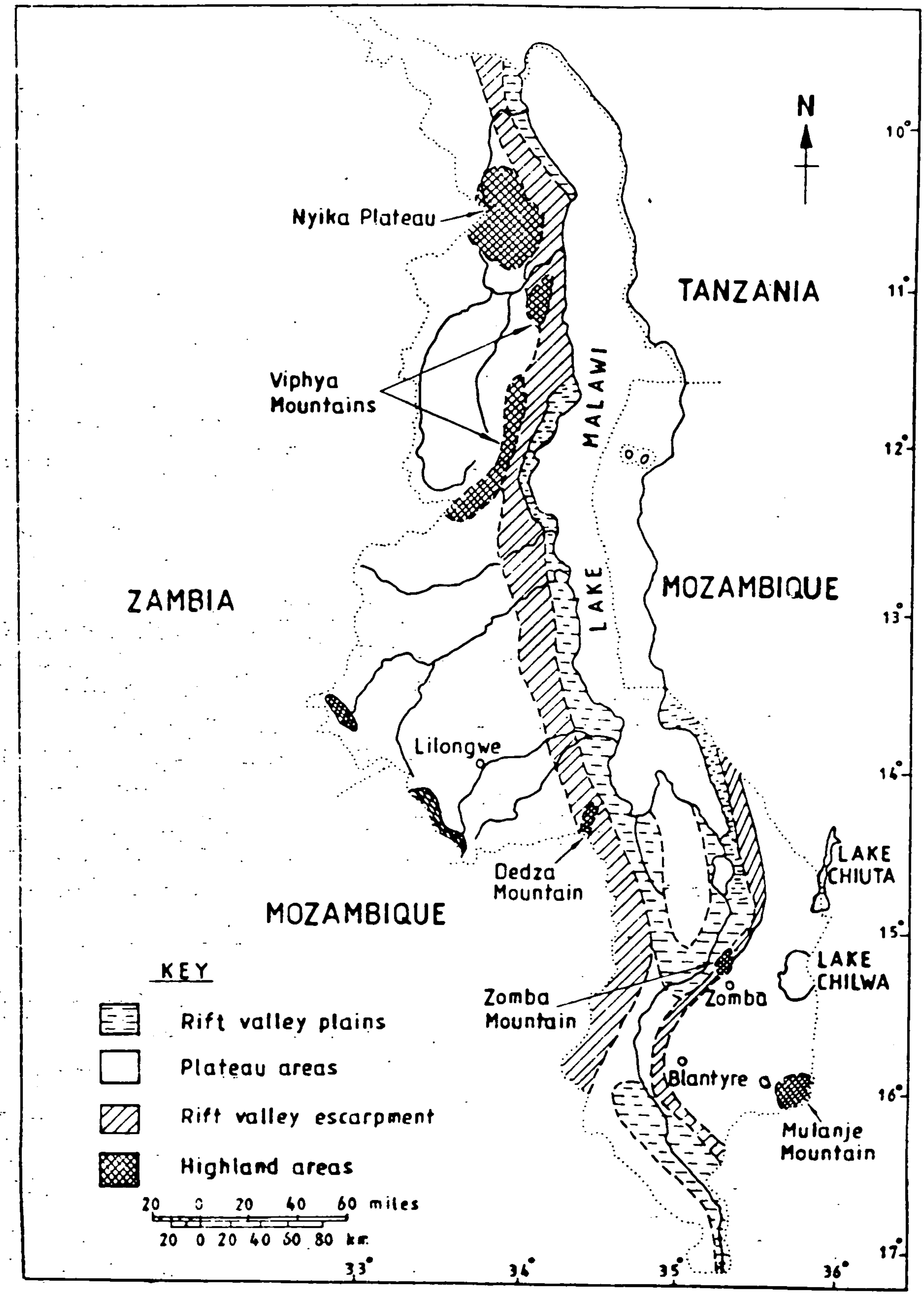


Figure 3.2 Physiographic Map of Malawi.

- extrapolation of lineament density patterns into areas of thick regolith which show a paucity of such features in consequence of the thickness of cover,

- correlation of thickness and other characteristics of the regolith with terrain analysis, and

- relative relief, stream frequency, dambo+ area and erosion surfaces.

(iii) Detailed hydrogeological, geological and geophysical studies made in cross sections of one or more dambos in different evolutionary states. Cored boreholes and shallow auger holes have been used as basic lithological control.

(a) Mineralogy, pore fluid chemistry and physical properties of core material.

(b) Installation of two dimensional piezometric network in cross section of a dambo; subsequent seasonal monitoring of water levels; geochemical sampling in saturated aquifer.

(c) Borehole geophysical logging. Spectral gamma and resistivity proved to be the most diagnostic of profile characteristics.

(d) Surface geophysical correlations by traversing across the same section using seismic, electromagnetic and resistivity techniques.

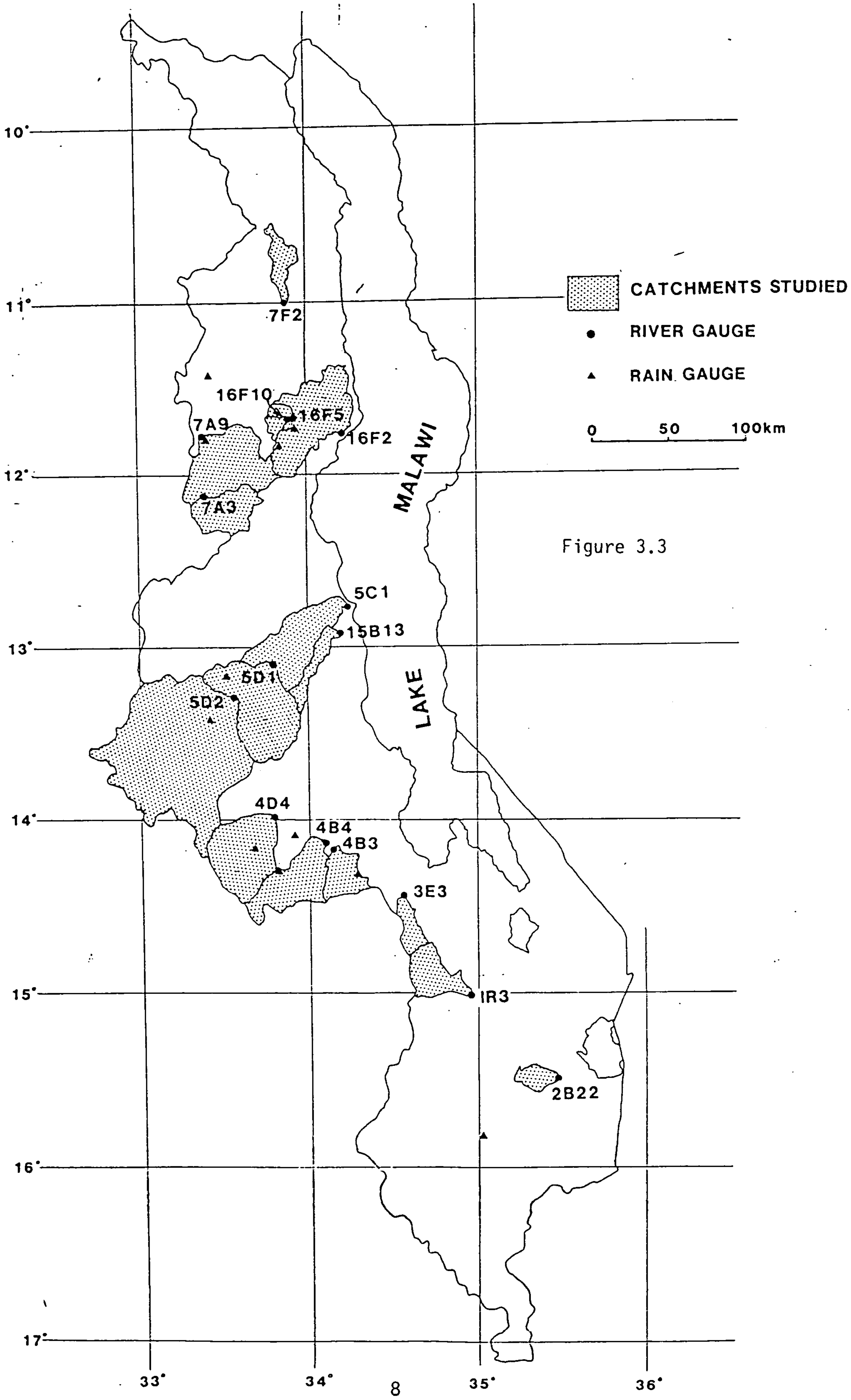
(iv) Hydrological studies - More extensive dambo surveys using hand augers to obtain data on water levels, fluid chemistry and near surface lithology. Since dambos include groundwater discharge areas, studies can provide information which may assist recharge and water quality considerations in the main aquifer.

(v) Catchment studies - Sixteen existing gauged catchments selected in Malawi from total network to show range of basement rocks and rainfall variation. Geomorphological characterisation of catchments included relative relief, stream frequency and dambo area. Monthly samples of runoff and rainfall were collected for geochemical analysis with chloride to provide information on recharge and other ions as indicators of rock weathering interactions. Surface runoff and areal rainfall data were analysed with main emphasis on low flows (Figure 3.3).

(vi) Data base - Boreholes in an area from Lake Malawi to the Mozambique border which encompasses all three project areas* have been computerised and used for correlative studies and statistical analyses (Figure 3.4).

+ Dambos are seasonally flooded valley lands and have distinctive shapes which are thought to relate to structural and other controls.

* These areas are the locations of recent integrated development projects, borehole data from which have been used for correlations and additional analysis.



CATCHMENTS STUDIED
RIVER GAUGE
RAIN GAUGE
0 50 100km
10°
11°
12°
13°
14°
15°
16°
17°
33°
34°
35°
36°
7F2
16F10
16F5
7A9
16F2
7A3
MALAWI
LAKE
5C1
15B13
5D1
5D2
4D4
4B4
4B3
3E3
IR3
2B22

Figure 3.3

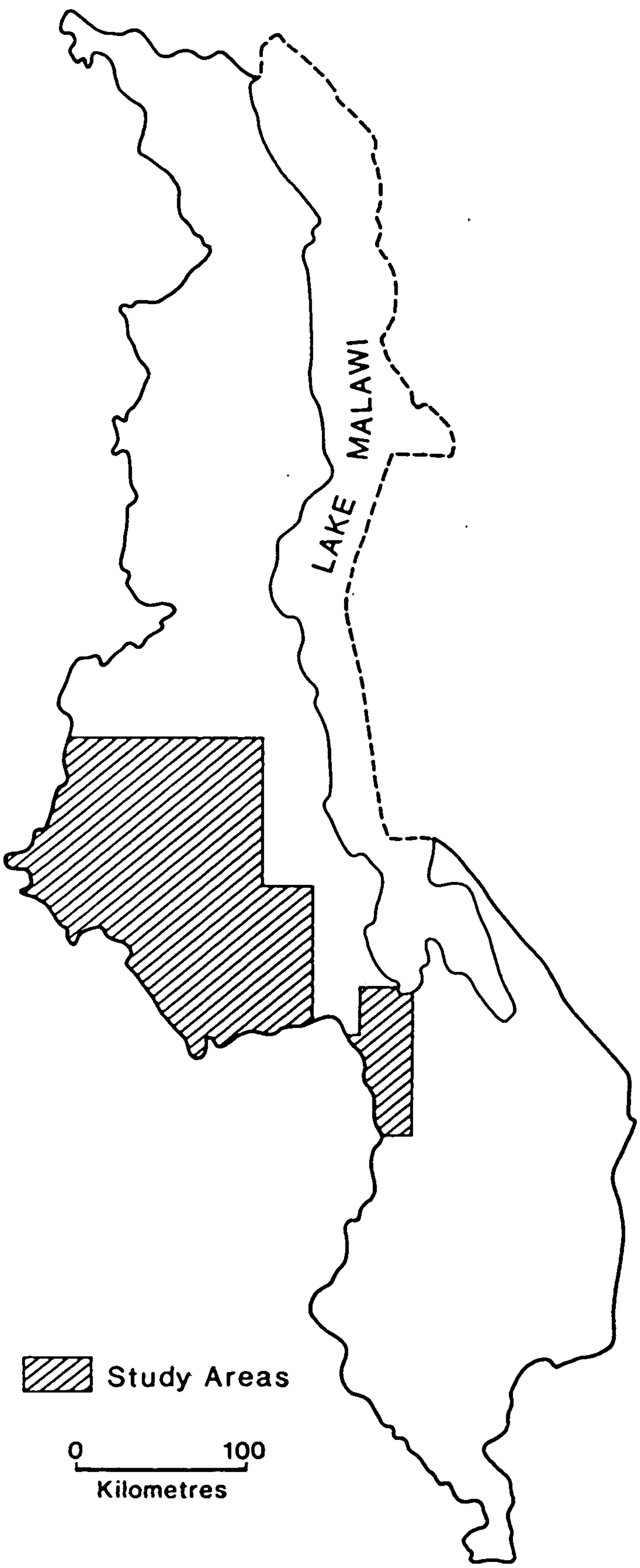


Figure 3.4 Map of Malawi indicating areas for which borehole data has been collected.

The results will be discussed later but it may be noted here that the catchment studies have been constrained by the rather irregular collection of samples of rainfall and runoff.

3.2 Zimbabwe

Background. Basement rocks outcrop over a greater part of Zimbabwe and are transected by a succession of geomorphological surfaces with the younger surfaces at progressively decreasing elevation and correlating also with decreasing rainfall (Figures 3.5 and 3.6). The younger surfaces have more extensive rock outcrop areas and thinner regolith, often of 15 m or less, as compared with the older upland surfaces where it may attain or exceed 30 m. Boreholes are typically cased through the regolith and completed open hole or slotted screen without gravel pack in the underlying weathered bedrock. Success rates reduce in these latter areas particularly where they coincide with reduced rainfall. Geophysics is used routinely for siting boreholes.

3.2.1 Summary of programme

(i) Borehole exploration and yield studies

(a) Selection of main study area in southern Zimbabwe, some 170 x 270 km. Several thousand boreholes exist, mostly Government drilled, but also include two recent aid-funded consultant projects (EEC/Japanese) with good basic data. Success rates in these two projects have been 60% and 50% respectively (assuming specific capacity criteria ≥0.008 l/s/m).

(b) Borehole (and dug well) data base has been set up and records edited and computerised.

(c) Structural analysis of the project area has been carried out including the production of a lineament map based on satellite imagery (scale 1:250,000) and calculations of slope ratios on kilometre square grid.

(d) The locations of all dry and low yielding boreholes and all very high yielding boreholes have been plotted.

(e) Selection has been made of special study areas which include main basement rock groups (schists, older gneisses and older granites, younger intrusive granites, mobile belt gneisses) and which have a high concentration of dry or low yielding boreholes.

(f) Study areas have been subjected to detailed analysis (terrain, air photo, borehole yield and lithology), the geology plotted from any larger scale maps and all boreholes and wells plotted. Lineaments have been digitised and lineament density maps prepared. In a selected area drainage patterns were categorised and analysed.

(g) Borehole sites were visited and general hydrogeological, topographical and structural observations made.

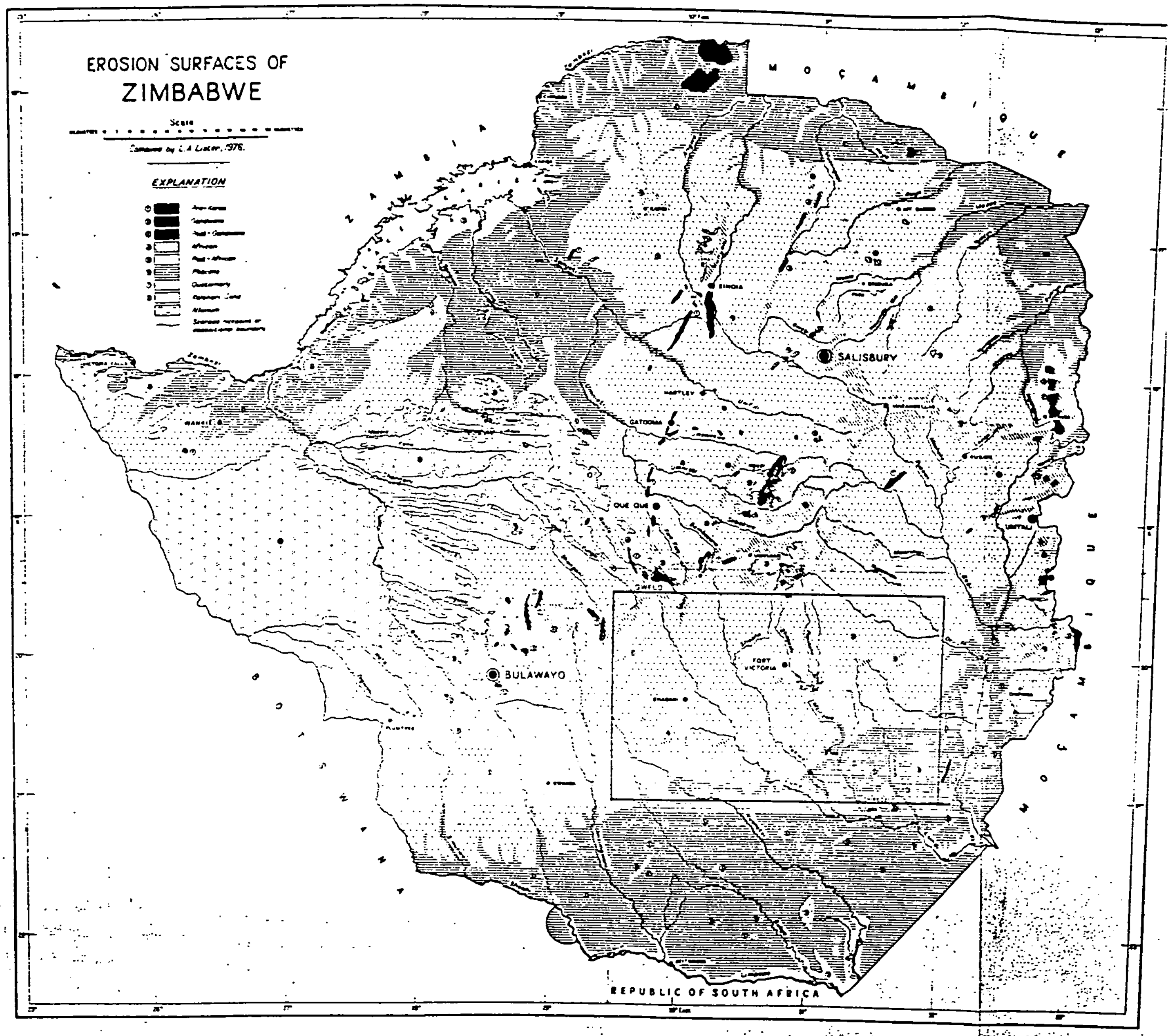


Figure 3.5 (Masvingo Project Area outlined)

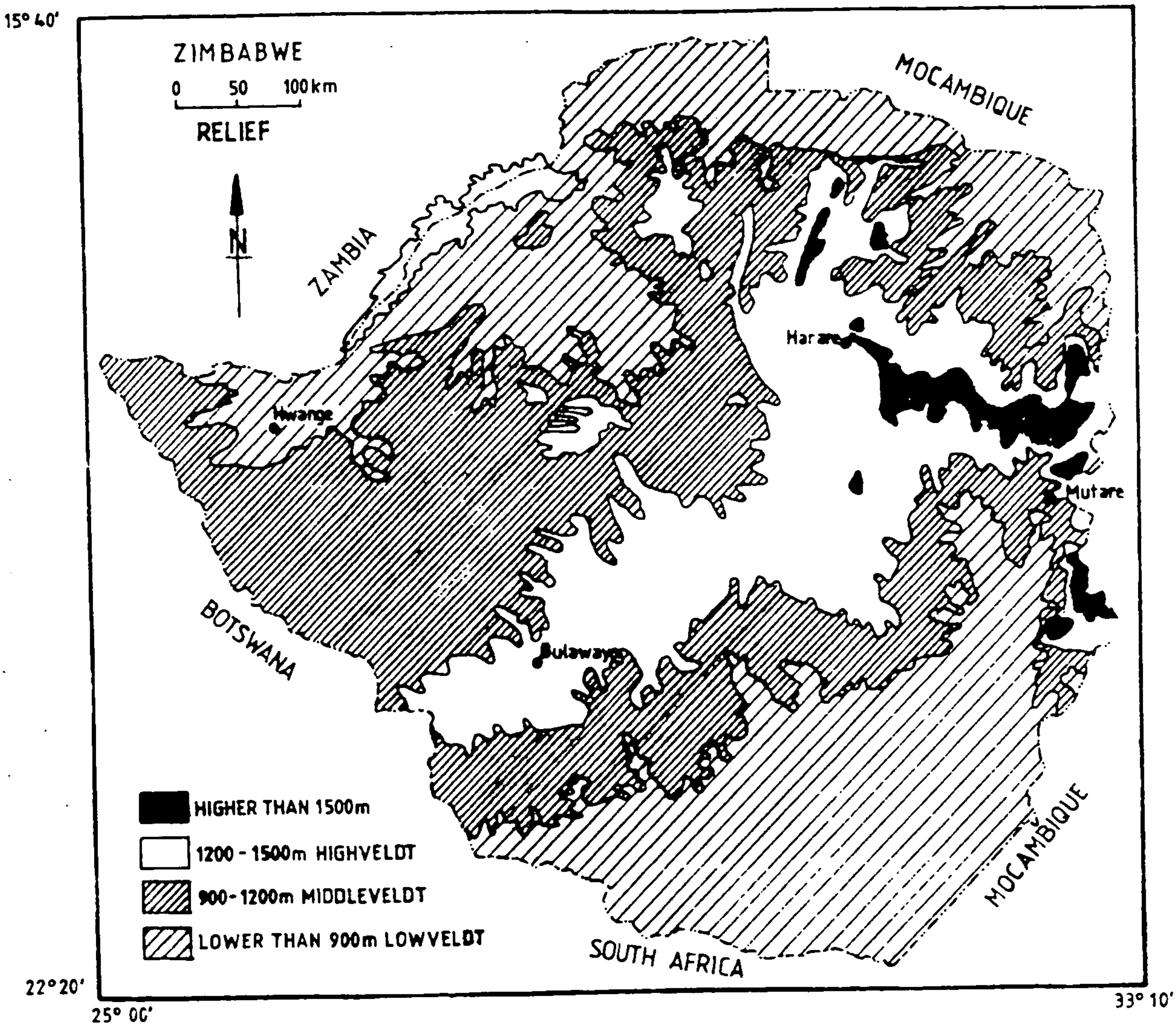

15° 40'
ZIMBABWE
0 50 100km
RELIEF
N
ZAMBIA
MOCAMBIQUE
Harare
Hwange
Mutare
BOTSWANA
Bulawayo
HIGHER THAN 1500m
1200 - 1500m HIGHVELDT
900-1200m MIDDLEVELDT
LOWER THAN 900m LOWVELDT
MOCAMBIQUE
SOUTH AFRICA
22°20'
25° 00'
33° 10'

Figure 3.6

(h) Selected sites were used for detailed geophysical surveys with particular emphasis on dry or low yielding boreholes. Various surface and borehole geophysical techniques were employed. The objectives of the surveys were as follows:

- to allow comparisons to be made between the effectiveness of different surface geophysical techniques: resistivity, EM and seismic,

- to ascertain whether more detailed geophysical studies would have resulted in either a rejection of a dry borehole location or a small but significant shift in the precise site,

- to identify width (and orientation) of fracture zones and determine whether features in the geophysical responses gave any indication of fracture fillings which could affect aquifer parameters,

- to ascertain whether regolith thickness varied over the fracture zone.

(ii) Catchment studies - Eleven catchments were selected with similar criteria as those described for Malawi but with greater climatic variability and over a wider range of erosional surfaces (African, Post-African, Pliocene - Figure 3.7).

(iii) Dambo discharge analysis - A dambo being used for an agricultural water balance study was selected. The studies were expanded to include consideration of the hydrochemistry of rainfall and runoff but more importantly, groundwater discharge areas were surveyed by ground radiation thermometers to allow correlation with TM imagery (Landsat V).

(iv) Data base - A strip of terrain stretching from latitude 17 30'S to about latitude 21 00'S and incorporating the Masvingo Project area is being subjected to detailed borehole data base analysis in combination with general geology and terrain analysis (Figure 3.8). The 'strip' also incorporates the recent series of collector wells.

3.3 Sri Lanka

A more limited programme of work was carried out in this country, concentrating on specific objectives in relation to geophysical techniques of exploration and the geochemistry of saline waters.

(i) Geophysical studies

(a) A comparison was made of EM, seismic and resistivity profiling and soundings for determining thickness of regolith and differentiation of sub units.

(b) Examination of validity of breaks in curves of VES soundings as fracture indicators including correlation of surface surveys and core drilling.

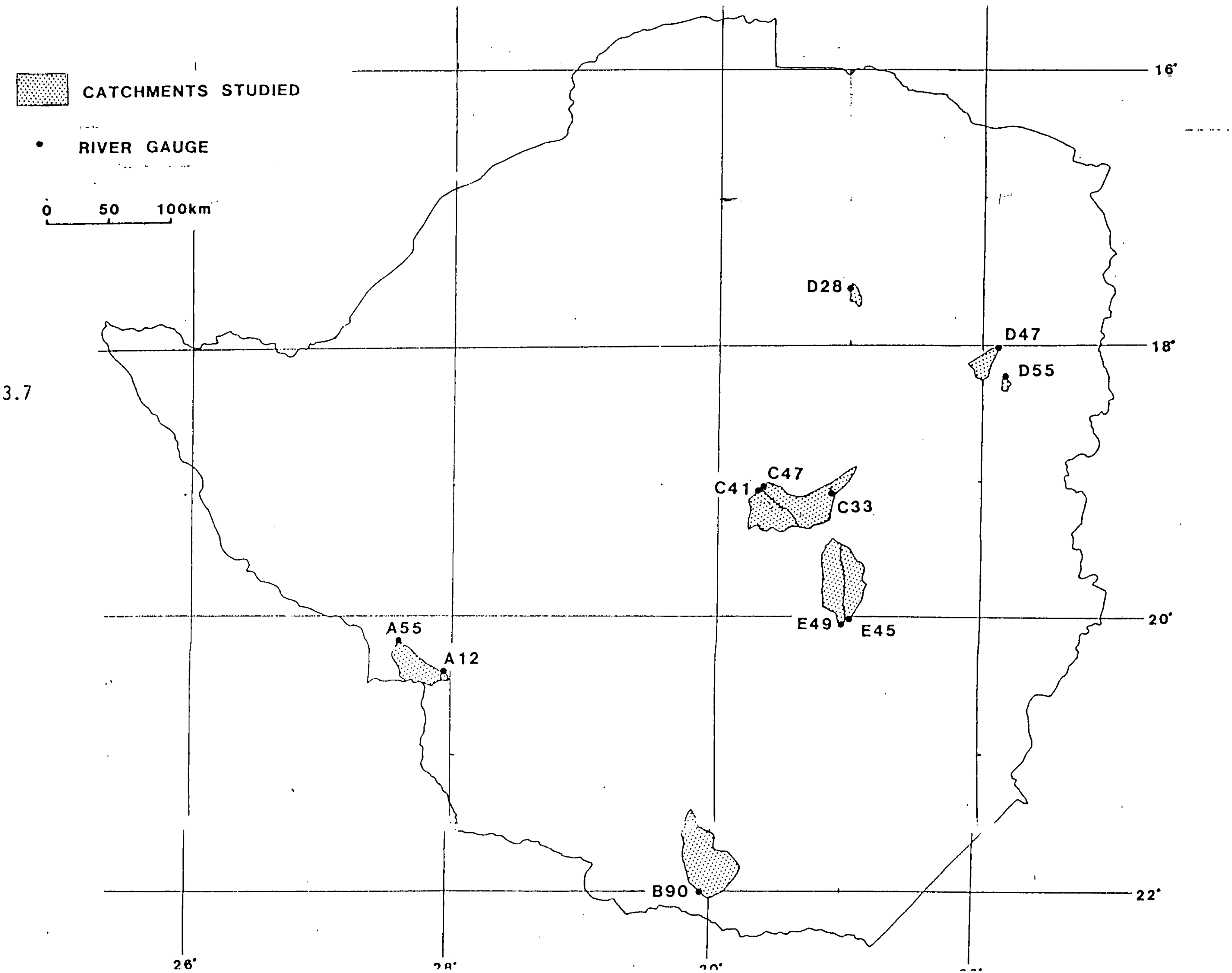

CATCHMENTS STUDIED
RIVER GAUGE
0
50
100km
16°
18°
20°
22°
26°
28°
D28
D47
D55
C41
C47
C33
E49
E45
A55
A12
B90

Figure 3.7

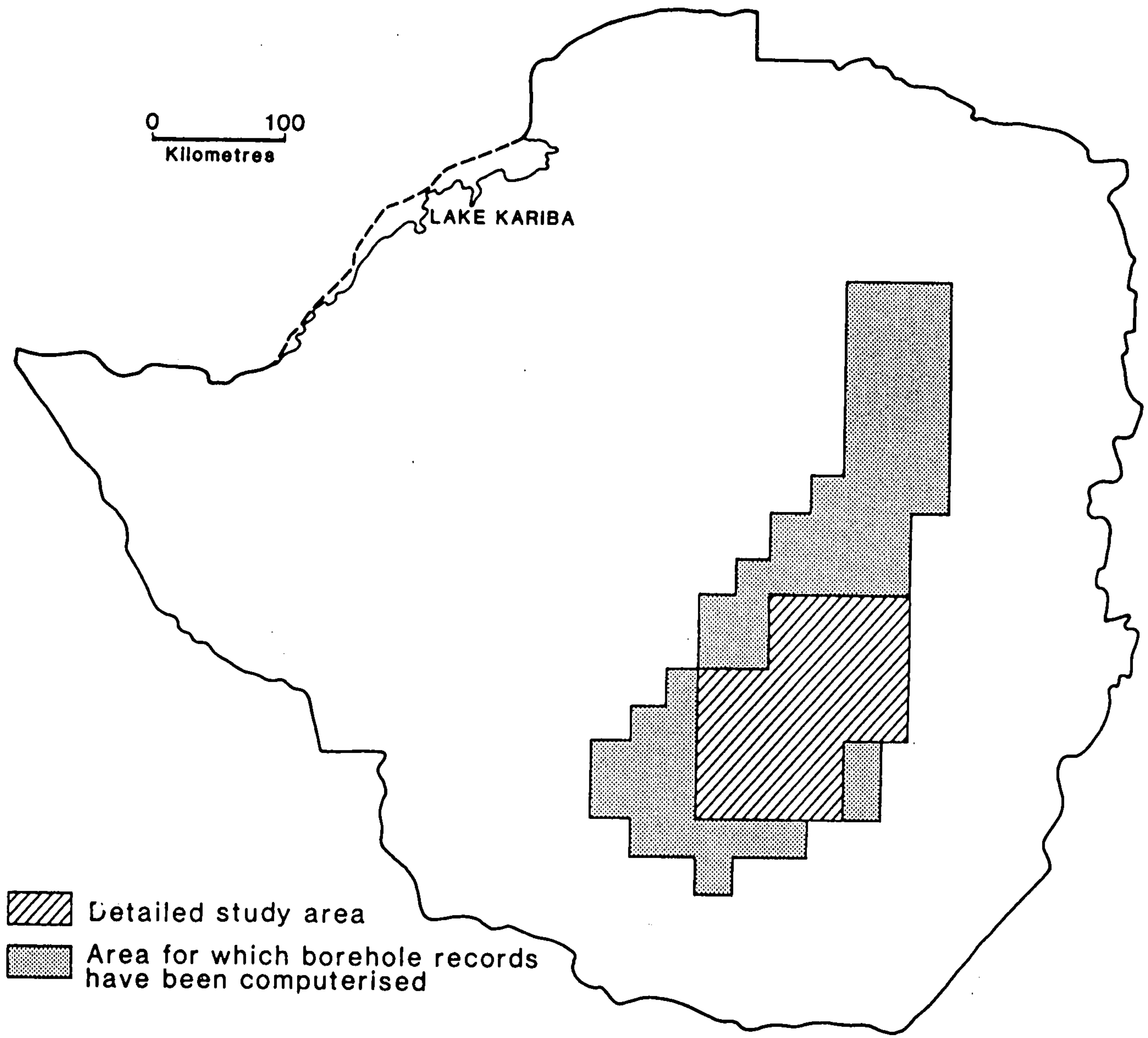


Figure 3.8 Map of Zimbabwe indicating areas studied by BGS.

(ii) Geochemistry - Consideration was given to the origin of certain saline waters in basement aquifers in Sri Lanka, thought to be derived from a previous climatic epoch which resulted in increasing concentration by evapotranspiration. The study involved age determinations of groundwater.

4. DISCUSSION OF RESULTS

These are included under various subheadings as follows:

- Geomorphology and terrain analysis
- Hydrological studies
- Dambo hydrology
- Malawi: Dowa West, Lilongwe and Livulezi project studies
- Zimbabwe: Masvingo project study
- Chisengeni dambo: groundwater discharge by satellite imagery analysis
- The application of borehole geophysical techniques
- Aquifer occurrence; resource evaluation and potential
- Exploration and development

5. GEOMORPHOLOGY AND TERRAIN ANALYSIS

In areas where African and Post African erosion surfaces dominate the landscape, it is already known that the thickness of weathered overburden is greater on the older surfaces than on the younger. This is attributable to the greater time available for weathering on the older surfaces and the facilitated evacuation of dissolution products afforded by incision. Regional variations of weathering thickness are attributable to the continental location with respect to the climatic belts throughout the leaching period. Africa has rotated such that its eastern flank has moved northwards since the breakup of the supercontinent of Gondwanaland in later Jurassic times. High latitude effects would therefore be expected to be more apparent in Zimbabwe than in Malawi. An expression of this appears to be the generally thinner regolith on the African Surface in Zimbabwe as compared with Malawi. Also the degree of weathering is less; together with the quartz, orthoclase feldspar survives, unaltered to secondary clay minerals in the sandy colluvium in Zimbabwe but not in Malawi where the sand is essentially quartz.

The origin of the erosion surfaces - whether by etchplanation or pediplanation - has important implications for hydrology and hydrogeology. Following King (1962), the literature on Malawi and Zimbabwe assumes the mechanism of pediplanation to apply. This involves the mechanical 'stripping' of weathered material, implying the activity of direct surface runoff as the main agent. By contrast, etchplanation involves differential leaching to the extent that the weathered rock (saprolite) collapses, yielding a surficial residuum, thus implying that planation is achieved not by the activity of direct surface runoff but by infiltrating water which then constitutes interflow or contributes to the deeper groundwater movement system. In both the case of Malawi and of Zimbabwe this project has found that etchplanation is the operative mechanism.

5.1 Malawi Relative Relief Studies

By means of inter contour analysis, the African Surface in the selected study area of the central plateau region has been identified as polycyclic, comprising eight surfaces with altitudinal separations of 33 to 66 metres. Since the mean regolith thickness is 30 m, that is less than the altitudinal separation, each surface may have a profile with sufficiently distinctive components to require that they be regarded as different hydrogeological units.

The development of appropriate methodologies for the characterisation of the terrain in digital form is important in attempts to correlate landscape with hydrological and hydrogeological parameters. Earlier attempts to correlate terrain with hydrological characteristics of a number of selected catchments failed to establish any correlations (Drayton et al., 1980; Meigh, 1987). The BGS studies allowed the recognition of improvements and relevant additions to the characterisation of terrain features.

(i) Relative relief was digitised on a 1 sq. km. basis, allowing relief characterisation in terms of:

- % area with relative relief less than 50 ft/sq. km. [c.15 m]
- % area with relative relief less than 100 ft/sq. km. [c.30 m]
- Mean, median, mode relative relief.
- Inter-quartile range of total relief and of areas with relief in excess of 100 ft/sq. km. [c.30 m]

This provides more sensitive characterisation of relief than does the earlier use of main stream gradient, a parameter more appropriate to a monocyclic situation than to polycyclic areas.

(ii) Stream frequency was revised, on the basis of fieldwork and air photo interpretation, to correct the erroneous assumption that all dambos contain streams.

(iii) Dambo area was recalculated from the 1:50,000 topographic maps which represent them more accurately than do the 1:250,000 maps; (these are biased towards the representation of dambos with fluviatile-like configuration as opposed to discrete or reticulated occurrences). Dambo perimeter was also measured since the evolution of dambo patterns involves reduction in area which does not correspond closely with reduction in perimeter. This followed recognition that the central areas of the dambos are dry in the dry season and evapotranspirative losses, which may affect yield and baseflow, are predominantly at the dambo margins.

Analysis of terrain relationships, on a map basis, within the selected study area (the Malawi Strip, comprising 26 1:50,000 topographic maps) showed:

- a close positive correlation between dambo area and low relative relief,

- a close negative correlation between stream frequency and both dambo area and low relative relief,

- low relief corresponds with increased saturated zone.

These various revised terrain parameters have been used in a reassessment of hydrological parameters in selected catchments. Results are discussed in Section 11.

5.2 Zimbabwe Relative Relief Studies

Terrain was similarly characterised and digitised in an area comprising a strip extending southwestwards along the main watershed where the African Surface is preserved, and down onto the Post-Africa Surfaces in the south. Relative relief analysis, on a 1 sq. km. basis showed the African Surface to comprise two major components in the Harare-Wedza area. Variations in weathering profiles, which relate to location within this bi-cyclic context, are discussed elsewhere (Wright et al., 1988), on the basis of profiles exposed at collector well sites. These have important implications for well response characteristics.

At the local level, because weathering here is thinner than on the African Surface in Malawi, bands of harder rock transverse to groundwater and drainage direction of flow are likely to backup the water-table and affect the weathering profile, an effect most pronounced in the break zones between the erosion surfaces, where incision and accelerated leaching have increased the relative relief on the basal surface of weathering such that the 'highs' outcrop, sometimes as koppies or small inselbergs, with deeper local pockets of regolith between them. A similar effect, but on a much larger scale is found on the Post-African Surfaces where areas of flat land at various altitudes, and with relatively high water-tables, occur between major outcrops (e.g. the greenstones and some granites) which are transverse to the drainage direction.

Terrain digitisation in a number of catchments selected for detailed hydrological studies (discussed elsewhere) showed interesting contrasts with the similar Malawi data. For example, there was a poor correlation between relative relief and dambo area on the African Surface. This may be attributable to its geomorphological situation, here surviving on a narrow interfluve, encroached upon, on both flanks, by incision to younger surfaces. This is likely to have lowered the water-table such that discharge into the local terrain 'lows' is insufficient to support the seasonal waterlogging which is an essential characteristic of dambos. That is, in this geomorphological situation, high water-table and areas of low relief do not equate and areas with relatively high water-tables may be identified in terms of % dambo area rather than relative relief.

On the Post-African Surfaces local geomorphology becomes extremely important to the location of pockets of deep weathering and saturated regolith thickness. As indicated elsewhere, even where terrain is relatively low, regolith thickness is highly variable. A systematic examination of the geomorphological context of individual boreholes sites, beyond the scope of this present study, would be required in order to identify terrain characteristics which would allow a degree of prognostication of regolith thickness.

5.3 Development of Weathering Profiles

Fundamental weathering processes are well understood but the regolith occurrence at any particular location depends on a range of factors which include climatic controls both past and present, terrain and local leaching conditions, bedrock structures, mineralogy, petrography and textures. In hydrogeological terms. the features of the profile need to be correlated with permeability and storage.

The typical weathering profile is shown in Figure 5.1 and the horizons briefly described below.

(i) colluvium or collapsed zone: on interfluves, this is sandy with a more clayey basal zone. Where there is a basal stone line, the transition with underlying saprolite is sharp. Otherwise it is gradational. In the valley floors (dambo), heavy clays which are neoformed overlie a sandy residuum. In mid-slope positions (palaeodambo), sands overlie the old dambo clay.

(ii) saprolite: in situ weathered rock with varying mineral transformations and with relict structures, textures and resistant bands, e.g. quartz veins. The basal saprolite is disaggregated and sometimes brecciated but showing little chemical weathering. Brecciation may be associated with pressure release joints in the bedrock. The downward passage into saprock below may be rapid into a homogeneous rock such as granite or transitional to fluctuating into a banded rock such as gneiss.

(iii) saprock: very slightly weathered rock. Primary mineral bonding is still strong. Weathering is restricted to fracture faces, stringer margins, and only a few of the most vulnerable primary minerals.

Weathering profiles vary in thickness and degree (advancement) of alteration. The thick weathering profile on the older erosional surface is a result of the lengthy duration of development and, in some cases, 'favourable' (hot and humid) conditions. Weathering varies with the susceptibility of minerals, with micas and other ferromagnesian minerals and Ca/Mg feldspars being the most susceptible, and alkali feldspar and quartz, the least. Texture is another control with coarse grained rocks weathering more deeply. Structural features promote groundwater throughflow and hence weathering. To the latter control must be added any other factors, such as local relief, stream incision, falling water tables etc. which affect leaching conditions and groundwater throughflow rates and hence weathering.

The sandy residuum of the collapsed zone has high infiltration capacity. The lower compacted and illuviated basal layer has low permeability and promotes the occurrence of perched water tables and interflow during heavy rainstorms. The basal laterites, which occur in mid and lower slope

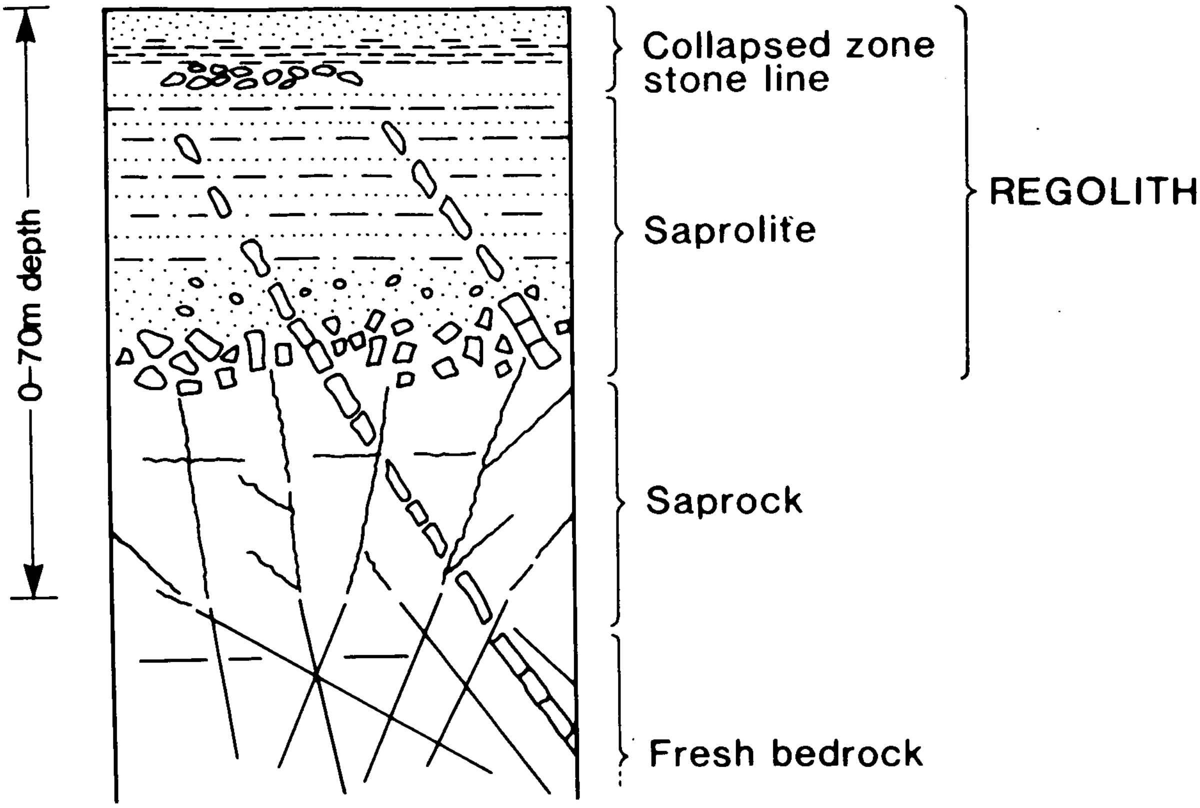


Figure 5.1. Typical weathered profile above crystalline basement rocks.

Notes:

(1) Collapsed zone. This may show marked lateral variations being generally sandy on watershed areas with illuviated clay near the base and sometimes a stone line changing to predominantly neoformed clay minerals in valley bottomlands (dambos). Slope bottom laterites may also occur associated with the peripheral dambo clays.

(2) Saprolite is derived by in-situ weathering but is disaggregated. Permeability and effective porosity tend to decrease at higher levels as a consequence of increase in secondary kaolinite minerals.

(3) Saprock is cohesive weathered bedrock.

profiles, usually retain adequate permeability. Even when exposed by erosion and indurated, fracturing often maintains permeability. Stone lines are likely to have high permeability.

The normal process of weathering development in the saprolite will generally result in a low permeability and high porosity in the main altered matrix, increasing somewhat at lower levels where alteration is less. This generally corresponds with an upward increase in kaolinite clay mineralisation. Other mineral transformations also affect permeability. If weathering is slow, biotite alters to hydrobiotite which, as a result of expansion, produces low permeability. The basal transitional zone in which chemical weathering is not marked has high permeability and is a key target for both boreholes and collector wells.

Aggressive leaching which is commonly associated with rejuvenation and stream incision tends to produce more advanced weathering profiles and greater relative relief on the basal surface of weathering. Some of the effects, such as the transformation of biotite to vermiculite without an intervening hydrobiotite stage will increase permeability. Further development of kaolinite will reduce permeability in the deepening vadose zone. However congruent kaolinite dissolution may also occur which results in vertical piping in the vadose zone, which will increase vertical infiltration by development of bypass mechanisms. Other bypass mechanisms include residual hard bands with fractures (e.g. quartz), tree roots and the like.

The studies on weathering have concentrated largely on two catenary profiles in Malawi and the various profiles associated with contrasting collector well sites in Zimbabwe. Ancillary studies have included some mineralogical assessments on drilling samples from selected boreholes in the Masvingo Project area on Post African and Pliocene erosion surfaces and a range of statistical correlations with the data base.

One of the Malawi catenary profiles (at Chimimbe, Figure 5.2) occurs on a flat erosional surface, the second (Chikobwe, Figure 5.3) in a more incised situation. The assessment has been based on descriptive observations, mineralogy by XRD and chemical analysis. Pore water was sampled by elutriation and centrifugation.

The Chimimbe profile is on granite gneiss and the saprolite contains significant kaolinite in both the vadose and permanently saturated zone and is in an advanced weathering state. The saprolite is thinner below the dambo which is attributed to accelerated weathering by groundwater flow downgradient and below the dambo clays. The saprock is transitional with the more micaceous bands converted to saprolite. The Chikobwe dambo is more deeply inset and its orientation appears to be fracture related. On the flanks of both the Chimimbe and Chikobwe dambos, areas of more micaceous rocks are more deeply weathered.

These features have significance to borehole and well siting. The shallow water levels in valley locations provide a thicker saturated regolith but where the saprolite is thin, it becomes increasingly important for boreholes to penetrate thick saprock or a fracture zone in the bedrock in order to draw upon sufficient storage within the spread of the cone of depression. Drilling to penetrate a structural zone below a dambo would present site problems unless angled drilling is used. Although angled

Figure 5.2 Geological cross-section at Chimimbe dambo.

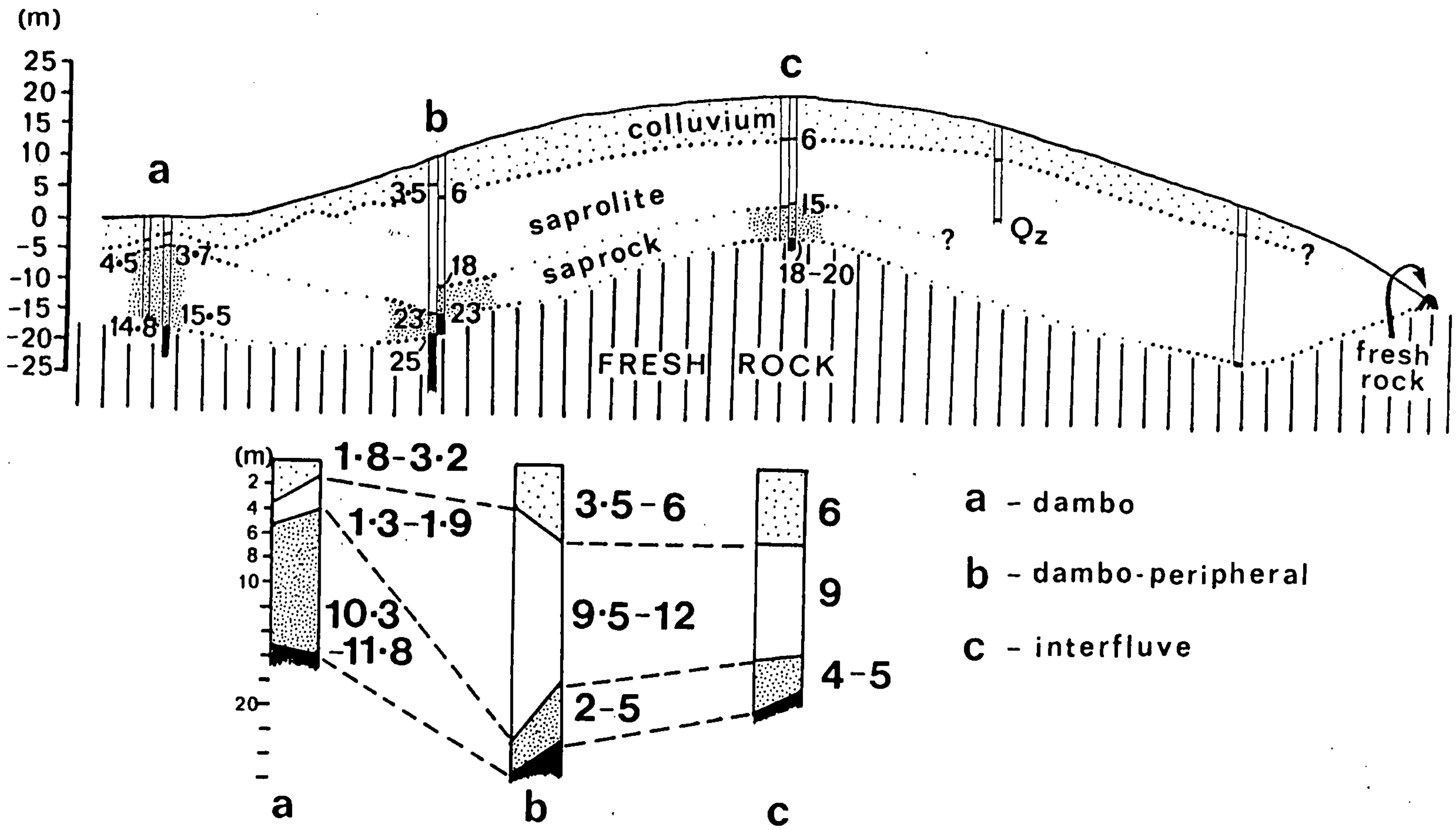
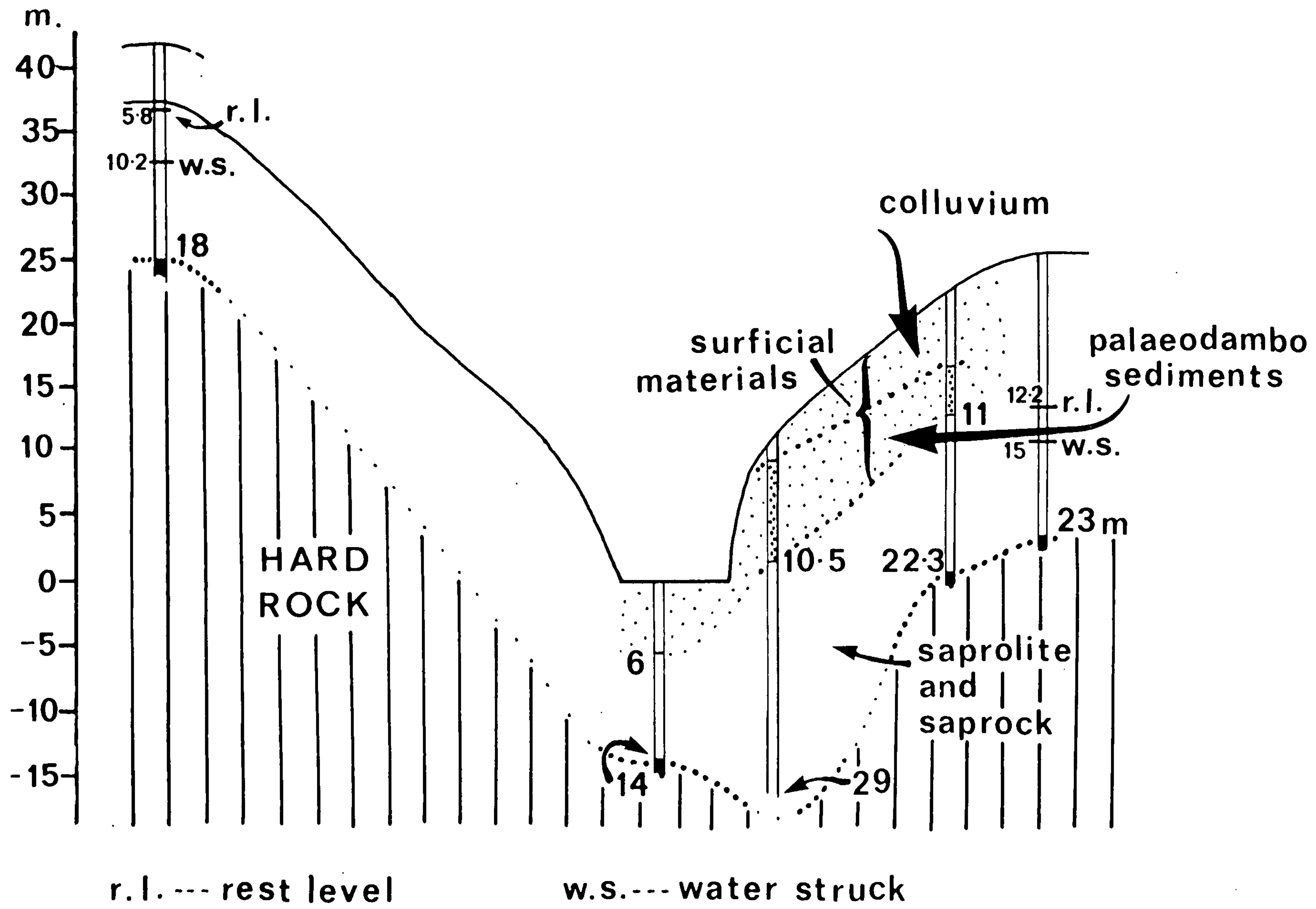


Figure 5.3 Geological cross-section at Chikobwe dambo.



drilling is not normally used for standard water supply boreholes, the method is technically feasible and some handpumps can be operated in an angled borehole.

Wells, to be successful, will need to intersect the more permeable saprolite in the basal layers, other than at dambo margins where they can be completed in the uppermost sandy colluvium which overlies 'palaeodambo' clays.

In Zimbabwe, weathering is generally thinner and less advanced than in Malawi, becoming progressively thinner on the younger erosional surfaces. It is not uncommon to find gneissic rocks outcropping intermittently on the valley (dambo) floors below a thin cover of saprolite. Permeability of the regolith is likely to vary in such conditions and is probably least in the micaceous rocks in which biotite has converted to hydrobiotite. Where weathering is poor, these may, however, be the only situations in which weathering reaches appropriate depths.

These characteristics go some way to explaining the main practice in Zimbabwe of completing boreholes in the weathered bedrock with the regolith cased out. Traditional dug wells are mainly shallow holes on the edges of dambos. In recent years there has been increasing emphasis on deeper wells constructed by the non-Government organisations and UNICEF. It is perhaps not surprising that some of the programmes have had mixed success. A better knowledge of the weathering profile and the controls to its occurrence could greatly assist these searches.

Three contrasting collector well sites have been studied (Figure 5.4). Makumba occurs on the upper component of the African Surface (see section on geomorphology), St Nicholas on the break zone between upper and lower components of the African Surface and St Liobas on the break zone between the African and Post African Surface. Makumba, located on a dambo, has adequate thickness of saprolite at the well site but with much reduced thickness up the slope. The biotite has been converted to hydrobiotite and the saprolite has very low permeability. The large diameter well of some 12 m depth with water level at some 3/4 metres was of almost negligible yield but converted to a collector well of moderate yield in consequence of radials drilled at the basal regolith boundary.

At the St Nicholas and St Liobas sites, in consequence of more aggressive leaching at the junction of two surfaces, the regolith is more permeable with biotite generally converted to vermiculite and with the upper (oxidised) saprolite deeply invasive of the lower along fractures. The large diameter wells are more productive than at Makumba. The St Liobas site has proceeded to a further stage with the regolith occurring in a 'suspended' dambo within a narrow valley which is disappearing as a result of incision. In this case the leaching has been so aggressive that locally there is cavernous weathering due to saprolite collapse. Elsewhere the saprolite in the valley is composed of thick clay and overall storage is likely to be small which will constrain longer term yields, particularly in drought periods.

There is still much uncertainty as to how accurately the profile characteristics can be predicted from surface observations, either separately or in conjunction with geophysical techniques. Conditions which have promoted variable depths to the basal surface of weathering can

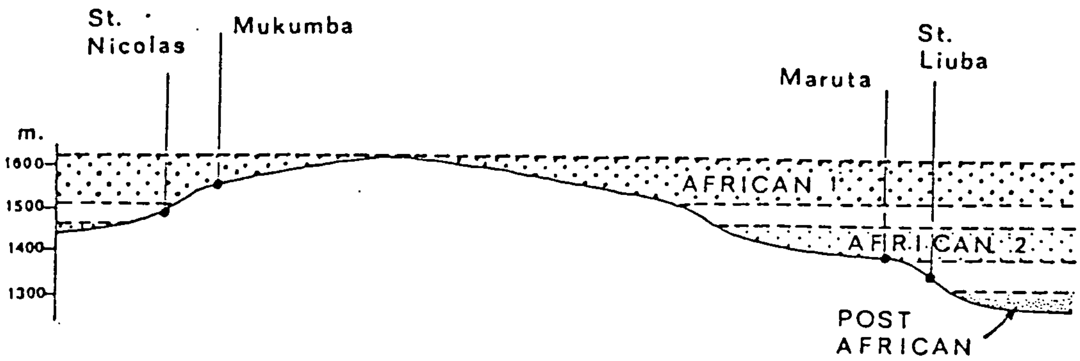


Figure 5.4 Schematic transect to show the location of the collector wells, in the context of the erosion surfaces in the study area of Zimbabwe.

also result in very variable hydrogeological conditions associated with significant variations in depths to water level, the basal surface of weathering and the regolith permeability. These features will be critical to the siting of wells/collector wells and to a lesser extent boreholes. In the case of the latter, the saturated regolith is mainly a control to storage with the main permeability occurring in the basal transitional zone into saprock and in the deeper bedrock. Conditions (such as coarse grained quartzo-feldspathic rocks with significant fracturing) which promote deep but not advanced weathering would seem likely to produce a thicker disaggregated basal saprolite and significant saprock.

6. HYDROLOGICAL STUDIES

6.1 Introduction

This section discusses the results and implications of hydrological studies undertaken on 26 gauged catchments in Malawi and Zimbabwe (Bullock, McFarlane and Meigh, 1989). Analysis of hydrological and geomorphological data from these catchments focuses on the controlling factors of groundwater baseflow and dry season low flows. Discussion is supplemented by conclusions from previous regional analyses of river flows (Drayton et al., 1980; Hill and Kidd, 1980; Bullock, 1988) and by other published literature concerning the hydrology of central and southern Africa.

Overviews of the hydrology and water resources in Africa are given in Wright (1988) and Balek (1977). The African continent has a low ratio of runoff to precipitation, which at 18% is approximately half of the global mean ratio. Continental ratios of runoff to precipitation and differences between the two principal drainage regions within Africa (Figure 6.1) are presented in Table 6.1.

Table 6.1 Ratios of Runoff to Precipitation

(i) Global Variations

Africa	Asia	N. America	S. America	Mean
0.18	0.40	0.43	0.35	0.35

(ii) Regional Variations within Africa

	Precipitation mm	Runoff mm	Runoff Coefficient
Mean	725	126	0.17
Atlantic Ocean Slope	728	225	0.22
Indian Ocean Slope	712	72	0.11

Source: World water balance and resources of the earth (UNESCO, p. 293)

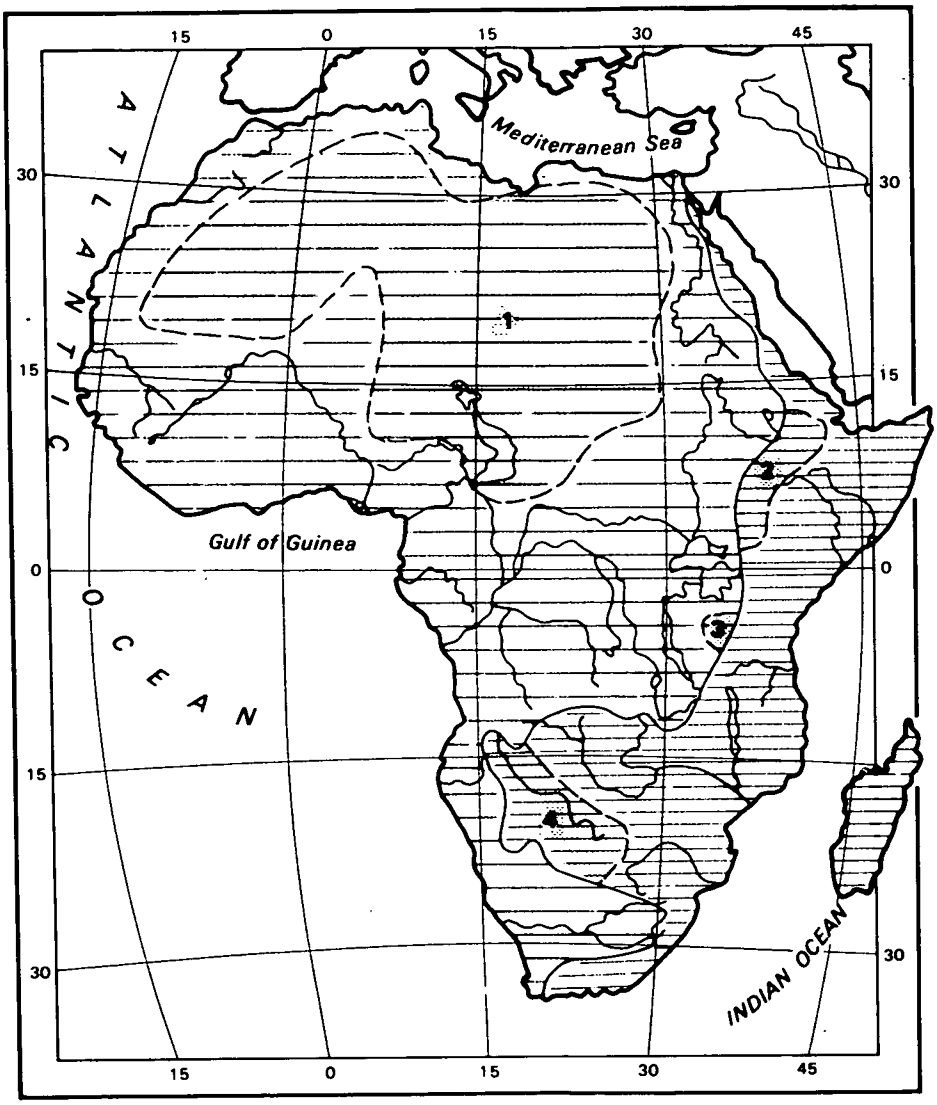


Figure 6.1 Distribution of the drainage basins in Africa. (from UNESCO, 1978)

——— boundary of the drainage basins

– – – boundary of the areas of internal run-off

drainage basins of the Atlantic Ocean

drainage basins of the Indian Ocean

areas of internal run-off

1 Sahara desert with the basin of Lake Chad

2 basin of Lake Rudolf

3 basin of Lake Eyasi

4 Kalahari semi-desert with the basin of the Okavango River

Observed catchment runoff:rainfall ratios within these regions are locally variable, and for example range from 4% to 54% amongst 38 catchments in Malawi (Hill and Kidd, 1980) and from 2% to 50% amongst 108 catchments in central Zimbabwe (Bullock, 1988). Higher catchment ratios are normally associated with higher average rainfall depths reflecting the basic non-linear nature of regional runoff:rainfall relationships. Mean ratios from the two regional studies are 27% in Malawi and 17% in Zimbabwe, with both areas located within the Indian Ocean Slope zone (mean ratio = 10%).

The low ratio of effective precipitation at catchment, regional and the continental scales in Africa is primarily attributable to a combination of high potential evaporation (PE) losses, low relief and low rainfall. Within Malawi and Zimbabwe, ratios of catchment mean rainfall to PE are typically less than 0.5 and exceed 1.00 only in the Zomba region of S.E. Malawi.

There is therefore an important water availability control upon the evaporation process within both countries, but this control is variable during the year because of the strongly seasonal climatic regime. In most areas, the wet season extends from November to March, during which period approximately 90% of annual precipitation falls, associated with the general migration of the Inter Tropical Convergence Zone, mid-level troughing and sub-tropical high pressure cells. Because rainfall generation is predominantly associated with convergence, rainfall intensities are high and it is estimated that 40% of rainfall recorded at Harare falls at intensities in excess of 25 mm/hour. It is only during the wet season that monthly rainfall depths exceed monthly potential evaporation, a feature which in association with high intensity storm events inhibiting infiltration and percolation explains the strongly seasonal river flow regimes in these countries. In addition, the low permeability of the basement aquifers means that river flow response is dominated more by rapid response runoff, with a lower groundwater component than would be expected from more permeable geologies.

The southern African savannah region is largely developed on two main erosion surfaces (African and Post African) overlying basement rocks. A dominant geomorphological feature of these upland plateau surfaces are dambos. Numerous definitions of dambos have been proposed in the scientific literature, but common amongst these are the diagnostic properties of dambos as grass-covered, generally treeless, valley bottoms of hydromorphic soil drained by a poorly defined stream channel. Dambos may typically cover 25% of the surface area in the core region of their occurrence, but their local density is variable and is determined by a combination of climatic, geological, topographic, vegetational and landscape stability factors. Their occurrence is dominantly influences by groundwater flow systems operating within the weathered profile above crystalline basement rocks. Local densities range between 0% and 70% of surface area within Malawi and Zimbabwe. Their relationship to groundwater occurrence is discussed elsewhere in this report (Section 7).

Dambo characteristics, formation and utilisation are comprehensively reviewed by Thomas and Goudie (1985), but data and conclusions concerning their role in the hydrological cycle are more disparate. Dambos have been considered widely as exerting a regulatory effect on river flows and in promoting higher evaporation losses. This effect can be attributed to a combination of valley bottom location, hydromorphic soil properties, hydrophilous vegetation, absence of well-defined channel characteristics and seasonally high water tables. However, these factors can each determine hydrological response in a variable and dynamic manner. Recent evidence of the hydrological function of dambos, while not establishing a coherent function, suggest that their function is certainly more complex than a simple regulatory role.

In relation to the promotion of evaporation losses, Balek and Perry (1973) conclude that in the Luano catchments of northern Zambia total losses from dambo surfaces are one third of those from miombo woodland. However, the expected increase in total runoff is not shown in data from four Luano catchments with different dambo densities, and despite the reportedly lower losses from the dambo components, the authors state that total runoff is independent of dambo density. Bullock (1988) also concludes that total runoff, and therefore total evaporation losses, are independent of dambo density amongst 108 catchments in central Zimbabwe. However, in Malawi, Hill and Kidd (1980) argue that each 1% of dambo density is responsible for an addition increase in annual evaporation of 6.4 mm.

Investigations of seasonal evaporation losses have focussed on dry season flow regimes, and again the conclusions of previous studies are inconsistent with the each other. From hydrograph separation and low flow analysis amongst 52 catchments in central Zimbabwe, Bullock concludes that baseflow contributions from dambos are minimal and do not contribute significantly to dry season flows. Rather, groundwater baseflows are more a function of the interfluve regolith and soil profiles, with typical baseflow components of runoff ranging from 0.6 on deeply weathered and permeable profiles (typically ferrallitic soils overlying granites on the Post-African surface) to 0.3 from shallower and less permeable siallitic soils. It is only where dambos occur in association with regoliths yielding the higher groundwater baseflow components that dambo density is significant in reducing dry season flows by the promotion of evaporation losses at the dambo margins. Drayton et al. (1980) state that dry season flows in Malawi are not significantly different between catchments with dambo densities up to 27% and unaffected catchments, although on the other hand, it is suggested that the presence of dambos increases evaporation with a corresponding decrease in long-term runoff.

In summary, previous studies of dambo hydrological response display an interesting complexity. Reduced dry season flows in certain regions of Zimbabwe are not reflected in increased total evaporation losses while in Malawi arguably reduced total evaporation losses cannot be attributed to increased dry season evaporation losses from dambos.

6.2 Hydrological Studies in Zimbabwe and Malawi

Hydrological studies were undertaken as a component of the Basement Aquifer project to analyse the climatic and geomorphological controls upon hydrological response from 26 gauged catchments in Malawi and Zimbabwe (Bullock, McFarlane and Meigh, 1989). Conclusions from this study presented here focus on the quantification of the groundwater baseflow component, and upon climatic and geomorphological factors affecting baseflow:rainfall ratios, total evaporation losses and dry season flows.

River flow and catchment characteristic data were assembled for the 26 catchments detailed in Table 6.2, and their locations have been presented in Figure 3.3.

Table 6.2 Availability of River Flow Data

		Period	Years with Data
Malawi			
1R3	Rivi-Rivi	1959/60-1986/87	19
2B22	Thondwe	1959/60-1974/75	16
3E3	Livulezi	1957/58-1974/75	18
4B3	Linthipe	1957/58-1974/75	18
4B4	Diampwe	1957/58-1974/75	18
4D4	Lilongwe	1955/56-1974/75	20
5C1	Bua	1974/75-1986/87	11
5D1	Bua	1959/60-1974/75	16
5D2	Bua	1953/54-1974/75	22
5B13	Kaombe	1976/77-1985/86	8
6F2	Luweya	1960/61-1974/75	15
6F5	Luchelemu	1958/59-1974/75	17
6F10	Luchelemu	1959/60-1974/75	16
7F2	Chilinda	1959/60-1974/75	16
7A3	South Rukuru	1956/57-1974/75	19
7A9	South Rukuru	1972/73-1984/85	13
Zimbabwe			
A12	Tegwani	1951/52-1983/84	26
A55	Tegwani	1969/70-1971/72	3
C33	Sebakwe	1956/57-1983/84	20
C41	Umvumi	1963/64-1983/84	21
C47	Sebakwe	1962/63-1983/84	20
D28/D5	Mazoe	1932/33-1984/85	52
D47	Nyagadzi	1979/80-1984/85	5
D55	Dora	1970/71-1984/85	13
E45	Umtilikwe	1959/60-1985/86	25
E49	Popotekwe	1959/60-1984/85	26

These catchments were selected in the basement aquifer project to represent a range of terrain features, including erosion surfaces, relief and drainage network characteristics including dambos, while ensuring that available flow records are long, relatively natural and of good quality. Catchment characteristics comprising indices of relative relief, dambo area and perimeter, drainage density, rainfall and potential evaporation were calculated above each gauging station. Flow data were analysed to derive total runoff, total evaporation losses, groundwater baseflow volumes, and low flow statistics. The methods of derivation and the calculated statistics are presented in the accompanying report.

Discussion here focuses on the conclusions from an examination of the relationships between catchment characteristics and groundwater baseflow, total evaporation losses and dry season flows.

Groundwater baseflow

Hydrograph separation involving the Base Flow Index technique (Institute of Hydrology, 1980) was applied to time series of daily mean flow data for each of the 26 catchments to quantify groundwater baseflow contributions to streamflow. Calculated groundwater baseflow values are absolute depths and as a fraction of mean rainfall are presented for each catchment in Table 6.3. Figure 6.2 presents observed mean annual baseflow expressed in mm.

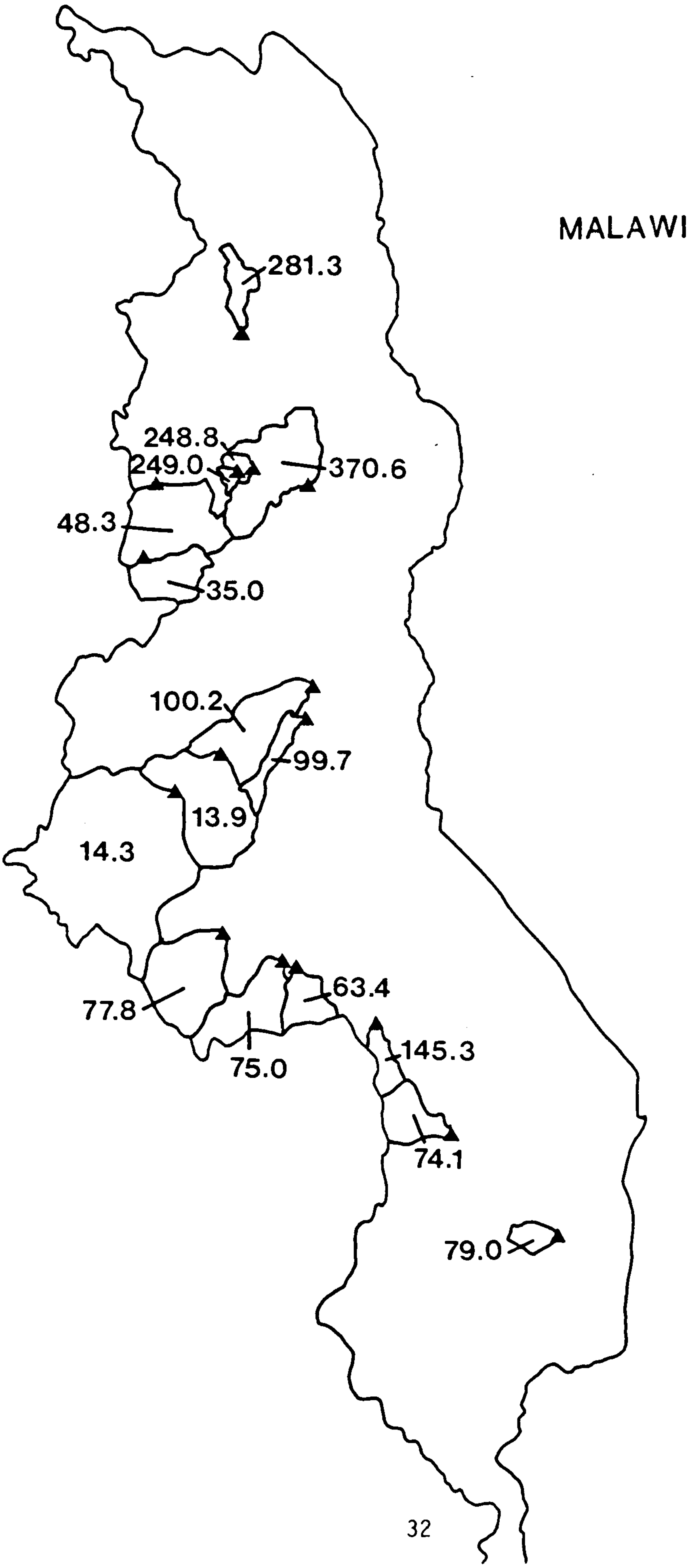
Table 6.3 Calculated catchment values of mean annual rainfall, mean annual runoff and mean annual baseflow.

Stn.	Mean Rainfall (AAR) (mm)	Mean Runoff (AAY) (mm)	Mean Baseflow (BF) (mm)	BF/AR	BF/ARsim
1R3	970.0	203.4	74.1	0.08	0.08
2B22	915.0	259.8	79.0	0.09	0.07
3E3	1000.0	277.2	145.3	0.15	0.12
4B3	910.0	192.1	63.4	0.07	0.08
4B4	830.0	184.8	75.0	0.09	0.10
4D4	930.0	138.1	77.8	0.08	0.10
5B13	1120.0	271.7	99.7	0.09	No data
5C1	920.0	148.3	100.2	0.11	0.09
5D1	900.0	74.7	13.9	0.02	0.09
5D2	900.0	77.0	14.3	0.02	0.08
6F2	1480.0	487.7	370.6	0.25	0.12
6F5	1090.0	309.8	248.8	0.23	0.18
6F10	1130.0	297.9	249.0	0.22	0.17
7F2	1260.0	334.5	281.3	0.22	0.21
7A3	900.0	62.3	35.0	0.04	0.06
7A9	880.0	114.7	48.3	0.05	0.05
A12	604.0	14.9	0.5	0.00	0.00
A55	551.0	1.7	0.0	0.00	No data
C33	755.0	105.3	33.0	0.04	0.05
C41	730.0	80.1	15.9	0.02	0.04
C47	721.0	84.1	15.8	0.02	0.03
D28	896.0	147.4	79.6	0.09	0.12
D47	833.0	100.2	36.7	0.04	0.13
D55	856.0	155.0	58.1	0.07	0.08
E45	692.0	114.6	45.6	0.07	0.11
E49	686.0	105.6	54.4	0.07	0.10

Observed groundwater baseflow depths range 0.4 mm between 370.9 mm and are strongly controlled by mean annual rainfall as shown in Figure 6.3.

Ratios of groundwater baseflow to mean rainfall vary from zero to 0.25. Ratio values are generally higher in Malawi, with a range of 0.02 to 0.27 compared to Zimbabwe, where the range is between zero and 0.09. Correlations between the baseflow:rainfall ratio, termed BF/AAR show

Figure 6.2 Observed baseflow contributions to streamflow (in mm).
(a) Malawi



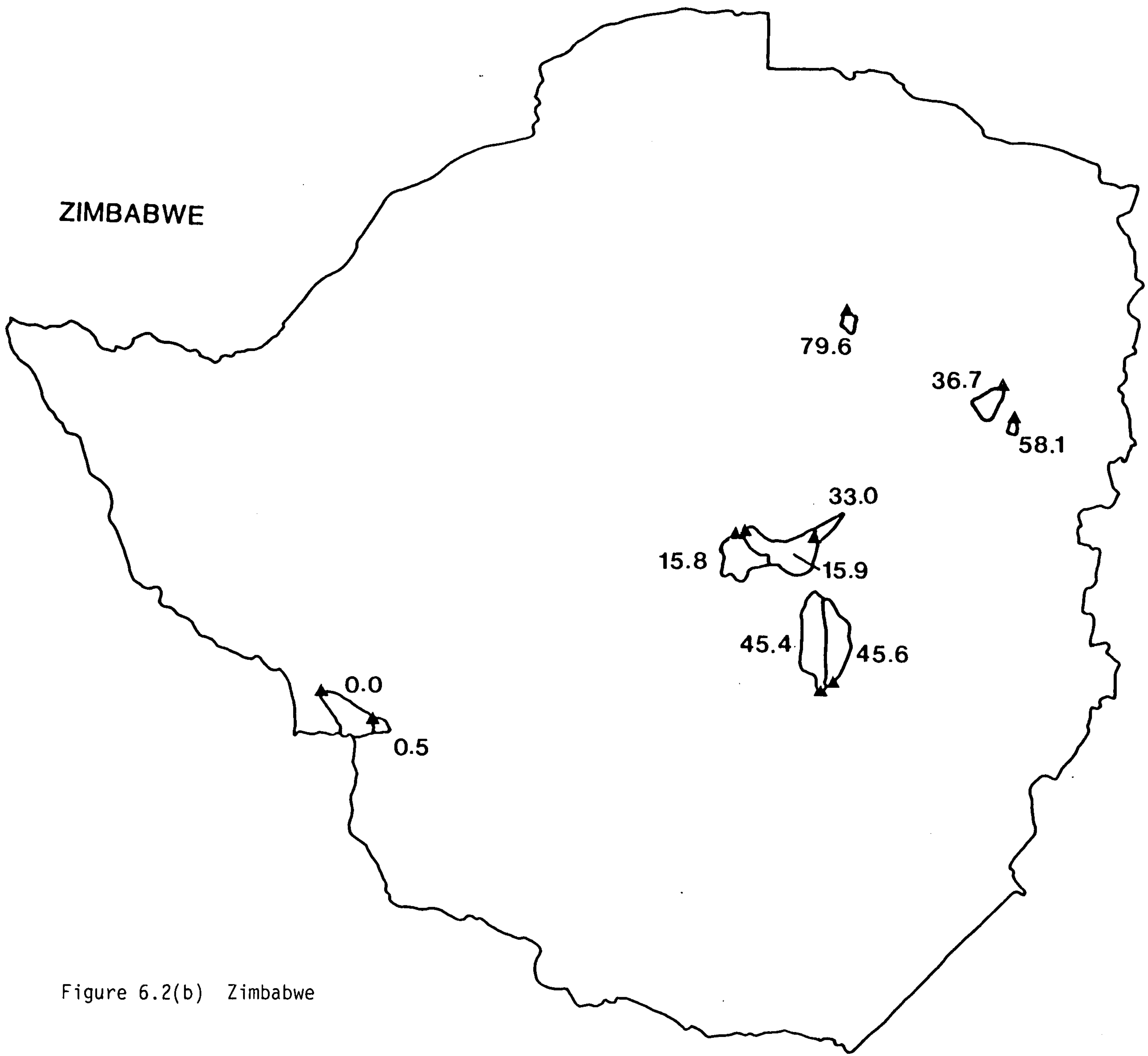


Figure 6.2(b) Zimbabwe

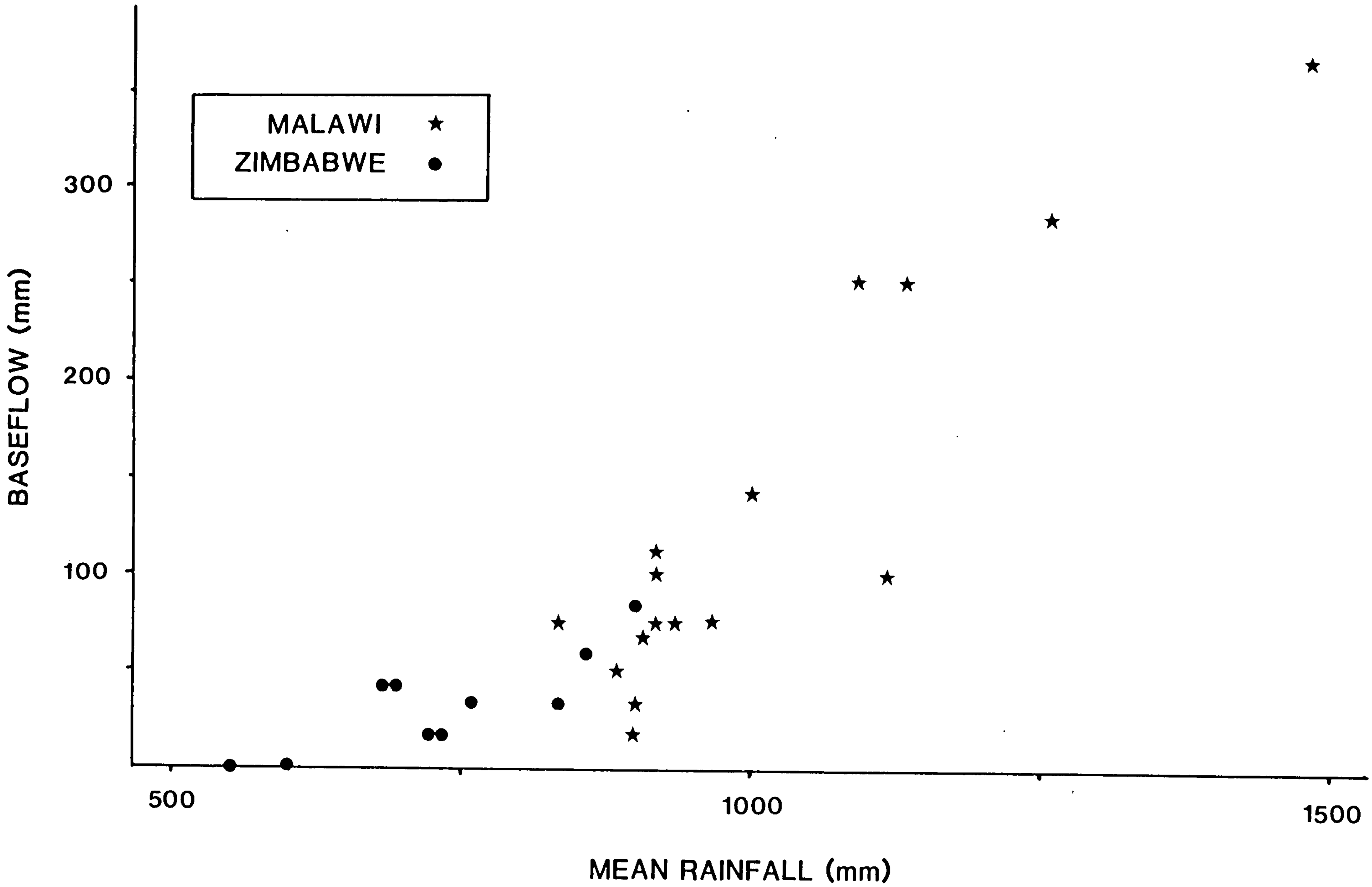


Figure 6.3 Relationship between mean annual baseflow and mean annual rainfall.

significant positive relationships at the 0.05 level with mean annual rainfall (r = 0.843) mean relative relief (r = 0.894) and a negative relationship with standardised dambo perimeter (r = -0.390).

To remove any non-linearity effects attributable to regional rainfall variations, baseflow contributions to streamflow were simulated under a scenario of 1000 mm of annual rainfall, termed BF/ARsim, using catchment regression relationships based on annual values of rainfall and baseflow. Under this scenario BF/ARsim values range from 0.002 to 0.206, with Malawi values ranging from 0.048 to 0.206 and Zimbabwe values generally increase from the observed values to a range between 0.002 and 0.129 as shown in Table 6.3.

Correlations of BF/ARsim against terrain and geomorphological indices show that the positive trend with relative relief (Figure 6.4a) is the only significant relationship at the 0.05 level. Figure 6.4b indicates a negative relationship with dambo perimeter, although this is not statistically significant at the 0.05 level.

It is therefore concluded that groundwater baseflow as estimated from hydrograph separation ranges in the study catchments between zero and 27% of mean annual rainfall, or between 0.4 mm and 371 mm in absolute terms. There is a strong rainfall control upon the baseflow:rainfall ratio, but when the effect is removed by standardisation, then groundwater baseflow contributions to streamflow appear to be related to relative relief and dambo density. Catchments with higher relative relief and low dambo density, characteristic of the Post-African surface in Zimbabwe and the high residuals along the Malawi Rift shoulder exhibit BF/ARsim ratios greater than 7% up to 20%. Catchments with low mean relative relief and high dambo densities characteristic of the African surface (typically below 30 metres per km^2) exhibit BF/ARsim ratios of less than 12% and down to zero.

Dry season flows

Flow data series were analysed using standard low flow procedures (Institute of Hydrology, 1980) to derive indices of duration of low flows, low flow frequency and recession in the 26 catchments. Investigation of the factors which determine dry season flow regimes reveal a dominant rainfall control, reflecting the reported relationship between groundwater baseflow and rainfall. In general, an insufficiently large data set restricted the identification of strong terrain and geomorphological controls upon dry season flow regimes, specifically because of the significant positive correlations between indices of relative relief and rainfall. Low ranges amongst the observed low flow statistics and absence of clustering amongst catchments within a small rainfall range do not enable conclusions to be drawn concerning the duration and volume of dry season flows.

However, more detailed analysis of the low flow data set assembled by Drayton et al. (1980) for Malawi (Figure 6.5) indicates that within a range of mean annual rainfall between 800 mm and 1000 mm there is a tendency for catchments with higher dambo densities to possess lower Q75(10) values and cluster below those with lower dambo density. This

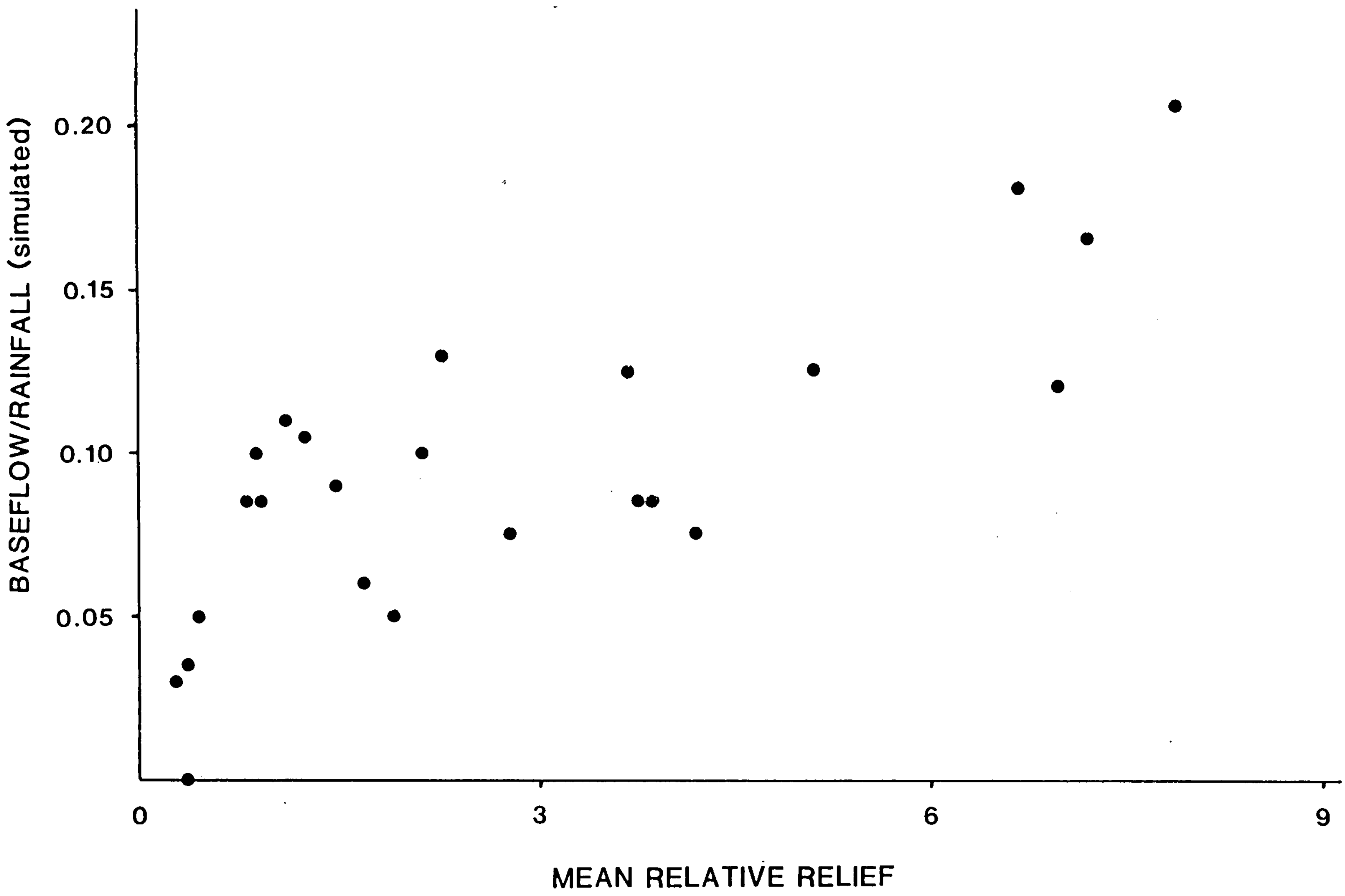


Figure 6.4a Relationships between baseflow:rainfall (simulated at 1000 mm of rainfall) ratio and mean relative relief.

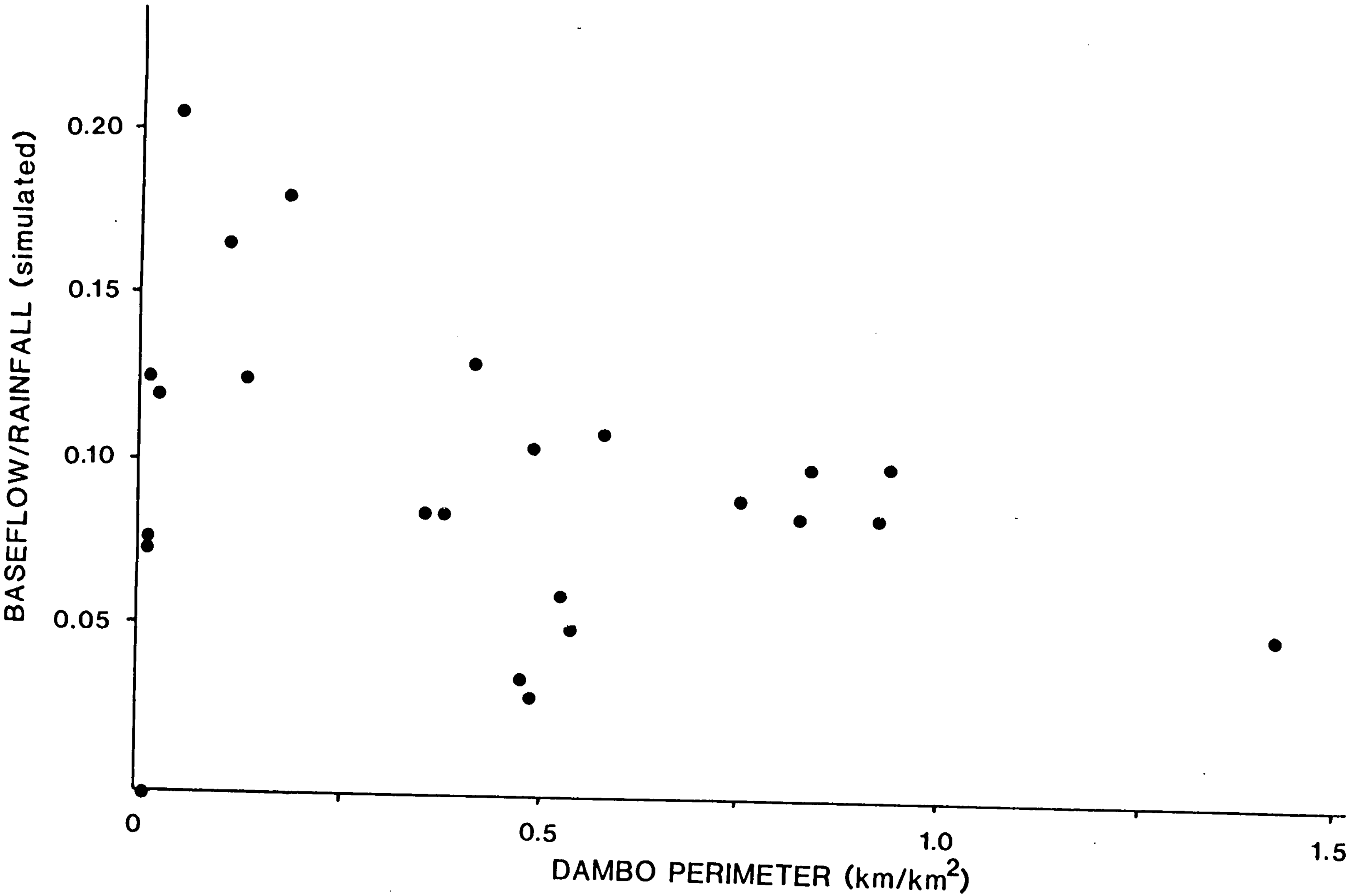
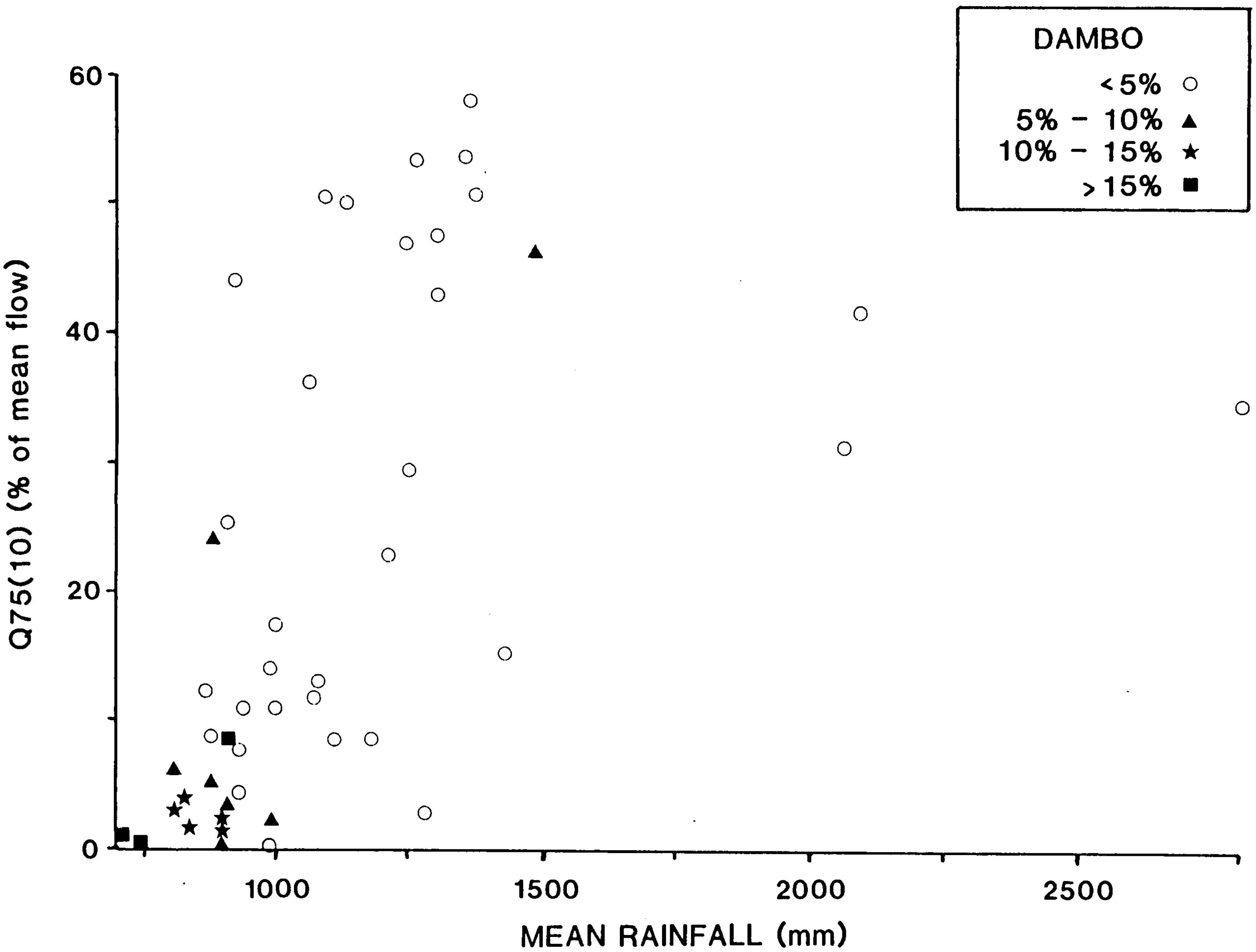


Figure 6.4b Relationships between baseflow:rainfall (simulated at 1000mm of rainfall) ratio and dambo perimeter.

Figure 6.5 Relationship between Q75(10) low flow and mean annual rainfall with catchments grouped by DAMBO.



trend is reflected in a regression equation of Q75(10) against catchment characteristics in which rainfall and dambo density are significant, with a higher dambo value reducing the value of Q75(10):

$$Q75(10)^* = 0.000133\ AAR\ 1.69\ (1 + DAMBO)\ -9.25 \qquad r^2 = 0.476$$

This evidence for the reduction of dry season flows by dambos in Malawi is corroborated by significant correlation between the duration of zero flows and dambo density in regions of central Zimbabwe (Bullock, 1988). This increase in the duration of zero flows with increasing dambo density is restricted however to catchments overlying ferrallitic and perferrallitic subsoils on the African surfaces of eastern central Zimbabwe, and no significant relationship was identified amongst catchments with predominantly siallitic soil profiles.

6.3 Estimation of Groundwater Recharge

Analysis of hydrological data has focussed on quantification of groundwater baseflow and dry season flows. Conclusions from these studies can be brought together to develop estimates of groundwater recharge within the gauged catchments and to consider the controlling factors on recharge.

Observed groundwater baseflow contributions to streamflow, expressed as a fraction of rainfall, range from zero to 25% and provide minimum estimates of groundwater recharge. Groundwater baseflow contributions to streamflow are strongly controlled by annual rainfall depths, and, when standardised by rainfall, appear to relate to relative relief and dambos. Catchments characteristic of the Post-African surface of Zimbabwe and the Rift shoulder of Malawi exhibit baseflow:rainfall ratios between 0.02 and 0.20 while ratios on the African surface are typically less than 0.12 and can be as low as zero in western Zimbabwe.

Groundwater baseflow estimates from this study should be considered as a minimum because recharged water can be lost to evaporation through a number of components of the hydrological cycle before being measured at a gauging station. Losses can occur through the transpiration and evaporation processes from vegetation, evaporation from the soil surface and from rivers. Variations in vegetation type, vegetation cover and channel characteristics can therefore each account for different amounts of recharged water being lost prior to measurement at the gauging stations. However, no streamflow evidence could be identified in this study of 26 catchments to show that dambos increase dry season evaporation losses, either through different vegetation community or shallow water table characteristics. However, previous studies involving larger data sets and less variable rainfall depths do present evidence of the reduction effect on dry season flows. No attempts have been made at the quantification of evaporative losses in these earlier studies and regional hydrological procedures are not inherently the most efficient in quantifying components of the hydrological cycle. Greater emphasis should be given to conclusions from process studies of evaporation to estimate the loss of recharged water to evaporation, such as those methods presented in Sections 7 and 8.

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* Q75(10) = ten day duration 75 percentile exceedance low flow (% of mean flow)
AAR = average annual rainfall (mm)
DAMBO = dambo density (%)

7. DAMBO HYDROLOGY

7.1 Background

The importance of understanding dambo hydrology relates not only to the context of groundwater resources evaluation but also to the occurrence and origin of the regolith and possibly to structural features within the bedrock. Both types of information have relevance to groundwater development aspects.

Regional hydrological analyses of catchments with varying dambo proportions show some ambiguous results although there is rather more emphasis on a role which reduces both total yields and baseflows. Ambiguity seems likely to relate to variations in dambo type which depends on its state of evolution from an initial condition with broad, streamless and flat valley forms to the results of later incision which produce narrow valley forms with steeper slopes. Incision also results in erosion of previously formed dambo sediments and steeper slopes to the groundwater levels in the vicinity of the incised valley form.

The detailed dambo studies have included the drilling of piezometers to varying depths and in selected position across dambo profiles in order to determine the permeability of the various aquifer layers by packer testing and to identify piezometric gradients by measurements of seasonal water levels. Two dambos (Chimimbe and Chikobwe) at contrasting stages of evolution were studied.

7.2 Discussion of Results

Lithological cross-sections of the dambos have been shown (Figures 5.2 and 5.3 and discussed earlier. Figure 7.1 shows the locations of critical piezometers and the levels at which hydraulic conductivity (permeability) were measured. Seasonal changes of water level and a schematic diagram of the flow system are shown in Figures 7.2 and 7.3.

Essential results of the hydraulic conductivity variations are given in Table 7.1. The values range from low to very low and are likely to be representative of the main matrix permeability. Higher values are probable in the vicinity of localised features such as stone lines (basal colluvium), residual quartz bands in saprolite and more significant fractures in saprock. The general pattern of variations is consistent with observed mineralogical and physical changes in the weathering sequence.

The water level data have indicated no occurrence of perched aquifer bodies although during intensive rain, shallow interflow in the uppermost sandy colluvium seems likely. Gradients in vertical sections are typically downward in the interfluves and upward below the dambo clay zone. There is a short period during the early onset of the wet season when recharge is occurring through the cracks in the dambo clays giving a positive downward gradient. The dambo clays when saturated are effectively impermeable and associated water levels fall during the dry season despite the upward gradient in the saprolite. The feature may be attributed to a greater rate of water loss by evaporation/transpiration from the cracking clays with insufficient compensation by upward flow through the basal saturated clays. The water levels in the peripheral

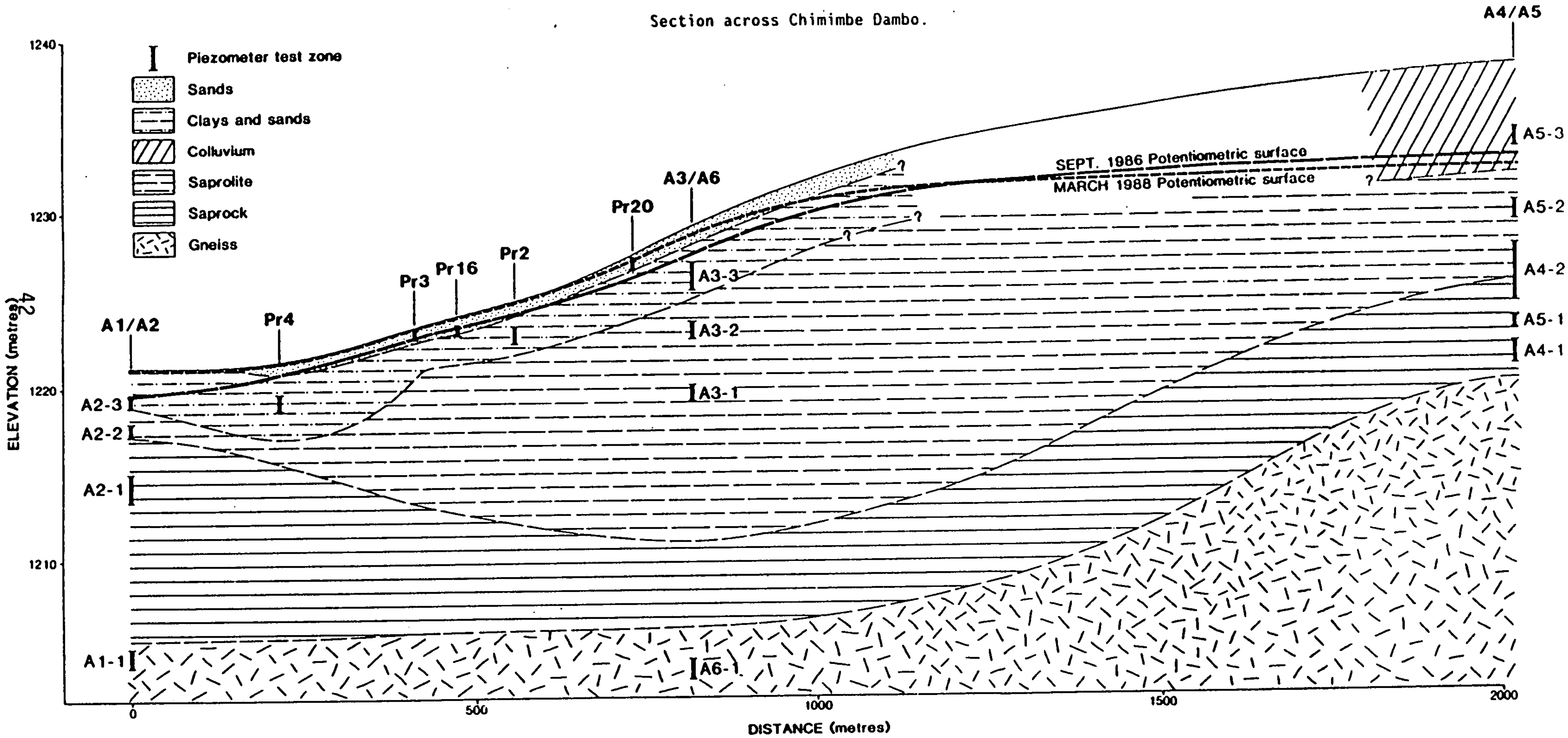
Table 7.1 Measured Hydraulic Conductivity Variations at the Chimimbe Dambo

Interfluve		Peripheral Dambo		Dambo	
1*	2*	1*	2*	1*	2*
Colluvium					
Surface sands c. 5 m	(n.m.+, high) 10^{-2}	Surface sands Palaeodambo clay	3-6 c. 10^{-3}	Dambo clay	10^{-4}-10^{-2}
Lower boundary 6-8 m	10^{-2}				
Saprolite					
Upper saprolite c. 8 m	0.1	Saprolite	0.05-0.2	Saprolite	0.1
Lower saprolite c. 12 m = saprolite/ saprock junction	0.3				
Saprock	0.4-0.7		-		0.1
Bedrock			0.1		0.2

Notes:
*1 - Zone
*2 - Hydraulic Conductivity (m/d)
+ - not measured

Figure 7.1

Section across Chimimbe Dambo.



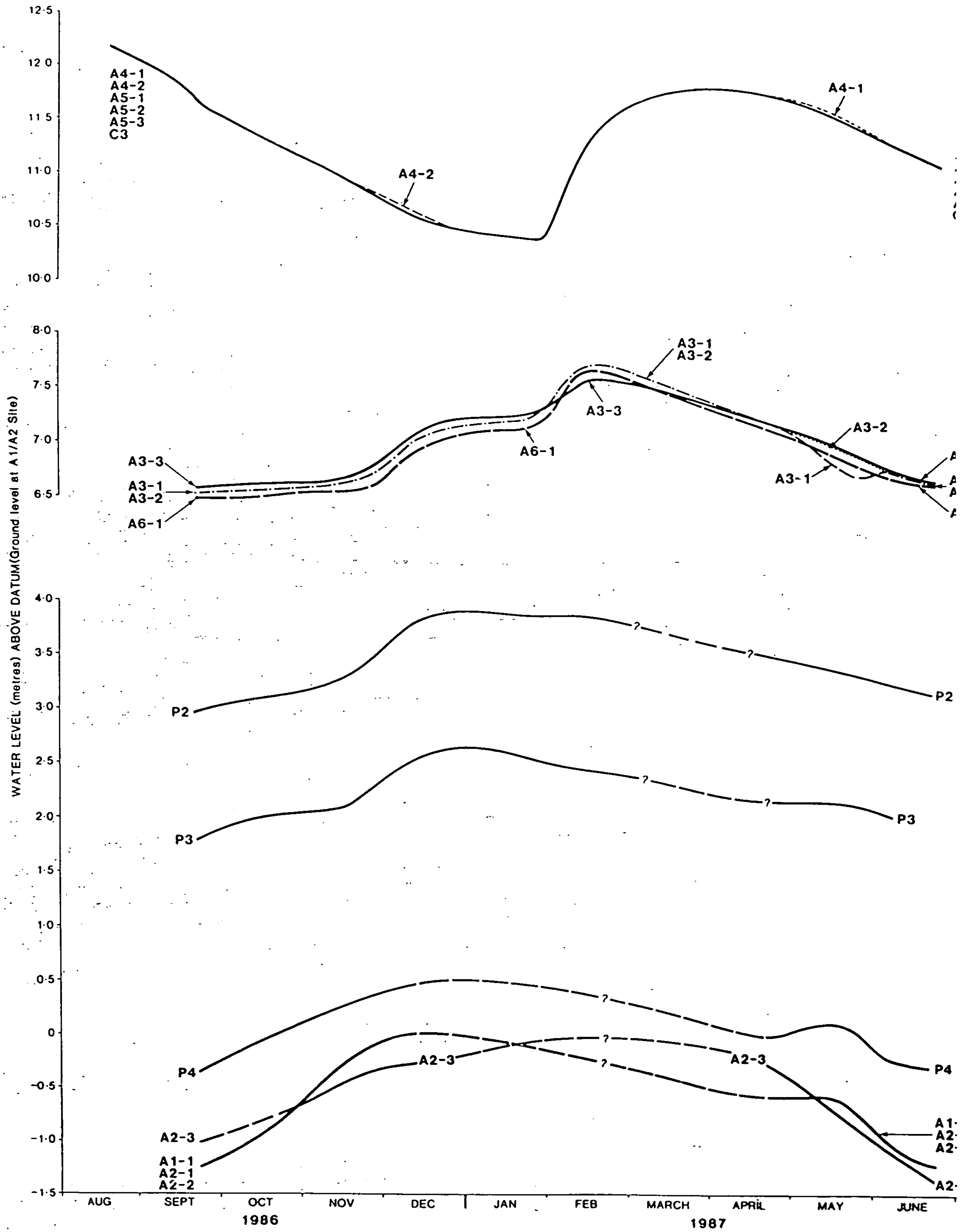


Figure 7.2 Water level variations in Chimimbe piezometers.

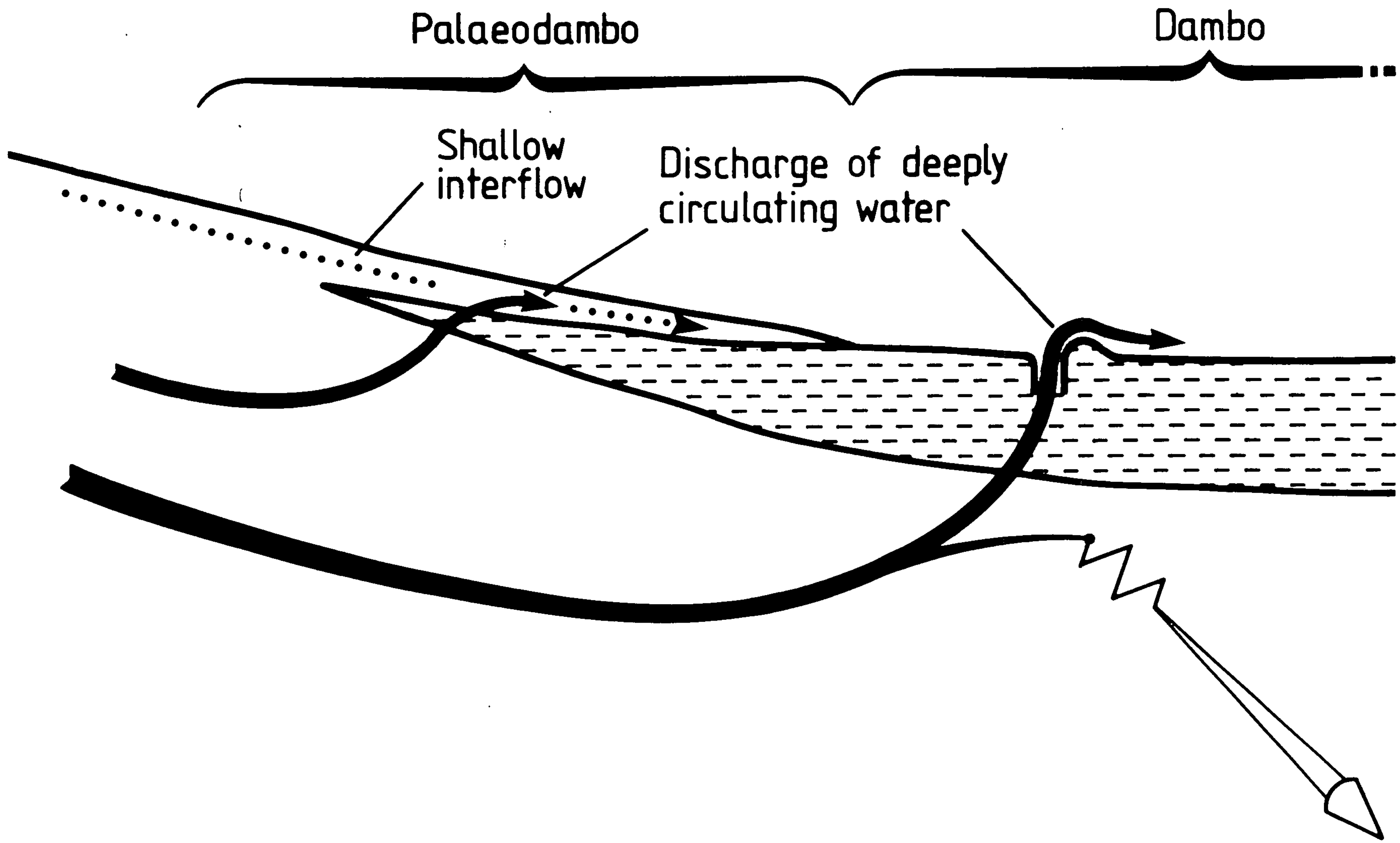


Figure 7.3 Groundwater circulation in vicinity of a dambo.

sands, thought to be of residual origin and overlying dambo clays, respond rapidly to rainfall but show an equally rapid fall off. Recharge in the wet season is thus from rainfall and shallow interflow. Recharge to the dambo peripheral sands in the dry season is from the interfluve and the hydraulic evidence of the piezometer levels favours a deep circulation as also do some of the chemical components (SO_4) although the Fe content of the groundwaters of the seepage zone favours a continuation of a more shallow 'interflow'.

The lag of water level changes apparent in the interfluve piezometer is attributed to the low permeability of the basal colluvium, with water levels generally occurring within or below this zone. Groundwater movement in the dry season must occur therefore through the overburden sequence below the basal colluvium but speed of movement may well be significantly affected by high permeability 'bypass mechanisms', as described earlier.

The chemistry of groundwater in the peripheral seepage zones and crescent springs (at Chikobwe) which exit through the dambo clays have been studied with a view to ascertaining the probable flow paths, with particular emphasis on Si, Fe, Ca, Mg, Na and SO_4. Although variations appear comparatively small, they are significant and indicate derivation from various levels in the saprolite-saprock succession. Chloride values are generally low with a main range from 1-6 mg/l. SO_4 values, with one exception, are high which would suggest that the groundwater flow to the seepage zone and the crescent springs has penetrated to a significant depth in the saprolite-saprock.

Some calculations of throughflow rates can be attempted by flow net analysis using the observed gradients and permeabilities. Flow moves from the interfluves towards the dambo and discharges at the seepage zone or springs and also laterally below the dambo clays to be discharged elsewhere, either as baseflow or evaporation at a seepage zone downstream. Assuming continuity of permeability to 70 m, sub-dambo flow would be of the order of 1 litre/sec across the observed section. Seepage losses were estimated on the assumption of a seepage zone equivalent to 10% of the dambo area upstream of the cross-section and evaporation at the rate of 1500 mm/a (pan evaporation rates on the plateau are in the range 1600-1950 mm). Total recharge is equivalent to 160 mm per annum with evaporation losses being more than 10 times the sub-dambo flow rates. These calculated seepage outflows by evapotranspiration are less than the lateral groundwater flow calculated by flow net analysis.

A chloride balance of rainfall and runoff might also help to evaluate recharge. Comparisons of these results with those from other areas of Malawi and Zimbabwe are discussed in Section 11. Rainfall chlorides from 53 samples in Malawi have a mean value of 1.01 mg/l and a standard deviation of 1.2 mg/l. For an estimated 160 mm of recharge and an effective rainfall of 800 mm (mean annual rainfall minus rapid response runoff), a groundwater chloride content of 5 mg/l would be anticipated. The groundwaters in the piezometers, seepage zone and crescent springs are in the main range of 1-6 mg/l with occasional higher values. The maximum value in the rain range accords with the estimate of recharge but the range is suggestive of the influence of bypass mechanisms with more limited fractionation of chloride.

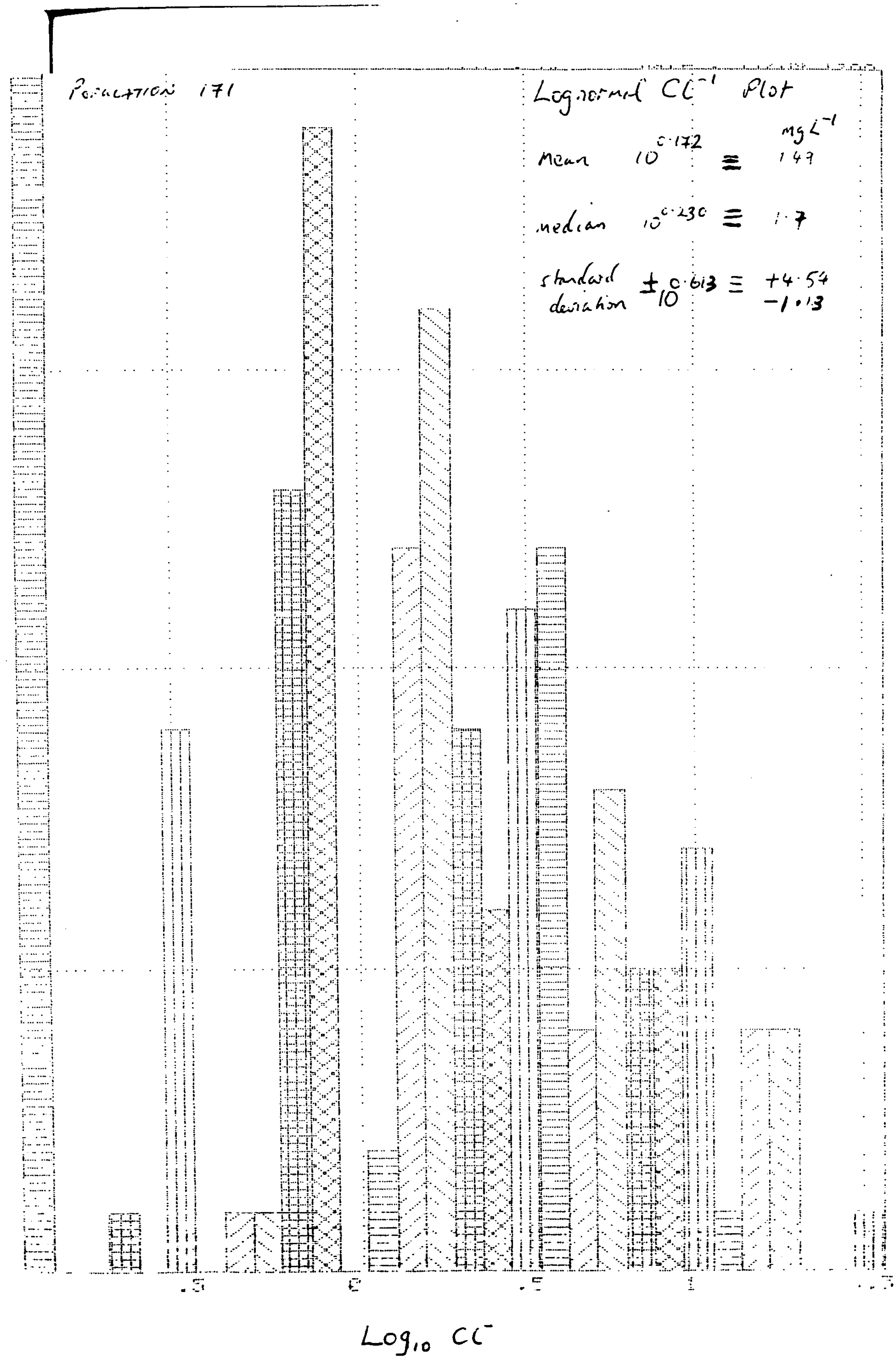


Figure 7.4 Chloride content distribution.

Table 7.2 Chloride Content in Core Samples at Chimimbe and Chikobwe Dambos

	Elutriation Cl (mg l^{-1})	Centrifugation (mg l^{-1})
Chimimbe		
Borehole A1 (m)		
0.07 - 0.13	33.1	-
1.01 - 1.09	15.4	-
1.58 - 1.65	17.9	8.5
1.95 - 2.00	15.8	6.4
Borehole A6 (m)		
0.50 - 0.70	42.4	-
1.20 - 1.27	23.8	9.0
1.75 - 1.80	14.1	4.3
2.15 - 2.20	10.7	36.0
4.08 - 4.16	23.4	6.0
Chikobwe		
	31	76
	144	12
	61	10
	137	271
	28	90
	-	27
	337	200
	14	47
	10	36
	9	23
	10	14

Summary

Chimimbe	Mean	Standard Deviation	No. of Samples
Elutriation	21.8	9.6	9
Centrifugation	11.7	10.9	6
Chikobwe			
Elutriation	90	98	10
Centrifugation	73	81	11
Dambo Surveys	3.2	4.6	176

A dry season survey of dambos (by University of Malawi students) in the same general area collected 175 water samples from auger holes, streams and wells. The auger holes were drilled through the dambo clays to the underlying more sandy material. Of the 175 samples collected only 6 exceeded 10 mg/l of Cl. The sample chlorides gave an arithmetic mean of 3.2 mg/l and a harmonic mean of 1.05 mg/l. The samples showed a log-normal distribution (Figure 7.4) with a geometric mean of 1.7 mg/l. The results would again imply a high rate of recharge but with the main springs and seepages probably dominated by the more rapid throughflow systems.

The core samples collected were analysed for chloride by elutriation and centrifugation (Table 7.2). Of the six sets of samples in the regolith profile at Chikobwe, the mean chloride values were 78 mg/l (elutriation) and 73 mg/l (centrifugation) but there was a poor correlation of individual values. The results do demonstrate however a much higher value in the matrix chlorides than in the main groundwater throughflow.

To summarise, groundwater recharge in this area would appear to be of the order of 17% of mean annual rainfall but with a complex throughflow system with a strong emphasis on more rapid bypass channels leading to significant seepage zones and springs in the vicinity of dambos. Boreholes are more likely to be associated with the slower and deeper matrix flow system as evidenced by the higher chloride values.

8. ESTIMATION OF AREAL EVAPORATION FROM DAMBOS IN ZIMBABWE USING SATELLITE DATA

8.1 Introduction

To assess the hydrological balance of a catchment area, measurements or estimates of each of the hydrological variables averaged over the catchment are required. In the case of evaporation, data measured at one location are usually considered to be representative of the whole catchment. Studies of atmospheric turbulence and dispersion have shown that the size of the area, whose evaporation is measured, is proportional to the height of the instruments. Thus for instruments mounted at a height of 1 m the area is less than one hectare. Until recently the only alternative to assuming that there was no spatial variation in evaporation, was replication of the measuring systems which is generally prohibitively expensive. With the availability of suitable remotely sensed data, it is now feasible to determine the evaporation over larger areas if the necessary additional information is available.

This report describes the method and the results of using Landsat TM data to evaluate the evaporation over an area of 15 x 15 km in a dambo area of Zimbabwe.

8.2 Theory

The energy balance at the surface can be expressed as:

$$R_n = \lambda E + H + G \qquad (1)$$

where R_n is the net all-wave radiation (W m^{-2}), λ is the latent heat of vaporisation (J kg^{-1}), E is the evaporation (mm s^{-1}), H is the sensible heat flux (W m^{-2}) and G, the heat flux into the soil (W m^{-2}).

The sensible heat flux can be expressed as:

$$H = \rho c_p \, g_a(T_s - T_a) \quad (2)$$

where ρ and c_p are the density (kg m^{-3}) and specific heat (J kg^{-1} $°C^{-1}$) of air, g_a is the transfer coefficient (m s^{-1}) between the surface and the height at which T_a is measured and T_s and T_a are the temperatures of the surface and the air respectively (°C).

Hence the sensible heat flux can be derived from measurements of the transfer coefficient and the temperature difference between the surface and the air. Using eq. (1) the evaporation can be calculated if measurements or estimates of the net all-wave radiation and the soil heat flux are also available.

8.3 Experimental Area and Data

The experimental area, where the ground based measurements were made, was within the Chizengeni dambo (latitude 18°14'S, longitude 31°16'E, altitude 1495 m), 40 km southeast of Harare Airport, Zimbabwe. Chizengeni dambo is roughly Y-shaped with a total area of about 1 km^2. The measurements were made within 100 m of the seepage zone in one arm of the dambo.

Table 8.1 Summary of dates and times of data collection in Chizengeni Dambo, Zimbabwe in August 1986.

Date	Time		Data available		
	start	finish	surface temperature	energy budget	satellite
6th	12:35	16:00	*		
8th	08:40	17:15	*		*[1]
19th	08:55	15:51	*		
20th	09:42	16:58	*		
21st	10:38	17:30	*	*	
22nd	07:58	15:49	*	*	
24th	08:30	17:00	*	*	
25th	08:00	16:00		*	

[1] Overpass at 09:17 local time

Table 8.1 summarises the measurements which were made during August, three months after the start of the dry season. Measurements of surface temperature were made with an infra-red thermometer having two sensor heads which could be up to 10 m apart. Each sensor head was mounted on a tripod at a height of 1.2 m and measured the surface temperature of an area of 0.1 m^2.

Measurements of the components of the energy budget using the Bowen ratio method were made by a system with sensors mounted at 0.1 and 1.4 m, operated by Loughborough University.

8.4 Results

8.4.1 Spatial Variation of Surface Temperature Measured by Ground-based Infra-red Thermometers

The spatial variation around a control point was measured four times at four locations within Chizengeni dambo. At two of the locations the surface was more variable and the standard deviation about the mean was 1.7°C with extreme differences from the mean of -3.0°C and 3.7°C. For the other two locations the standard deviation was 1.2°C with extreme differences of -1.9°C and 3.2°C.

8.4.2 Transfer Coefficient

Using the measured height of the vegetation of 40 mm in the Thom and Oliver equation (1977), the transfer coefficient was found to be 12.8 mm s^{-1} for a wind speed of 2.5 m s^{-1}. Using the measurements made by Loughborough University gave the transfer coefficient as 15 m s^{-1}, when the mean wind speed was 2 to 3 m s^{-1}.

8.4.3 Satellite Data

Landsat TM data was obtained on 8 August 1986 covering a roughly square area of approximately 8,000 km^2 whose corners were located at 17°55'S, 31°5'E; 18°5'S, 31°55'E; 19°45'S, 31°45'E and 18°35'S, 30°55'E.

This analysis concentrated on a 200 km^2 area within the Landsat image. This area included the Chizengeni dambo where the ground-based measurements were made. Using the higher resolution data in the visible and near infra-red bands, the boundaries around the dambo areas were drawn. These boundaries could then be superimposed on the lower resolution thermal infra-red data to identify the areas of interest (Figure 8.1).

(a) *Determination of surface temperature.*

The Landsat thermal infra-red sensor gave an average brightness temperature of the area, where the ground-based instruments were located of 24°C. During the 5 minutes centred on the time of the satellite overpass, 09:17 local time, the average temperature measured by the ground-based infra-red thermometer was 19.8°C. Therefore, the correction for atmospheric effects was -4.2°C. Physically a negative atmospheric correction is only possible if the surface temperature is less than the

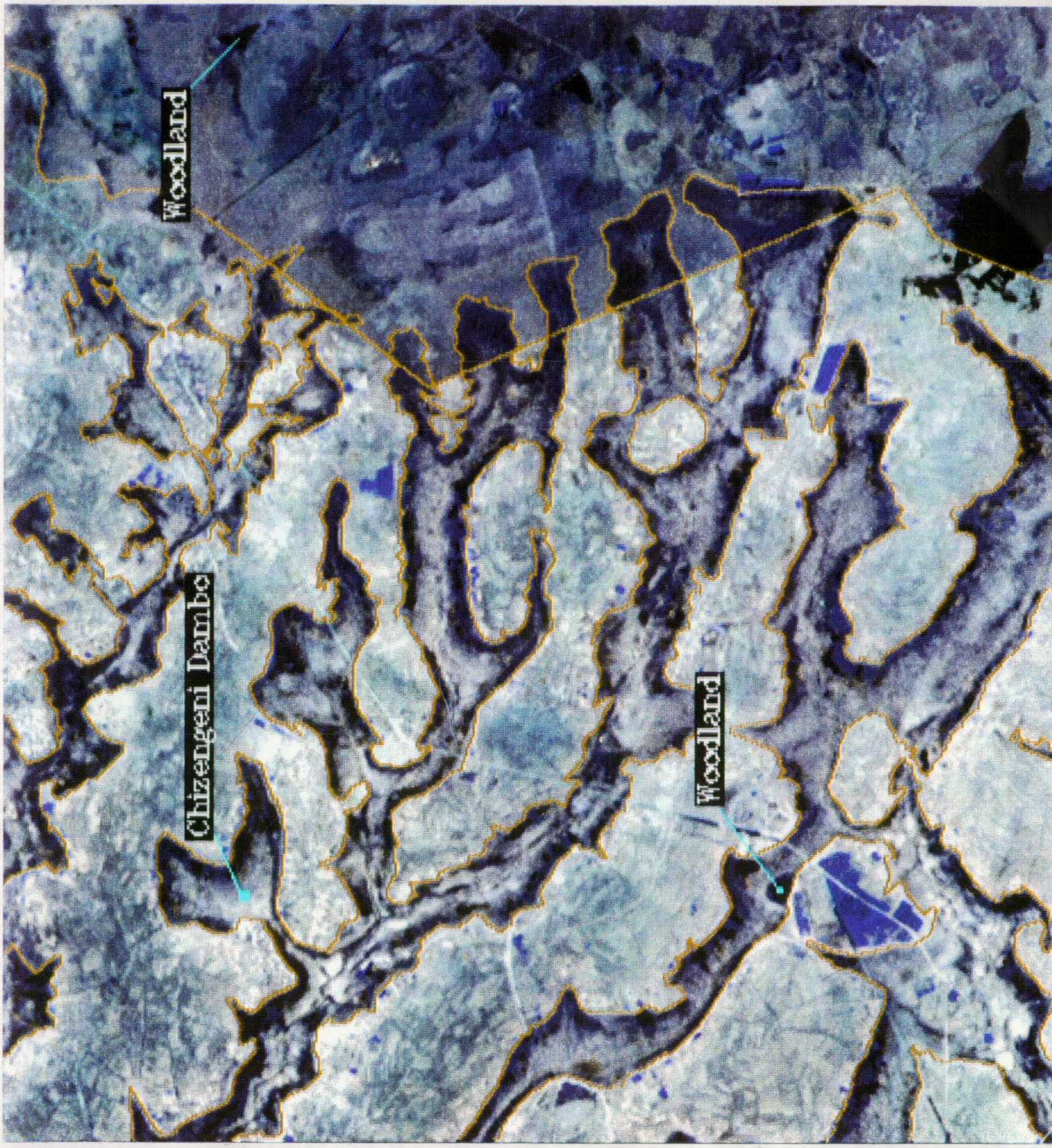


Figure 8.1 A false colour composite image derived from Landsat 5 data. The 15 by 15 km area is about 90 km SE of Harare. The Chizengeni dambo and the locations of the two woodlands are shown.

air temperature which can only occur at night, not during mid-morning. It is thought that the ground-based infra-red thermometer may have been faulty or there was a very large sampling error.

The atmospheric correction model developed by Reading University for Meteosat thermal infra-red data over the Republic of Niger, was used with the data for Zimbabwe. The atmospheric correction was found to be +0.3°C.

(b) *Determination of difference between surface and air temperatures.*

Within the 200 km^2 sub-area of Landsat image there were two areas of woodland less than 10 km from the Chizengeni dambo. The minimum temperatures within these areas were 16.2°C and 17°C. Previous studies have shown that the surface temperatures of wooded areas are only 1 to 2°C above air temperature. Therefore a value of 15°C has been used in this analysis as the satellite estimate of the air temperature to determine the difference between surface and air temperatures.

Figure 8.2 shows the spatial variation in the difference between the surface and air temperatures over the 200 km^2 area. The overage temperature difference for the three dambo regions and the area outside the dambos was calculated. The temperature differences were 10.1 and 11.3°C for the dambo region and the region outside the dambos. Over the Chizengeni dambo the difference between the surface and air temperatures varied between 6.2 and 11.9°C with a mean value of 9.2°C (Figure 8.3).

(c) *Determination of sensible heat flux.*

The only measurement of the transfer coefficient was available from the data obtained by Loughborough University. Therefore it was assumed that this value was appropriate to the whole of the 200 km^2 area. Figure 8.4 shows the spatial variation in the sensible heat flux. Over the Chizengeni dambo the estimated sensible heat flux varies between 116 and 222 W m^{-2} with a mean value of 171 W m^{-2} (Figure 8.5). Assuming the same transfer coefficient applied over the larger area, the mean value of the sensible heat flux over the dambo areas in the 200 km^2 region was 188 W m^{-2} respectively. For the area outside the dambos, the sensible heat flux was 211 W m^{-2}.

(d) *Determining the latent heat flux.*

Since there are no direct measurements of net all-wave radiation at the time of the satellite overpass, it had to be assumed that conditions were similar to those on cloudless days a fortnight later, i.e. 450 W m^{-2} for net radiation and 50 W m^{-2} for soil heat flux. Therefore the energy available for the sum of the sensible and latent heat fluxes was 400 W m^{-2}. Over the Chizengeni dambo the estimated latent heat flux varies between 178 and 284 W m^{-2} with a mean value of 229 W m^{-2} (Figure 8.6). These latent heat fluxes are equivalent to evaporation rates of 3.0, 4.8 and 3. mm day^{-1} respectively. The mean value of latent heat flux over the dambo areas within the 200 km^2 region was 212 W m^{-2} (3.5 mm day^{-1}) while for the area outside the dambos the latent heat flux was 189 W m^{-2} (3.2 mm day^{-1}) (Figure 8.7).

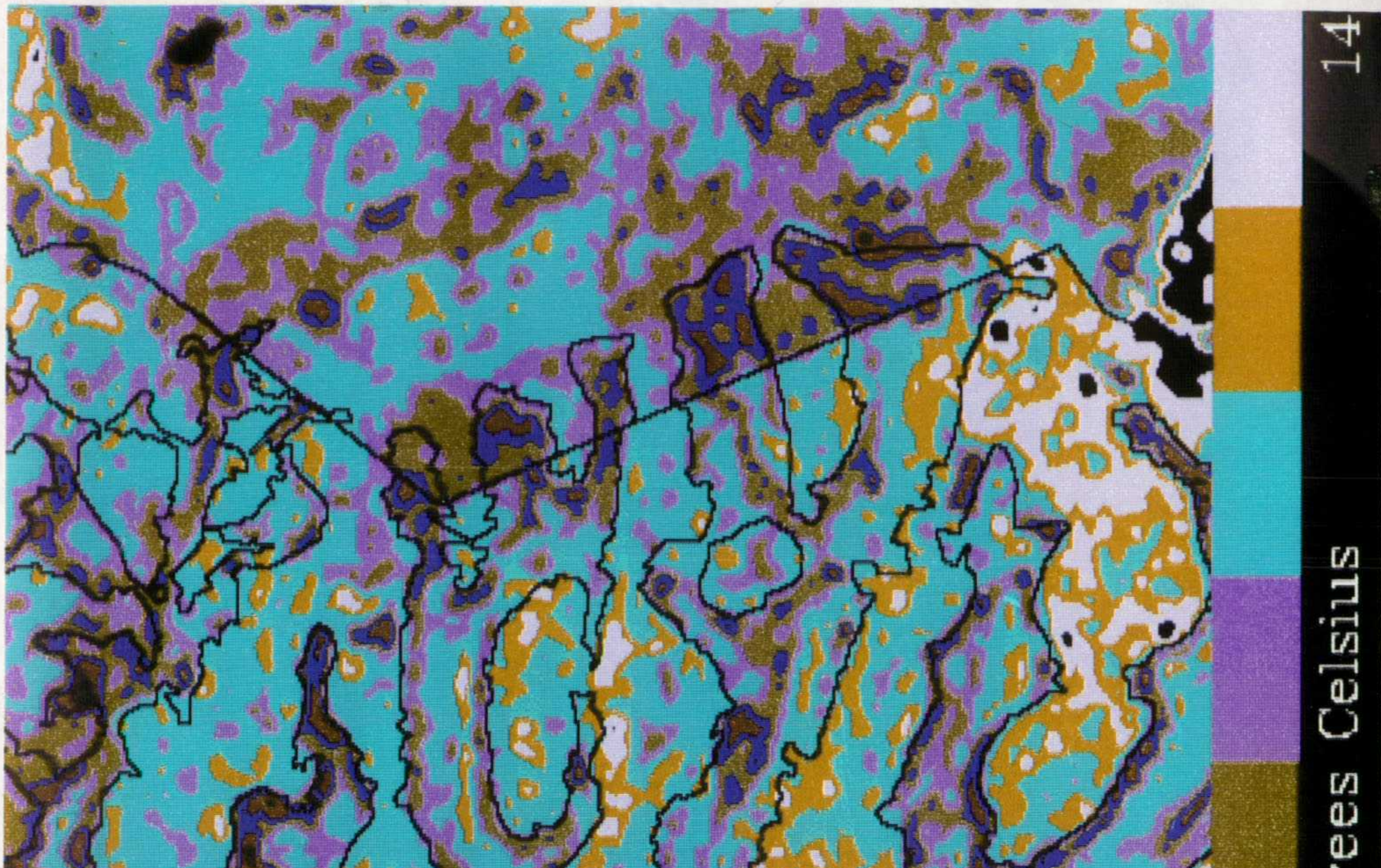


Figure 8.2 The difference between surface and air temperatures in ^{o}C derived from Landsat thermal infra-red data over the 15 by 15 km area.

Figure 8.3 The difference between surface and air temperatures in ^{o}C derived from Landsat thermal infra-red data over a 4 by 4 km area centred on the Chizengeni dambo.

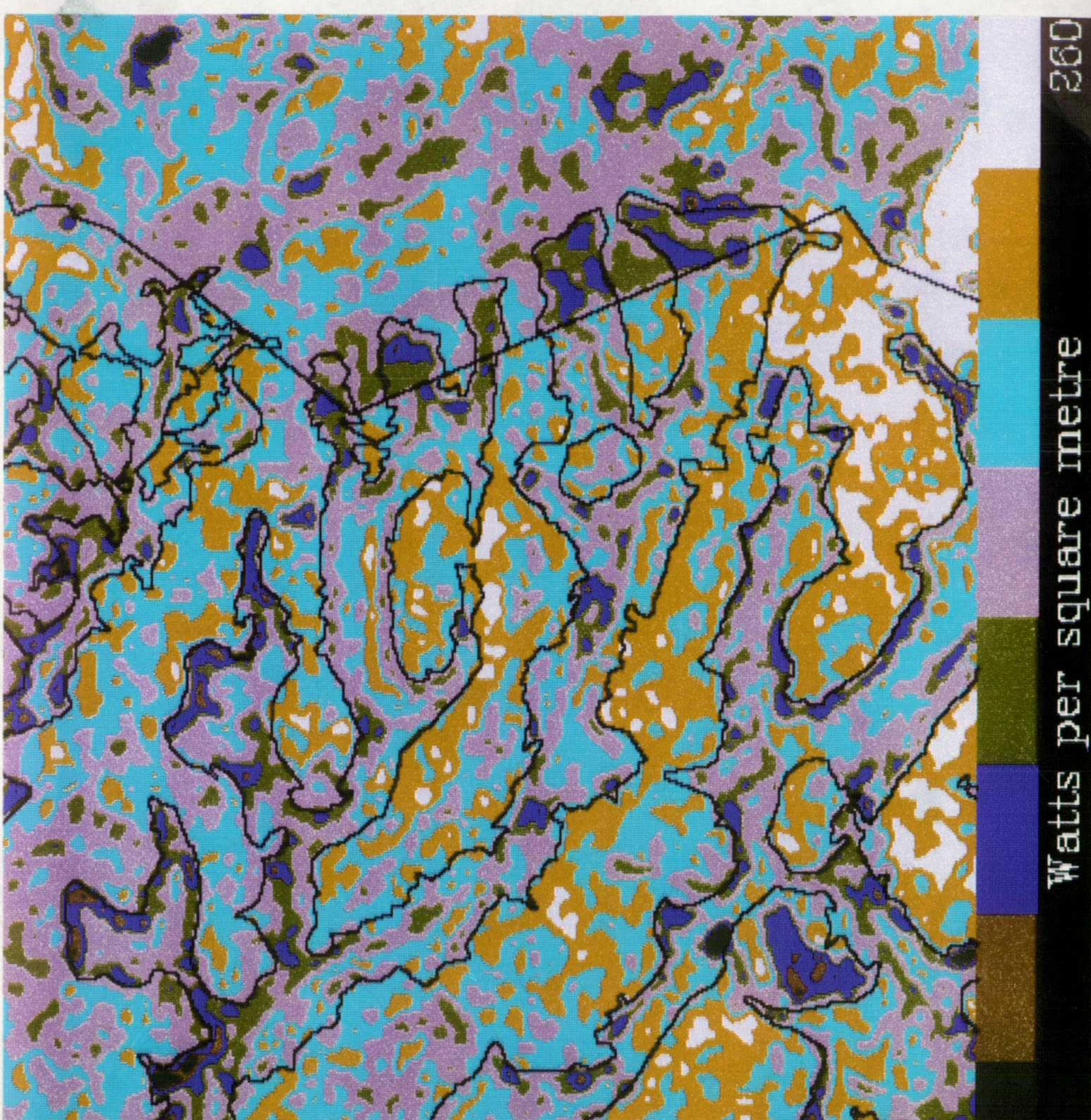


Figure 8.4 The sensible heat flux in W m^{-2} over the 15 by 15 km area.

Figure 8.5 The sensible heat flux in W m^{-2} over the 4 by 4 km area centred on the Chizengeni dambo.

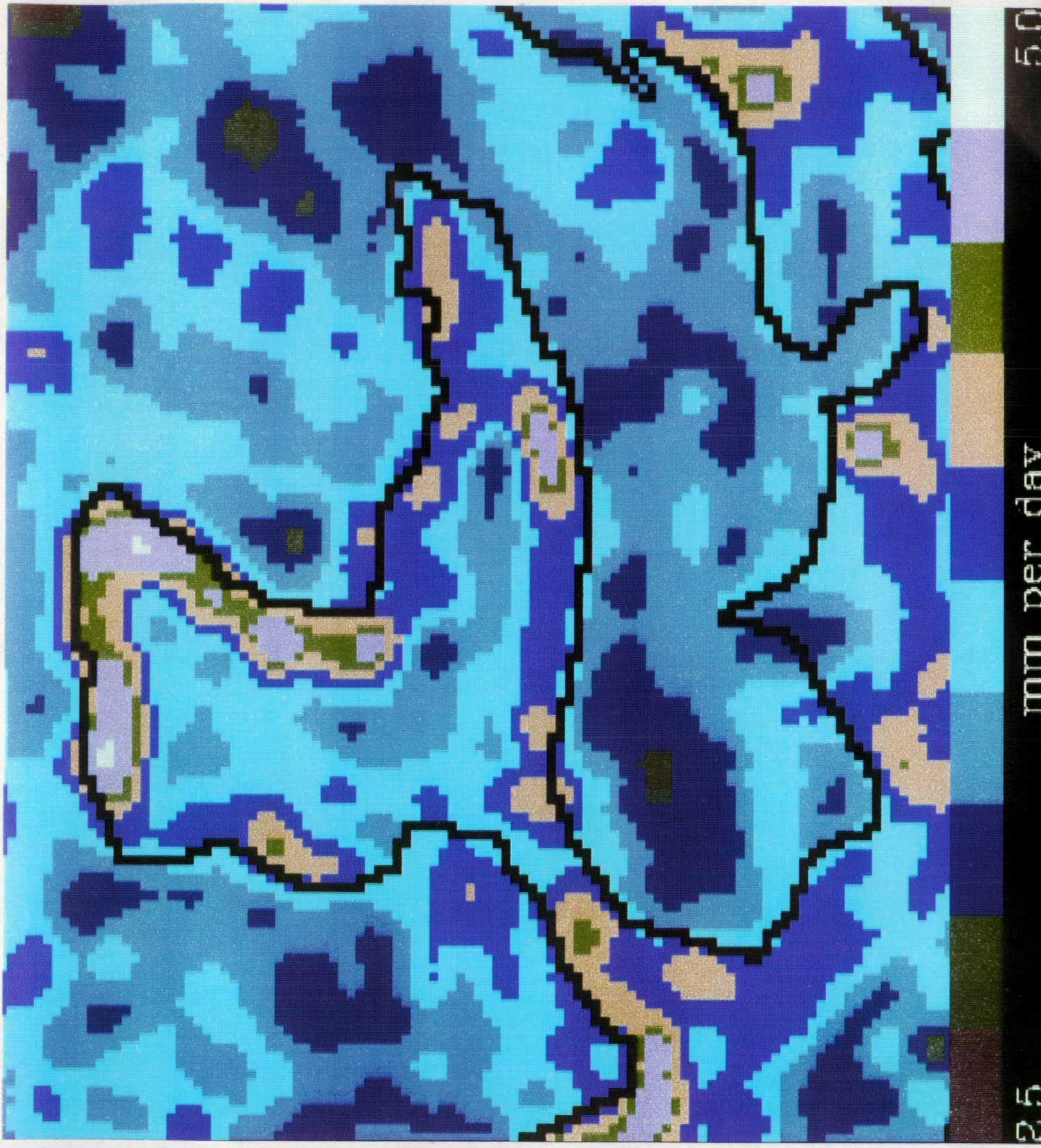


Figure 8.6 The evaporation expressed in mm day^{-1} over the 4 by 4 km area centred on the Chizengeni dambo.

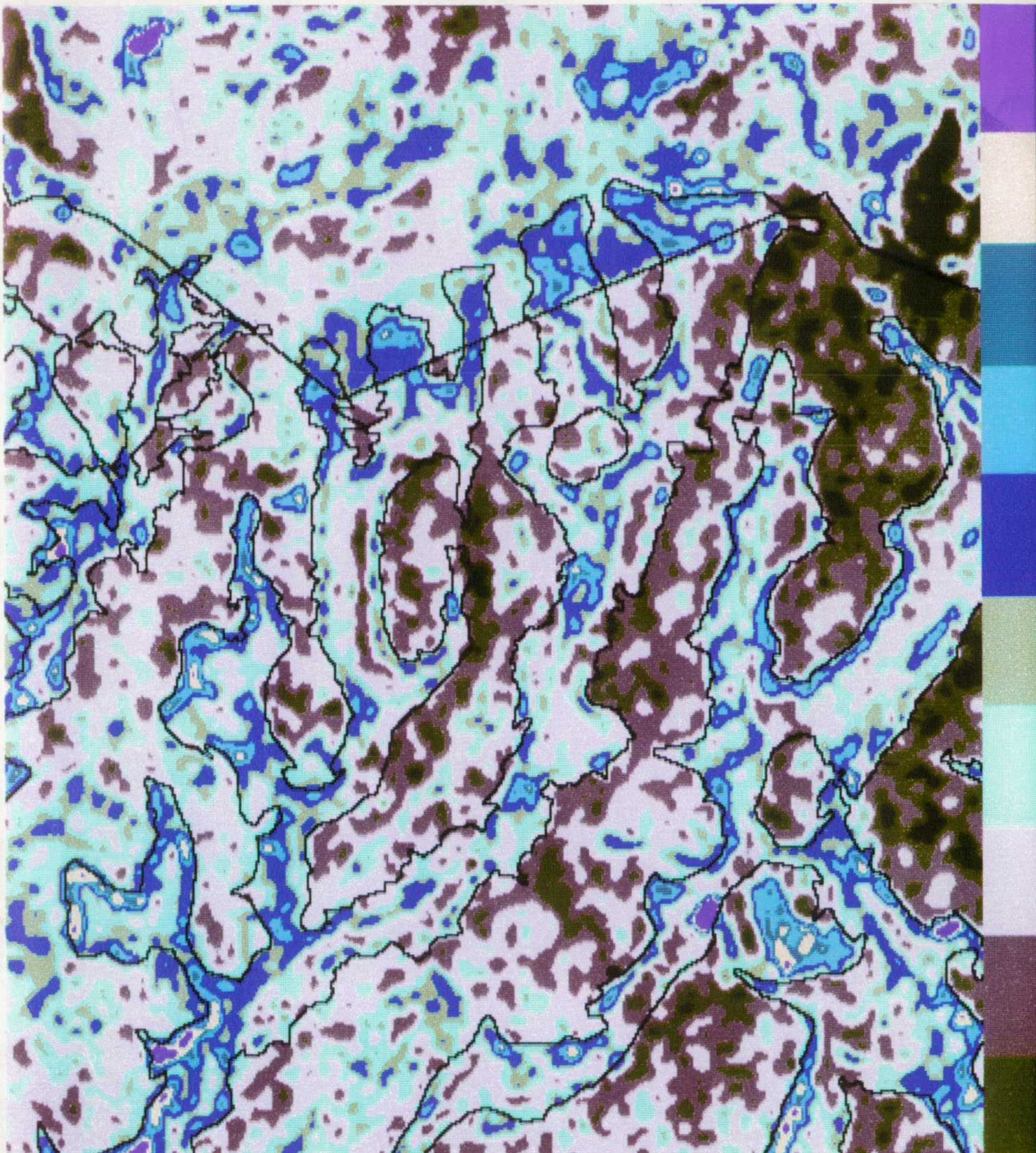


Figure 8.7 The evaporation expressed in mm day^{-1} over the 15 by 15 km area.

Figure 8.6 shows that the evaporation from the central area of the Chizengeni dambo is considerably lower than from the area close to the edge of the dambo. This pattern agrees very well with the dambo zones identified by Bell et al. (1987), see Figure 8.8. They comment that within the upper part of the dambo 'the water table is sufficiently close to the surface to permit growth of grass or crops'. Whereas 'the lowest part of the dambo may be dry throughout the year, except immediately after rain'. Outside the dambo the evaporation decreases rapidly to a low value again. A similar pattern appears within the dambos over the whole 200 km^2 area (Figure 8.7).

The estimates of actual evaporation derived from the satellite data can be compared to the potential evaporation at the time of the overpass. Using the Priestley-Taylor formula (1972) the potential evaporation was 314 W m^{-2} (5.3 mm day^{-1}) for an air temperature of 15^{o}C, net radiation of 450 W m^{-2} and soil heat flux of 50 W m^{-2}. Within the seepage zone of the Chizengeni dambo the actual evaporation was 250 W m^{-2}, i.e. 80% of the potential evaporation rate. In the dry dambo bottom the actual evaporation was 200 W m^{-2}, i.e. 64% of the potential rate.

9. THE APPLICATION OF BOREHOLE GEOPHYSICAL TECHNIQUES

The development of interpretative techniques within weathered and competent basement formations presents problems in the absolute calibration and analysis of the response of the different borehole geophysical techniques employed. To date the majority of well log analysis has been confined to sedimentary formations and the tool responses have been normalised to limestone formations. With the increased interest in geothermal resources these interpretative techniques have gradually been expanded to give generalised formation characterisation within basement formations. Although this analysis is still in its infancy there appears to be a clearer picture emerging of how different methods may assist in the interpretation and classification of these different formations either by direct tool response or by cross plot techniques.

Investigations in Malawi and Zimbabwe have enabled a closer understanding of the different tool responses to the degree of weathering and the type classification of the signatures obtained from that of the parent formation. Within Malawi where a more aggressive weathering profile was investigated the responses within two dambos at Chikobwe and Chimimbe showed a fairly simple correlation between the responses of the natural gamma radiation log and that of the point resistance log. Investigations in Zimbabwe included a far more comprehensive suite of logging techniques and the degree of weathering and formation type responses could be classified by other techniques.

The response of the natural gamma radiation log is predominated by the potassium content of the formation and analysis of the core has shown close correlation between the potassium oxide levels and that of the overall response of the gamma log (Figure 9.1). Surface conduction within the clay minerals dominated the resistivity response with the lower resistivities being observed within the dambo clays. This response increases in value down profile and indicated the degree of weathering undergone by the formation, from the dambos clays of low resistivity into the saprolite. The saprolite could be differentiated into two distinct

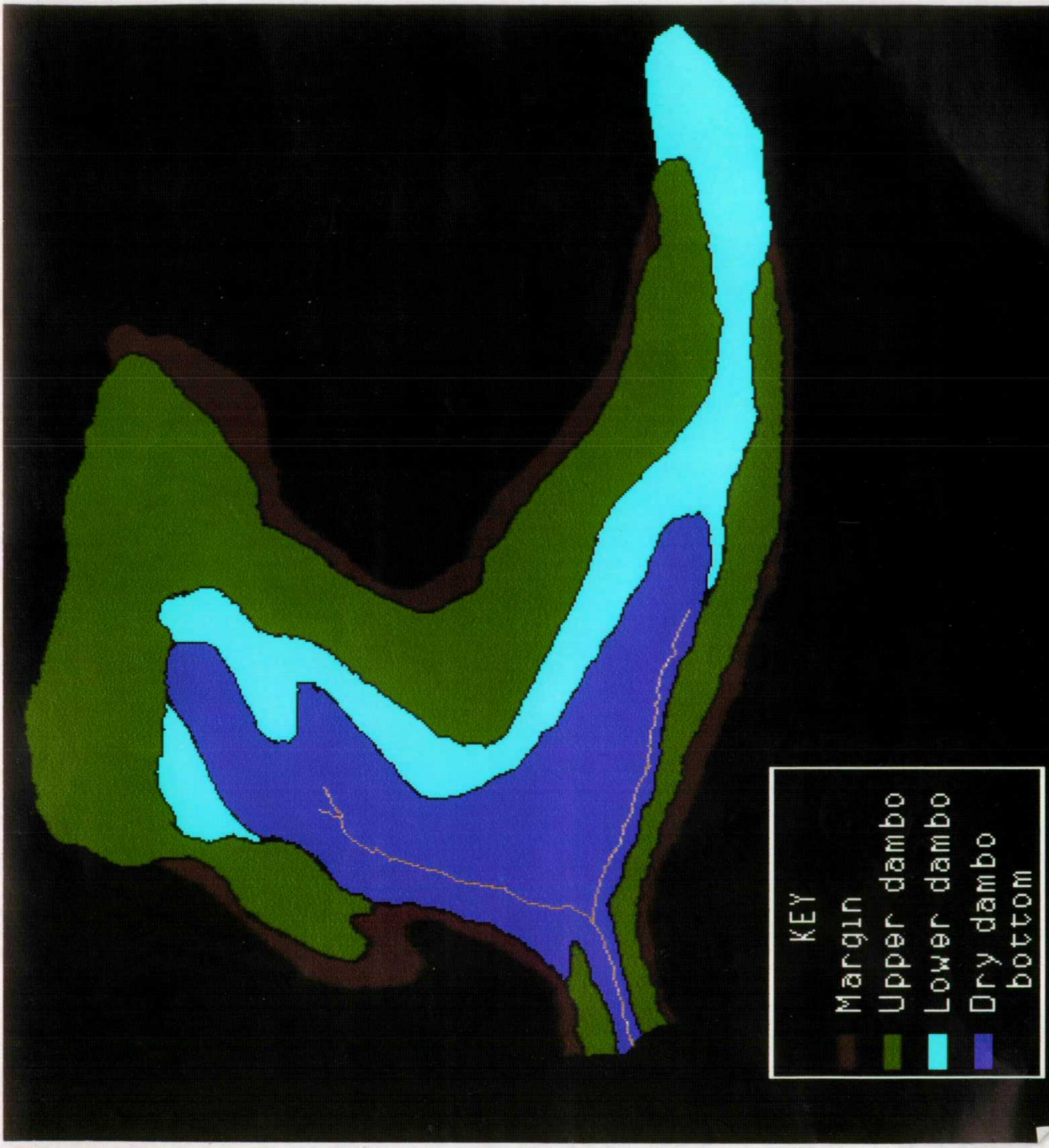
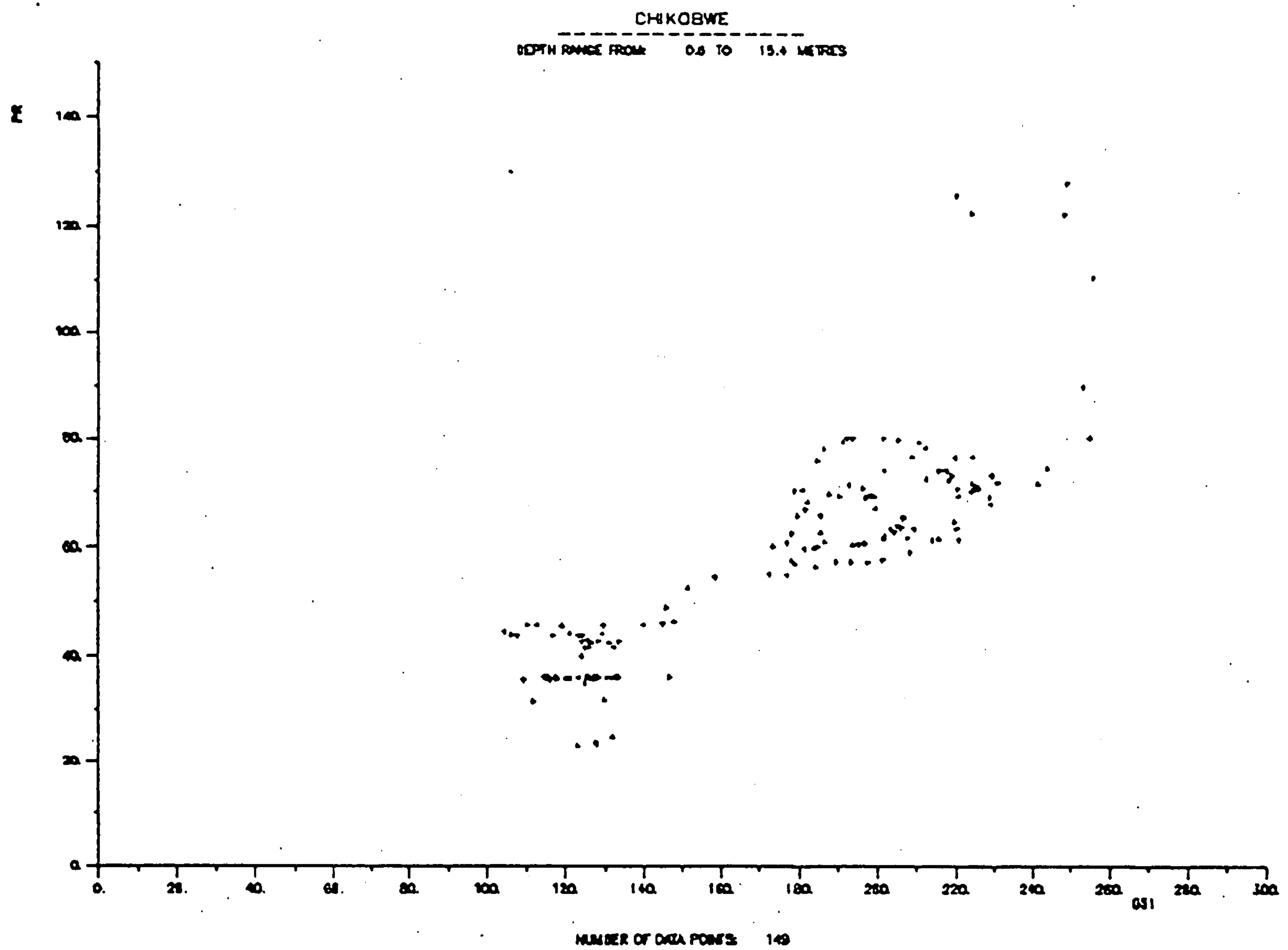


Figure 8.8 The four main zones identified within the Chizengeni dambo (redrawn from Bell et al., 1987).

Figure 9.1 Cross-plot of resistivity and natural gamma.



types, a 'soft' and 'hard' saprolite, showing a resistivity contrast. This demarcation indicated the different degrees of weathering of the formation. The transition to saprock was also clearly indicated with a sharp interface of increased activity into the more competent material.

The characteristic responses of the resistivity and natural gamma radiation curves has resulted in a cross plot of these two parameters, and as can be seen from Figure 9.1 a linear response was obtained. The lower field is associated with the dark grey dambo clays where quartz kaolinite and smectite (montmorillonite) dominated the dambo infill. Conduction by these clay minerals results in the lower resistivities. A mineralogical change to the saprolite results in a considerable reduction in the clay minerals with the potassium feldspars and micas predominating. The transition to saprolite is shown on the scatter plot by the small number of points joining the upper field to that of the lower. The upper field is representative of the saprolite indicating higher resistivity and gamma responses. The upper values of these two parameters in the second field is the response of the saprock. Several points exist outside the upper field indicating very high gamma and resistivities, and it is postulated that these may be responding to orthoclase associated with quartz within the saprock. As the degree of weathering is small these primary minerals still exist.

Where additional logging techniques were available a further attempt at formation weathering was undertaken with a suite of different spacing resistivities and a single detector neutron-neutron porosity sonde. These logging techniques were run at a number of locations and the following examples are indicative of the typical responses. These locations at Rungai and Mhatiwa in Masvingo Province of southern Zimbabwe illustrate a heavily fractured formation (Rungai) and a formation with only minor fracturing (Mhatiwa). The suite of logging undertaken is shown in Figures 9.2 and 9.3. The Rungai site shows discrete fractures to exist at depth and a zone of intensive fracturing at 13 metres. The different logging techniques illustrate the fracture response with low resistivities on all different spacing resistivity logs, or increases in the hydrogen index on the neutron log. The caliper log however does not indicate all the fractures as shown on the above methods as these fractures may be too small to be resolved by this technique. The resistivity logs indicate increasing resistivity with depth but due to the fracturing it would be very difficult to delineate the transition from saprolite to saprock. The neutron log shows formation porosity to decrease with depth and clearly indicates the increased bulk porosity at fractures. The neutron log does not on its own indicate formation changes from the saprolite to that of saprock.

Cross plotting the response of one of the resistivity logs with the neutron log against depth has resulted in the output shown in Figures 9.4 and 9.5. Two fields are established, that above the water table and that below. The below water table response indicates a logarithmic increase in both the resistivity and neutron count rate to a plateau where the formation porosity is extremely low (less than one per cent). Bulk porosity stays fairly constant at this value although resistivity increases with depth as a more competent material is measured. Dips in the plateau response (Figure 9.4) indicate the discrete fractures at depth and show these to be of greater porosity. The transition to the plateau response is indicating the depth of weathering undergone by the formation

Figure 9.2 Geophysical logs at Rungai (Site 13, Table 10.2)

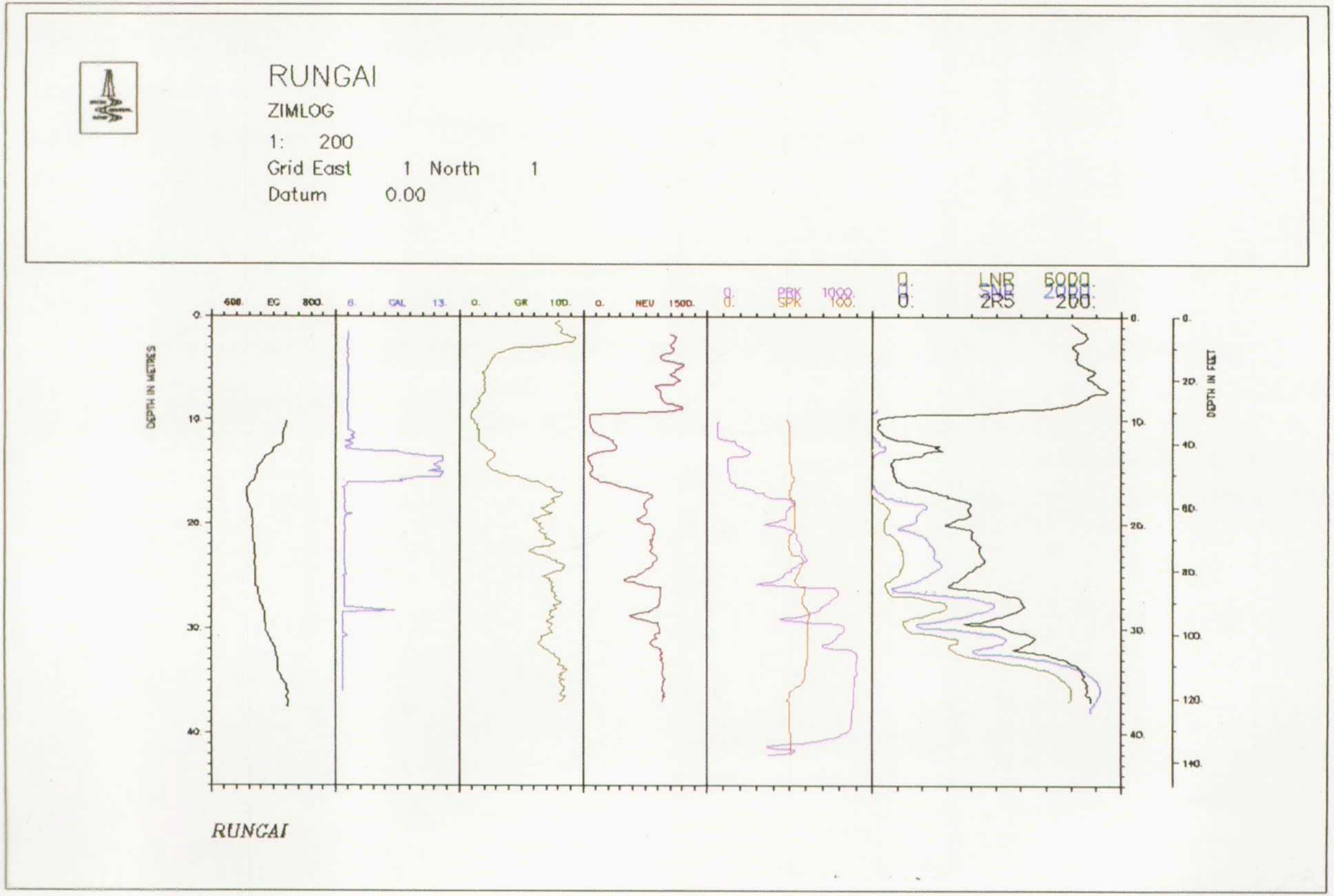


Figure 9.3 Geophysical logs at Mhatiwa (Site 10, Table 10.2)

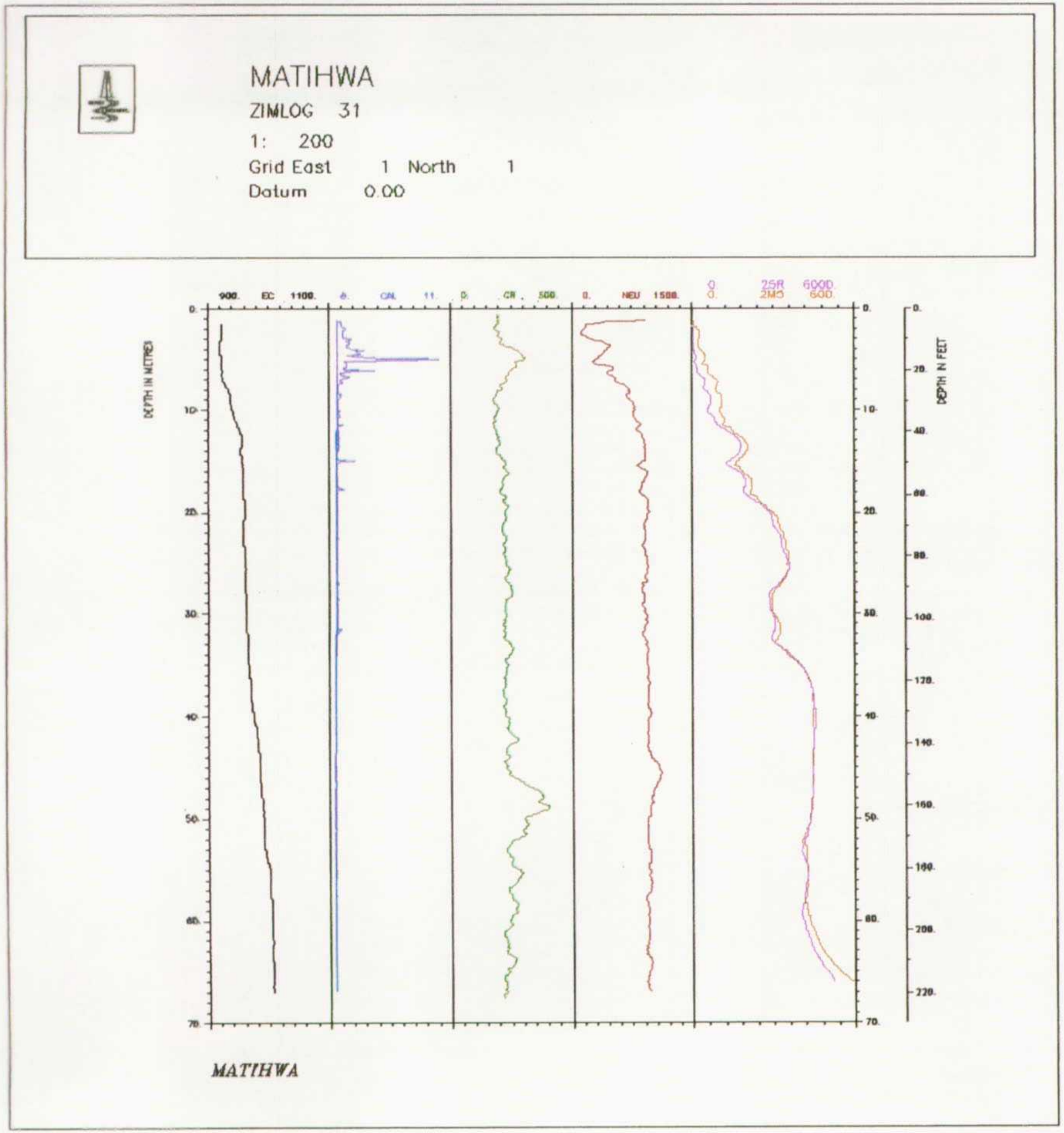


Figure 9.4 Cross-plot of resistivity and neutron (Rungai).

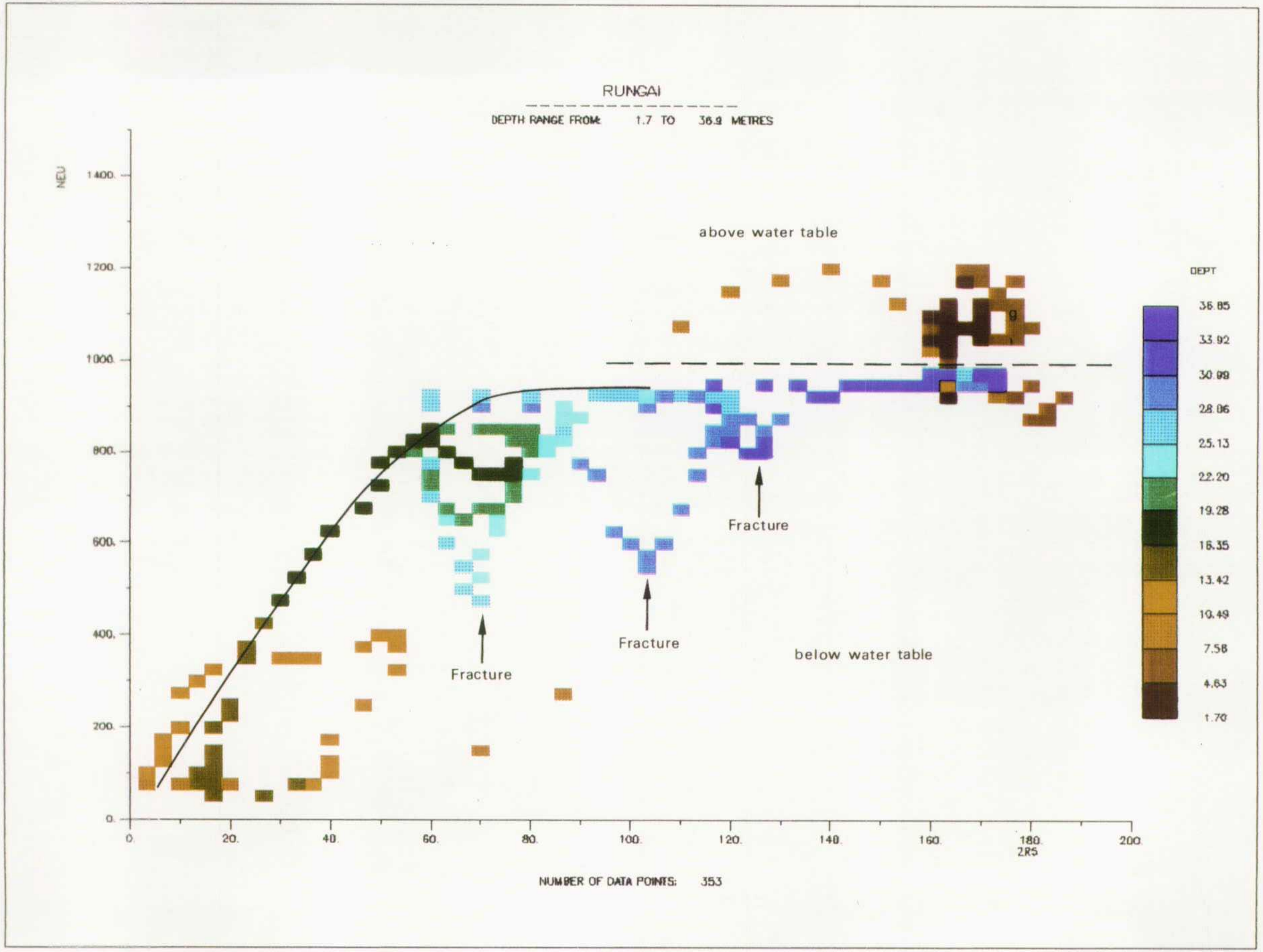
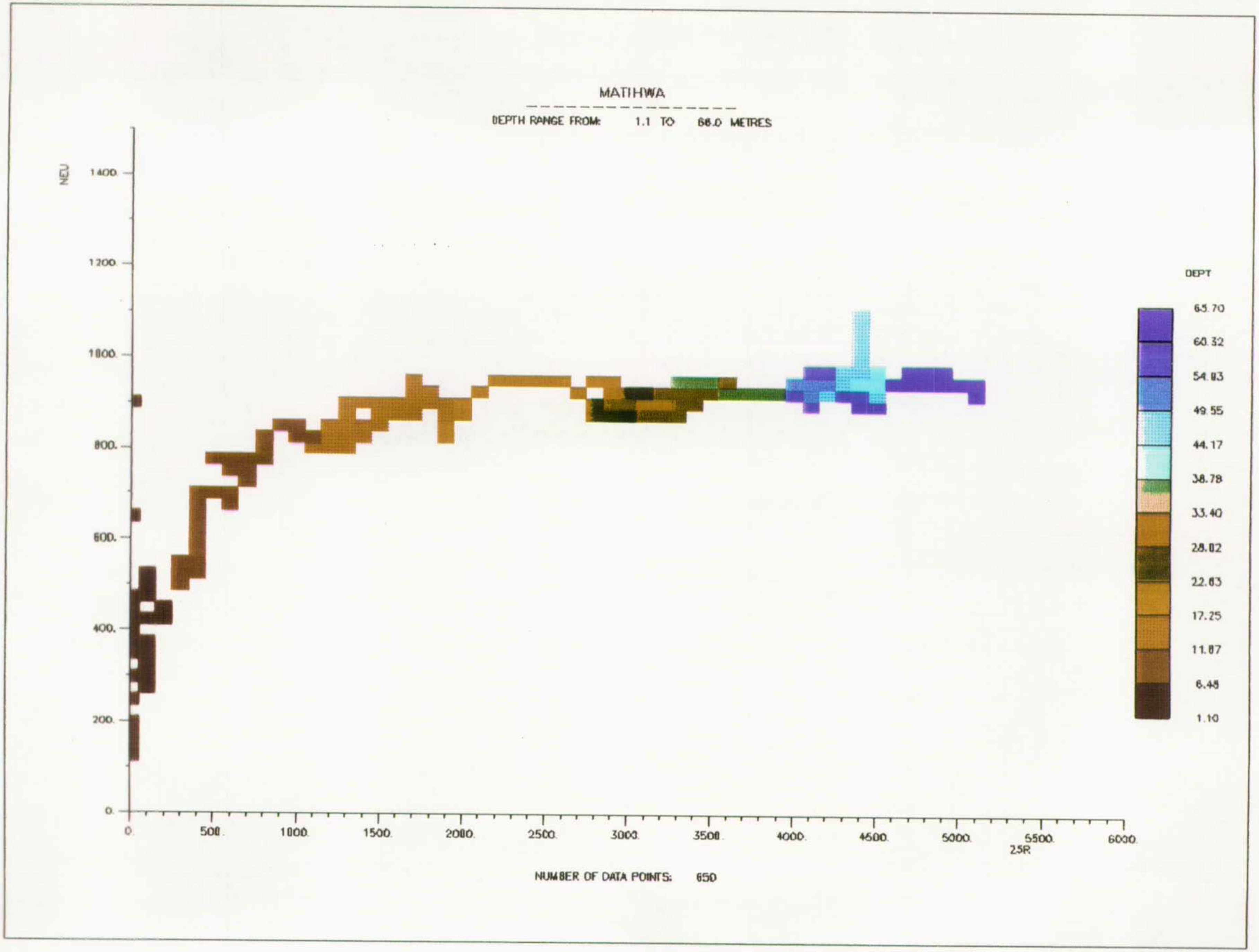


Figure 9.5 Cross-plot of resistivity and neutron (Mhatiwa).



and correlation of this depth with other methods, e.g. vertical electric sounding and drilling rate, shows this to correspond with the base of regolith.

At Mhatiwa (Figure 9.5) where a close to surface water table is encountered and no pronounced fracturing is encountered the resistivity/neutron response is more easily seen. The resistivity logs clearly show the increase of resistivity with depth and on the basis of these logs the base of the regolith may be deduced. The cross plot easily illustrates the classic response of the reduction in porosity and resistivity increase with the transition to the plateau response indicating the base of regolith. This depth again correlates with VES measurements although decreases in drilling penetration do not clearly indicate this boundary.

Not only does the resistivity/neutron cross plot delineate the boundary between the saprolite and that of the saprock but also the neutron response periodically drops below the plateau indicating porous fractures existing within the saprock.

The absolute correlation of borehole resistivity measurements to that of surface resistivity soundings is more difficult. This difficulty arises from a volumetric viewpoint. Whereas the borehole geophysics are undertaking measurements directly opposite horizons throughout the profile, the surface resistivity techniques are measuring a composite resistivity of all the horizons. A model of the VES response may be produced and the depth of formation boundaries deduced from the electrode spacing. Apparent resistivities are derived from the model and illustrate the formation resistivities. These values approach the values of resistivity determined from the borehole logging although the VES models relies on outside measurements to refine the model. The borehole geophysics are able to differentiate considerably more layers to greater depth than that of VES and by inputting data from the borehole geophysics, VES modelling is being refined.

Derivation of formation factors for these low porosity formations has been derived from both surface and borehole geophysics and shows good correlation with values of c. 350 ohm-metres being obtained from borehole geophysics and a value of 450-500 ohm-metres being obtained from VES. The derivation of formation factor is obtained empirically assuming a factor m, which is dependent on formation porosity. The factor in use is 1.05 (from the literature). Further analysis is being undertaken to refine the derivation of formation properties with an interactive correlation between VES and borehole geophysics resistivity.

10. MASVINGO PROJECT STUDY

10.1 Introduction

This study has been carried out over a large area of southern Zimbabwe (Figures 10.1. and 10.2) underlain by basement rocks of varying types and with mean annual rainfall in the range 600-800 mm (Figure 10.3). The Project Area occurs mainly on the Post-African surface of erosion and relief is variable with belts of harder rock outcrops trending ENE-WSW in accordance with the structural background.

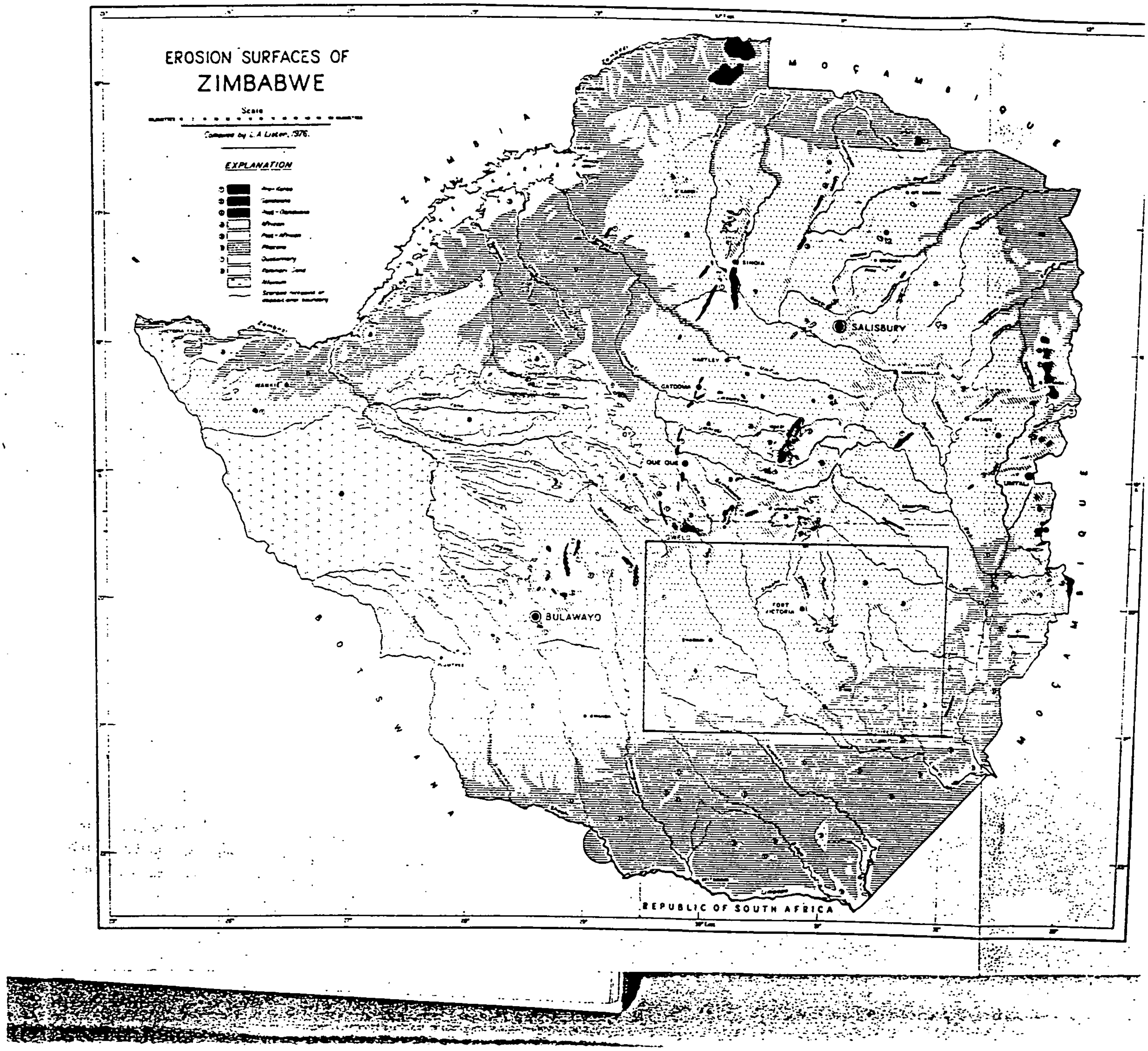
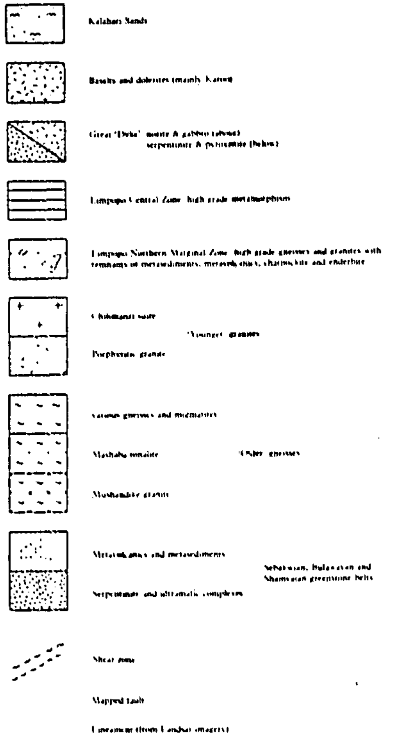


Figure 10.1 Masvingo Project Area (outlined)

Figure 10.2

GEOLOGY OF THE MASVINGO AREA



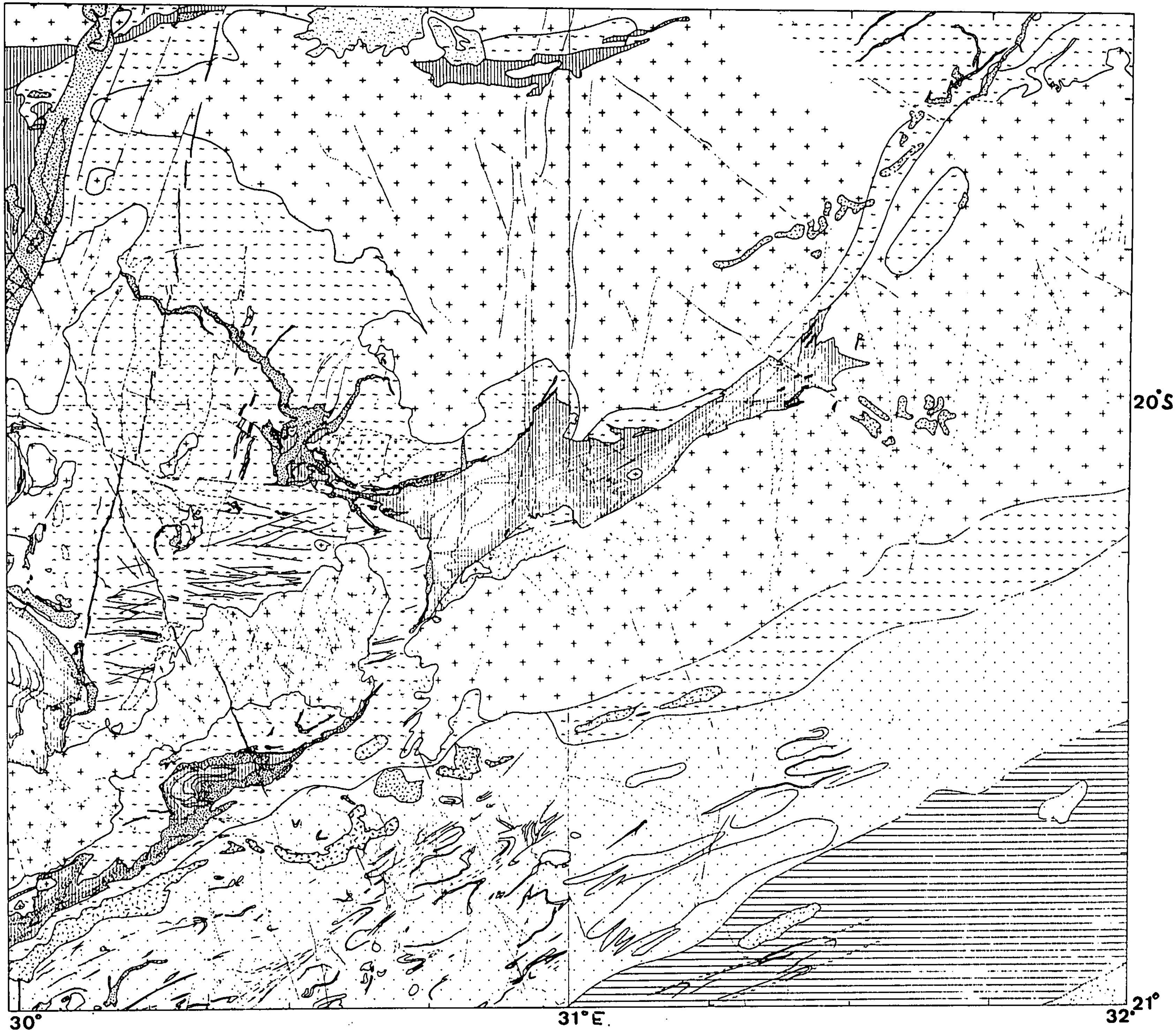
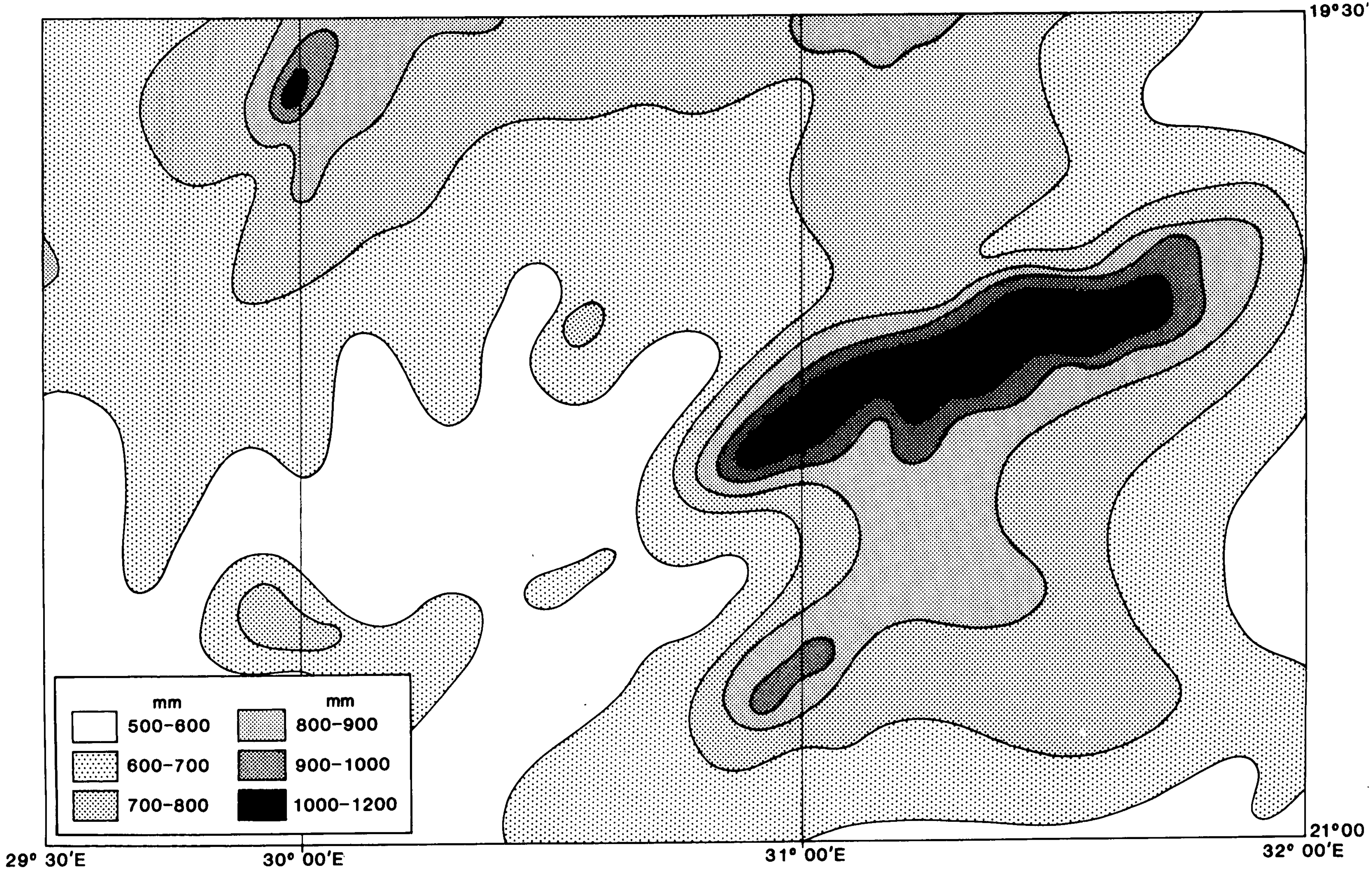


Figure 10.3

Mean Annual Rainfall



The weathered overburden (regolith) is typically less than 20 m and borehole completion is mainly within the weathered and fractured bedrock. Several thousand boreholes have been constructed. In two recent major projects in which several hundred boreholes were drilled, the percentages of dry-low yielding boreholes were in the range of 30-40 [specific capacity <0.008].

The area was selected because of the advantages of the well documented data bases compiled during the two recent projects referred to above. In addition to the project reports, one of the projects has been discussed in two publications (Houston and Lewis, 1989 and White, Houston and Barker, 1988).

In addition to regional appraisal of the whole study area (mainly structural and statistical), more detailed local studies were carried out in selected study areas (Figure 10.4) which have a high concentration of dry or low yielding boreholes, although often contrasting with boreholes in the same areas with above average yields. The programme of work in these study areas has been summarised in Section 3.2.1.

10.2 Borehole Development: Yield Criteria and General Siting Procedures

The minimum daily requirement of water per person according to the World Health Organisation's guidelines is 25 litres. A handpump operating for a 10-hour pumping day at a yield of 0.25 litres/second will provide sufficient water for some 360 people. These general assumptions form the basis for the numbers of boreholes required for appropriate population densities and taking account where feasible of distance factors.

It is not uncommon however for boreholes to be completed with handpumps which have test yields as low as 0.1 litres/second on the assumption that small yields are better than none at all. There are several possible consequences:

(i) Field investigations demonstrate that many low yielding boreholes may become wholly ineffective in use during the dry season, probably due to sensitivity to a seasonal or drought affected change of water level.

(ii) Low test yields may be even lower with a production handpump. Accurate measurements of specific capacity are therefore a better guide to handpump operating capacity.

(iii) Low production yields with consequential deep drawdowns are likely to result in higher than usual pump failure rate due to excessive use.

(iv) After a borehole has been completed, a village goes to the bottom of a priority listing even when the abstraction rate is clearly inadequate.

Borehole siting procedures in Zimbabwe typically combine the use of air photographs and geophysical surveys. The procedure is to identify from air photographs significant fracture or dyke related lineaments and to select potential sites on those features which have as large a catchment area as possible. These sites are then investigated by geophysical

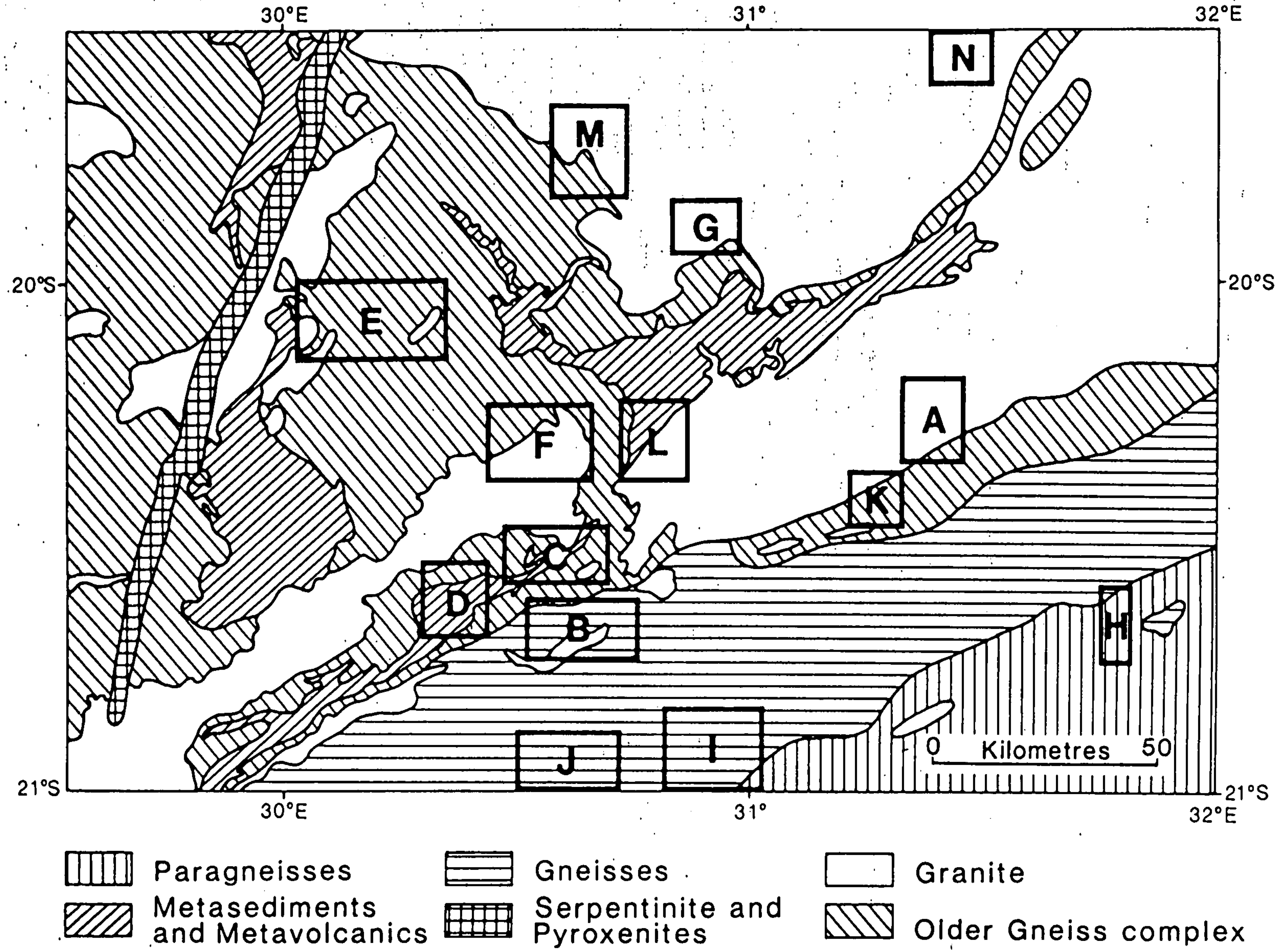


Figure 10.4 Regional geology and locations of the 14 sub-areas in Masvingo and Midlands Provinces, Zimbabwe.

surveys, usually resistivity or EM profiling and resistivity soundings, on the basis of which a drilling site may be selected. Despite this detailed procedure, a substantial failure rate has occurred in the Masvingo project area. If the success rate is set at 0.25 litres/sec test yield, the failure rate has a mean value of 34% (Table 10.1). The failure rates are somewhat higher in the areas for detailed study, of the order of 50%.

10.3 Geology and Geomorphology

Bedrock lithology, fabric, mineralogy and in particular larger macro structures such as joints and faults are the factors of main hydrogeological importance. The geology has been described and depicted in a number of maps and reports and the geological map of the Project Area (Figure 10.2) is based on this information. The study area straddles the boundary between the Zimbabwe craton and the Limpopo mobile belt (Figure 10.5). The oldest rocks (within the bedrock) are in excess of 3500 M.y. and the youngest include late dolerite dykes of Karoo age (c. 100 M.y.). The main land surfaces have developed in the Post African cycles (c. 26 to 2 M.y.) with remnants of older cycles apparent only as residual summit levels on the higher hills.

The research studies have emphasised structural aspects on the assumption that an improved knowledge of the occurrence and origin of the various structural features present might lead to a better understanding of the relationship which exists between fracture occurrence and borehole yields. Literature reviews, remote sensing studies (satellite imagery and air photographs) have been combined with field observations. The complex system of fractures and dykes has developed during repeated episodes of brittle deformation, mainly in the Late Archaen to Early Proterozoic times (2600-1800 M.y.). A simplified lineament map of the Project Area has been produced, mainly from satellite imagery (Figure 10.6). All lineaments have been digitised to assist analysis. Field observations show that lineaments fall mainly into four categories with the first two of most significance hydrogeologically:-

- fractures (joints and faults)
- dykes and veins (mainly dolerite and quartzite)
- gneissic foliation
- pegmatite veins

Reconstruction of the stress regime representative of a particular fracture set may indicate its original tensile or compressive origin but this will not necessarily determine its current character (i.e. open or closed) which will be a function of its history, including perhaps most significantly, the response to current stress fields.

Various tectonic models have been used on selected fracture sects (e.g. in Botswana) with a view to identifying the most likely occurrence and locations of associated open fractures but none as yet appear to have a valid application. The results of the BGS correlations of borehole yields with fracture occurrence in the Masvingo Project Area are described below.

Table 10.1 Details of Masvingo Province Boreholes

Sited by	Number of boreholes drilled	Dry holes	Specific capacity <0.0081/sec/m	Total [cols. 3/4]	% Dry and low yielding	Specific Capacity ≥0.11/sec/m	% high specific capacity
Government	697	90	102*	192	27	319*	46
Japanese	131	42	24	66	50	17	13
EEC	370	88	58	146	39	81	22
TOTAL	1198	220	184	404	34	417	35

* Specific capacity data was not available for the government holes, therefore yields of <0.25 l/sec and ≥1.0 l/sec had to be used instead of the quoted low and high specific capacity values.

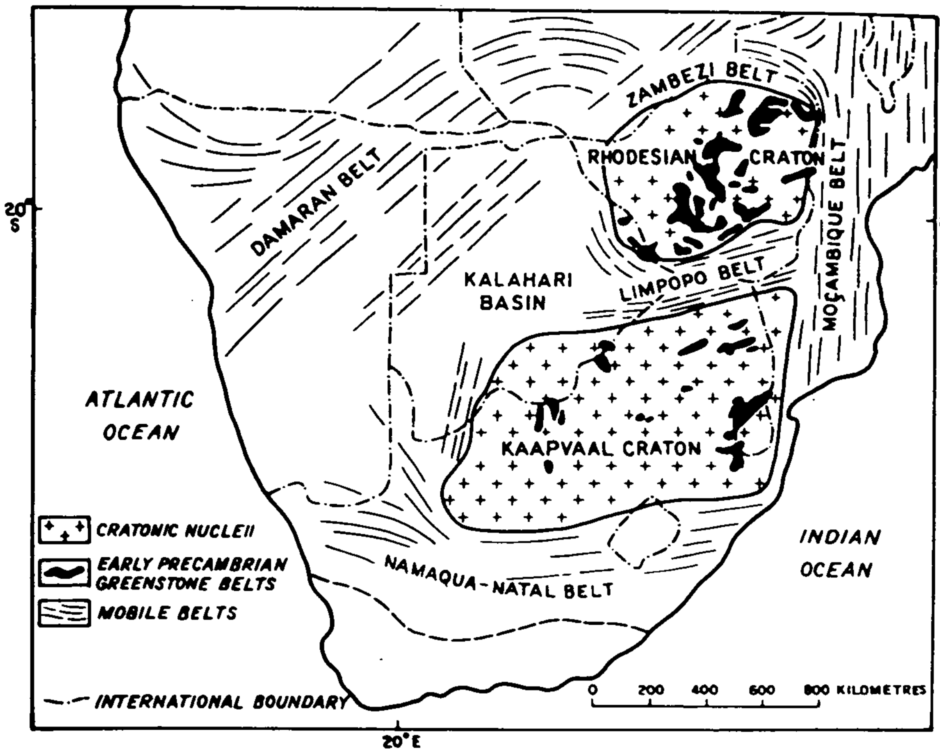


Figure 10.5 The Limpopo Mobile Belt and other metamorphic belts of southern Africa. (From Robertson et al. 1981).

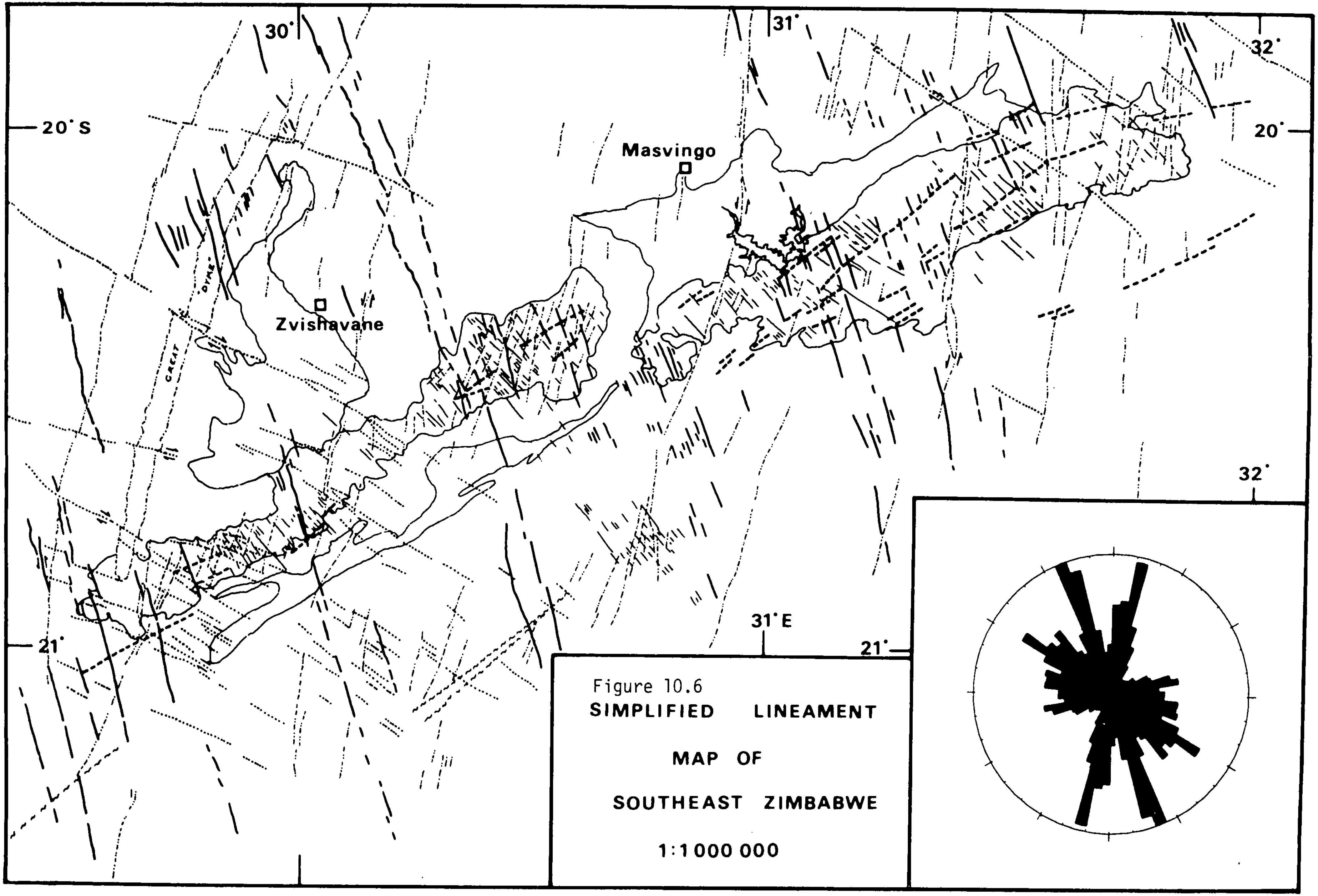


Figure 10.6
SIMPLIFIED LINEAMENT MAP OF SOUTHEAST ZIMBABWE
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10.4 Yield and Lineaments

A statistical study of the 163 boreholes in 5 study areas in relation to lineament trends has been carried out and the results are shown in Figures 10.7 to 10.9.

It is evident that a majority (85%) of all boreholes were sited at least partly on the basis of a fracture- or dyke-related lineament. The correlation with normal distance to lineaments (Figure 10.7) is constrained by the uncertainty of the precise location which is based on a grid reference with units of 100 metres. The resulting plot shows no apparent correlation with distance and indeed the sites more than 100 m from a lineament have a slightly higher success rate than those within this distance. The apparent characteristic is difficult to explain, other than by errors in location. However, a second control could also exist due to inclination of the fracture zone and which will be of more significance in narrow features and where the water table is comparatively deep. Failure and yield variations will relate to factors which include degree and depth of weathering, thickness of the overlying regolith and the width/dip of the fracture zone.

The yield vs. azimuth plot (Figure 10.8) shows a moderate correlation with certain dominant trends but with many successful borehole concentrations occurring on a wide range of lineament directions, several of which do not correspond with significant trends. The feature might be an expression of the influence of current stress fields acting on a wide range of the older fracture systems, possibly in association with unloading. A note on modern stress fields in Southern Africa is given in Appendix I.

The final plot of yield vs. lineament length (Figure 10.9) shows a slightly higher success rate for the 0.1 l/sec threshold but is constant for the 0.25 l/sec threshold.

The results of the correlative studies to date permit few definite conclusions. The locational accuracy of most boreholes is probably insufficient to obtain a reliable assessment of the detailed relationship between yield and proximity to a fracture. The wide range of azimuth trends of successful boreholes is suggestive of a pervasive influence such as erosional unloading operating on all existing fracture systems. And finally there is little to indicate that length of fractures influence yields or success rates. In drawing these general conclusions, it needs to be stressed that the fracture system associated with groundwater flow may not be a major feature with which geophysical correlation is made. The latter is generally targeting on the increased thickness of weathering associated with a fracture at depth.

10.5 Topographic Correlations

Several authors, notably Faillace (1973) and Houston and Lewis (1988), have commented upon the topographic correlation of borehole yields and success rates with higher values of both features occurring in valley sites as compared with watershed or piedmont sites. The correlation is not unexpected since valleys are frequently aligned along structural trends, thus providing a facility for both recharge and increased groundwater throughflow to greater depths.

YIELD vs DISTANCE TO LINEAMENTS

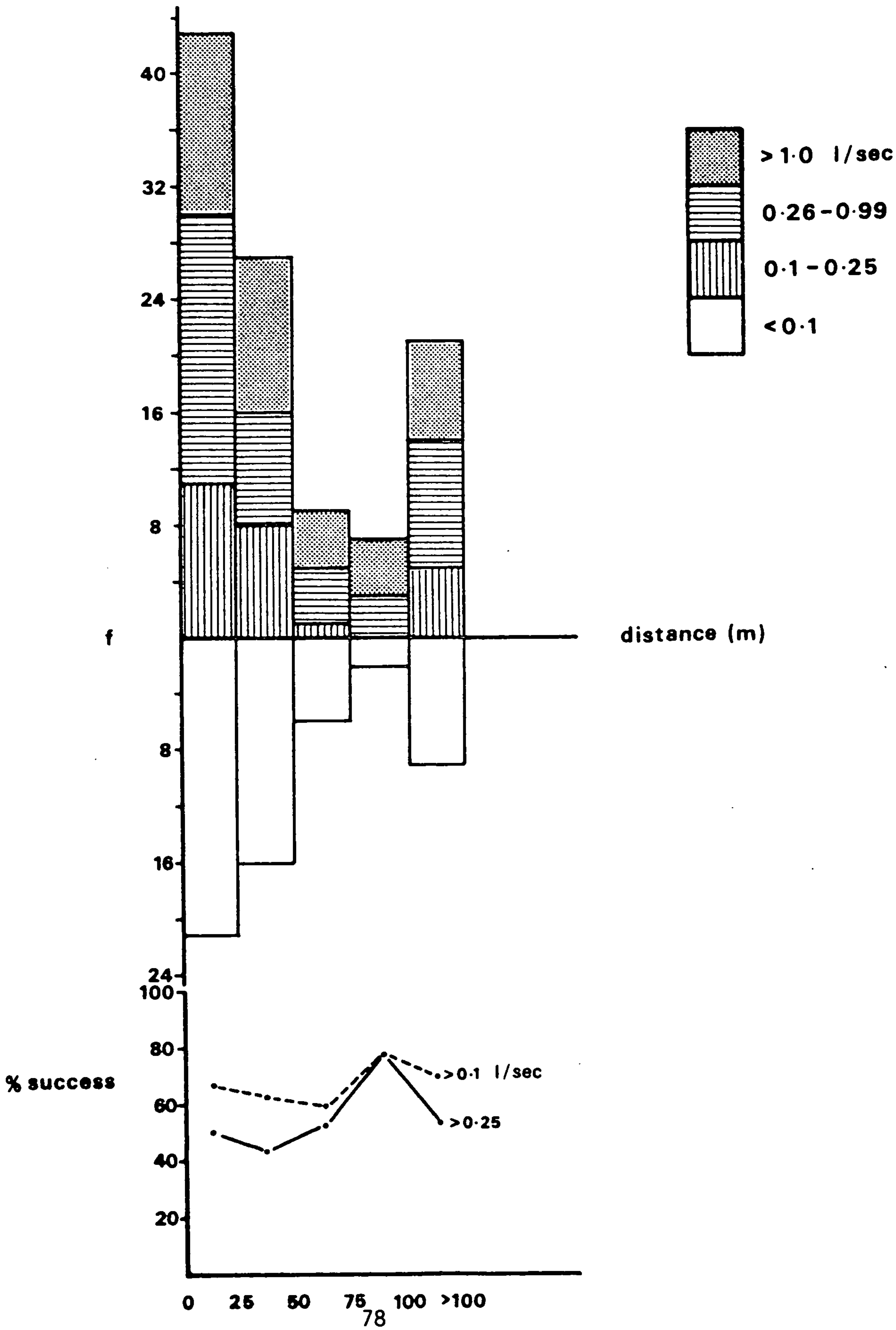


Figure 10.7 Frequency histogram showing the relationship between borehole yield and normal distance to lineaments. Combined data from areas C, E, F, G and J. Success rate is also indicated.

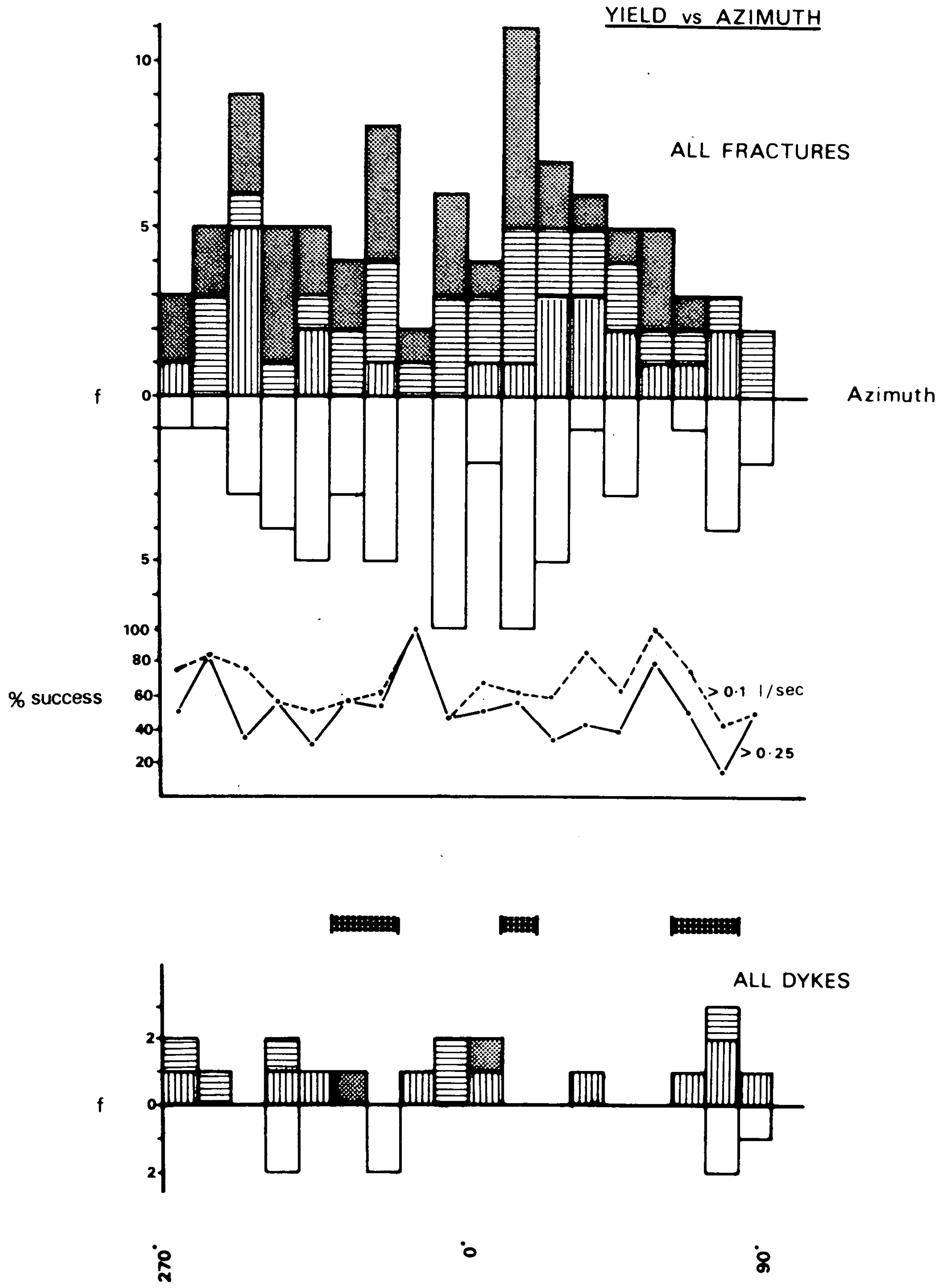


Figure 10.8 Frequency histograms for combined data from areas C, E, F, G & J showing the relationship between yield and azimuth of fractures and dykes, as well as dominant lineament directions. The success rate for each 10° class is also shown. (For legend see caption to Figures 2A to E).

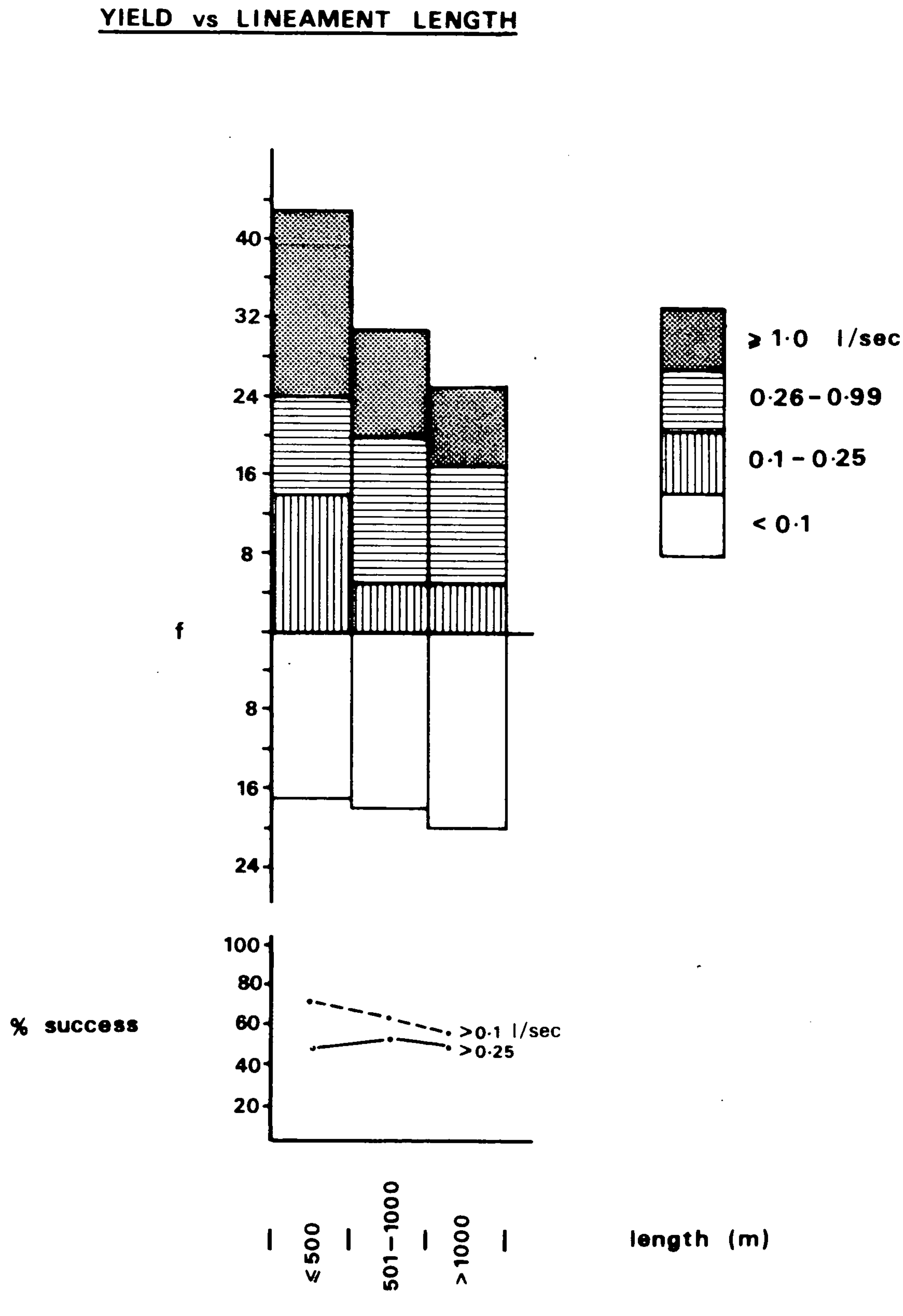


Figure 10.9 Frequency histogram for combined data from areas C, E, F, G & J showing the relationship between borehole yield and length of lineament in 3 length categories.

Sites away from valleys will generally (other than at the base of inselbergs) be expected to have smaller thicknesses of saturated regolith and therefore a greater probability of borehole failure or low yield, unless the fractured bedrock has sufficient transmissivity to compensate. Borehole siting in these more difficult locations must take these constraints into account in assessing the probabilities of success.

In a more local context, other considerations can also apply to the generalisation. A successful borehole requires sufficient accessible storage, which is mainly derived from the saturated regolith, combined with sufficient transmissivity which is largely provided by the saprock and basal saprolite. Stream incision or mineralogical dissolution by groundwater flow below a clay soil can both result in reduced regolith thickness and consequently a reduction in accessible storage. More precise correlations of borehole yields and regolith thickness with local relief, drainage status and soil cover might help to confirm these probabilities.

10.6 Borehole Yields and Regolith or Overburden Thickness

Two factors, resistivity values and the thickness of the overburden, in combination, constitute the essential siting criteria of the Master Plan of Zimbabwe which is based on the research results by the UN. The resistivity correlations will be discussed later. The thickness of overburden correlations of the Master Plan criteria are set out below.

Thickness of Overburden	Success Rate
<10 metres	0%
10-20 metres	25%
20-25 metres	45%
>25 metres	70%

For the 70% success rate, a further requirement is that the saturated thickness of the overburden must exceed 20 metres. Similar criteria, although not defined, may be assumed to be required in the other cases.

The relation between 'overburden' as interpreted from resistivity data and 'regolith' as defined by drilling records and sampling is likely to vary in accordance with the nature of the contact zone between saprolite and saprock which may be abrupt or transitional. The former is related to the zone of relatively low resistivity which is expected to comprise essentially the main saprolite; interpretation may include an additional layer of intermediate resistivity which could relate to the basal disaggregated saprolite without clay minerals and the underlying saprock. More detailed correlations of resistivity values with varying conditions of saprolite would be desirable. In assessing the mean regolith thickness of the various yield classes and rocks groups in the detailed study areas, it is apparent that very few of the mean regolith values exceed the 25 metres thickness criteria and none of the saturated thickness values attain the 20 metres requisite for the 70% success rate. To some degree, the discrepancy must relate to the difference in definition between regolith and overburden although in the Masvingo Project Area, the overburden is likely to correlate fairly closely with the regolith thickness since deeper weathering down a fracture zone is usually too localised for it to influence the resistivity sounding data.

The mean values of total thickness of regolith for the dry boreholes are relatively low, less than 14 m and the majority less than 10 m. In the case of the two intermediate yield groups, the regolith total thickness values are comparable and often higher than the thickness values of the dry holes, but by no means always so. The saturated thickness likewise shows no correlation with yield which suggests that the main control to borehole performance is transmissivity, provided that a minimum thickness of saturated regolith is available, in the range 4-10 metres. The transmissivity is mainly determined by the permeability and thickness of the basal saprolite/saprock and the fractured bedrock.

The required saturated thickness of the overlying regolith will depend to some extent on its 'effective porosity' in addition to the spread of the cone of depression which is a function of the transmissivity. Some correlation of the 'effective porosity' with resistivity is to be anticipated but the information would not serve to predict yields since it is only one of the two basic controls. The rest water level is also difficult to determine by geophysical techniques, particularly where the regolith is clayey.

10.7 Borehole Yields and Geophysical Data

The Zimbabwe Master Plan identifies calculated electrical resistivity (from vertical electrical soundings) as the single most important guideline in optimising borehole siting procedures. The following correlations are stated to exist for resistivity values in the weathered overburden aquifers within basement rocks.

<20 ohm metres	Clays with limited groundwater potential
20-100 ohm metres	Optimum weathering and optimum groundwater potential
100-150 ohm metres	Medium conditions and medium potential
150-200 ohm metres	Little weathering and poor potential
>250 ohm metres	Negligible potential

Expressed in this format, resistivity (and associated thickness) is correlated with potential, i.e. borehole yield. The relationship is likely to hold only, if at all, with regolith aquifers and even in these cases, a direct correlation with yield seems unlikely if the resistivity (of the layer correlating with the main layer of the overburden) is assumed to relate to the main saprolite. The resistivity is more properly correlated with porosity and water quality/clay content and may also correlate with effective porosity, controlling release from storage.
These circumstances should apply most readily to the aquifers in Malawi but the resistivity data base is regarded as inadequate for making these assessments. With thinner regolith, such as is common on the Post-African surface of erosion in Zimbabwe, there is much greater likelihood of borehole failure due to inadequate storativity within the cone of depression. The effect is enhanced as soon as the cone of depression reaches the base of the regolith when the reduced storativity of the

saprock begins to have more influence. This constraint can be counteracted only if the transmissivity is sufficiently high for the cone of depression to have a shallow gradient to spread widely and therefore to draw upon the storativity of the thin regolith over a wider area. This is the main objective in locating a borehole on a strong lineament on the expectation that it indicates a fracture zone of high transmissivity. Geophysical surveys will help in locating the trace of a fracture zone and may provide evidence of its geometry, i.e. width and dip. Whether the profiling surveys are responding in any way to the fracture occurrence at depth is less certain and appears unlikely.

A thin fracture zone is difficult to intersect with a borehole. With a dipping fracture zone, the angle of dip has to be taken into account to ensure intersection below the water table and hydraulic access will be increasingly constrained with increase of dip from the vertical. Many fracture zones are the sites of stream channels which reduce site accessibility. Angled boreholes have potential advantages in a number of ways - drilling along the dip of a fracture system, drilling to intersect the fracture below a stream channel, greater probability of intersecting more than one set of vertical fractures. The precise geometry of a fracture zone is necessary if this increased facility is to be made use of. Fracture zones of even steep dip can be critical for vertical boreholes.

The initial phase of the geophysical studies included re-surveys at 18 existing sites in 5 of the detailed study areas. The sites were mainly dry boreholes but included a few high yielding boreholes. Seismic, electro-magnetic and resistivity methods were mainly used. The general conclusions were as follows:

(i) Profiling surveys, both EM and seismic, frequently confirmed the structural relationship of a photo-lineament. The majority of structures were of narrow width (generally less than 30 m across) and vertical to steeply dipping. The survey methods were not sufficiently detailed to determine the dip angle with precision and only qualitative assessments were feasible. Seismic surveys appear likely to be less accurate than EM to determine dip angle.

(ii) Seismic surveys generally gave a good correlation with regolith thickness based on the drilling results.

(iii) Virtually all the dry holes had poor 'hydrogeophysical' parameters: negligible thickness of regolith and often no marked structural feature at depth. Some dry holes appear to be offset slightly from the main EM anomaly but the uncertainty in interpreting a dip might have precluded selection of a better site. Sites in the vicinity of narrow late 'Karoo' dykes had a variable success rate. It is possible that the dyke body may mask evidence of degree of fracturing.

10.8 Drilling Programme (Table 10.2)

The drilling programme was carried out in the second phase of the project study, using the BGS collector well rig (operating in the vertical or angled mode) and a lightweight air hammer rig provided by the Ministry of Water Resources and Development. The results may be summarised as follows:-

(1) Eighteen sites were drilled, the majority in locations of previous dry or low yielding boreholes. Five of the locations are on younger granite, eleven on older gneiss complex and two on mobile belt gneiss.

(2) All the sites are on photolineaments and in valley locations.

(3) The majority of photolineaments showed EM anomalies, which were often offset from the photolineament.

(4) The majority also showed radon anomalies, 8 of which closely corresponded with EM anomalies and 7 of which are offset (Figures 10.10 and 10.11).

(5) Seven boreholes showed high yields in excess of 0.25 litres/sec; three showed marginal yields, one a low yield and six were effectively dry. Five of the seven high yielding boreholes had test yields in excess of 1 litre/sec which is much higher than the statistical average, particularly for gneissic rock aquifers.

(6) Twelve sites show a reasonable correlation of weathered overburden with the VES prediction. The drilled overburden commonly corresponds with the decomposed bedrock or regolith but in a few cases the predicted overburden includes weathered bedrock or saprock. The VES soundings also corresponded with the EM responses when semi-quantitatively soundings were made both on and away from the anomaly. EM soundings may be able to substitute for resistivity soundings, although not with the EM34 equipment being used.

(7) The predicted thickness of the overburden was marginal by Master Plan standards in six cases, two of which were dry holes. The saturated regolith met Master Plan standards in only three cases. Several of the successful boreholes had negligible saturated overburden which demonstrates the major control of the underlying fracture system.

(8) Of the six dry holes and one low yielding borehole, two of the sites showed both a negligible radon count and negligible EM anomaly and would not have been drilled in a normal development programme; four of the sites may well have been affected by dip of the structural zone, indicated both by the shape of the EM anomaly and the offset position of the radon anomaly. It is possible that a successful site might be located a short distance away at a down dip location. More closely spaced EM surveys might provide better identification of the geometry. One borehole produced very muddy water and it may have been feasible to develop this into a successful borehole.

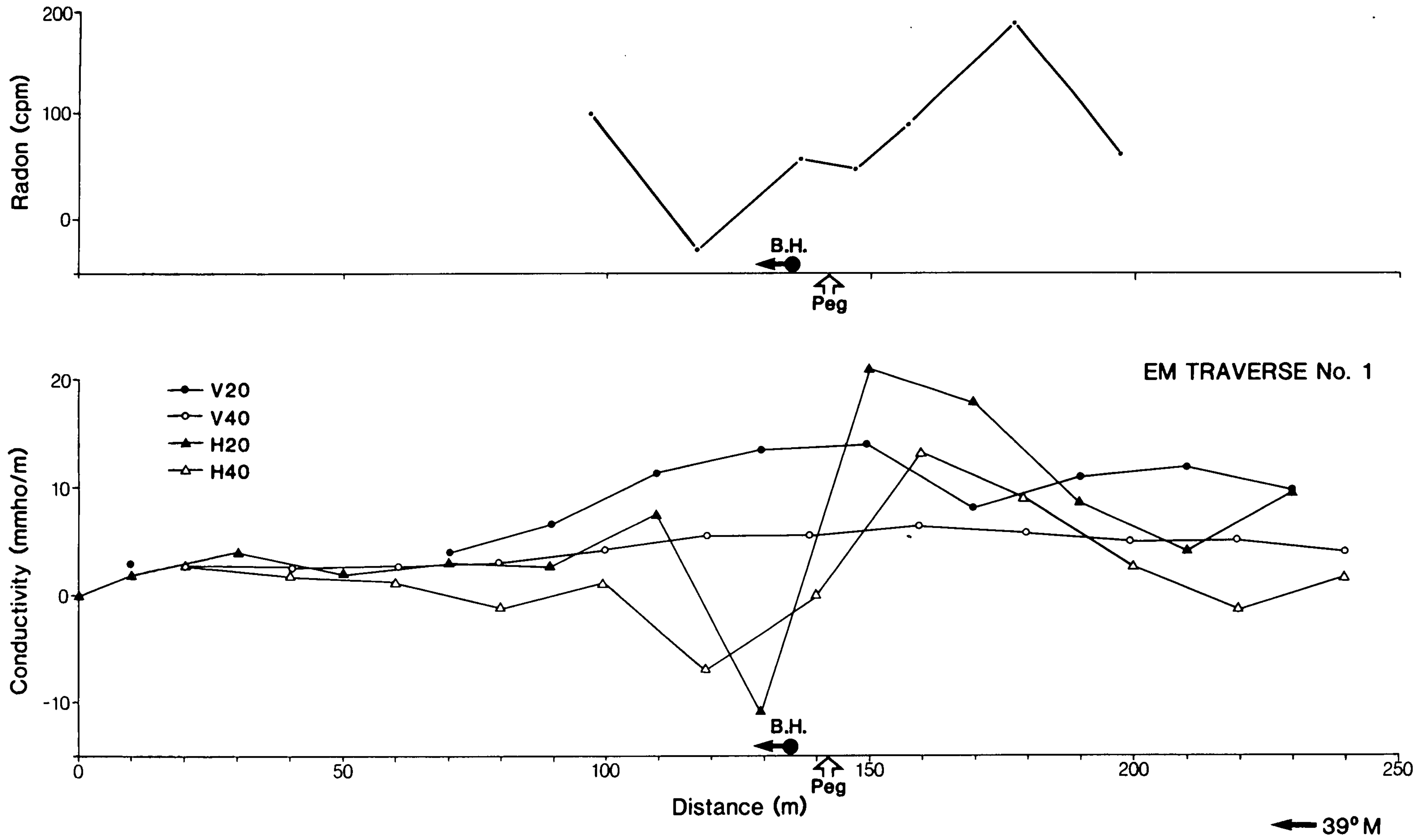
Table 10.2 Summary of Selected Information from Masvingo Project Drilling Programme

	Location	Depth	VES Resistivity (ohm-m)	Drilling Decomposed*	Drilling Weathered+	RWL (mbgl)	Test Yield (l/sec)
1	Nanwi	0	-	1	-	2.0	0.28
2	Nemarundwe	1.3	1000				
		5.3	165	5	13	3.0	0.29/0.015
3	Matatire	0.4	2000				
		2.9	25				
		22.9	250	33	-	3.1	0.25
4	Zimuto B.S.	0.3	350				
		2.3	25				
		22.3	100	13	-	4.3	0.32
5	Zimuto Siding	0.3	500				
		8.3	40				
		28.3	100	24	-	20	0.55
6	Chibi	0.5	150				
		7.7	10				
		47.7	105	28	40	7	0.27/0.57
7	Chinambiri School	0.3	560				
		5.3	9	5	-	-	-
8	Chinambiri Valley	0.8	600				
		20.8	50	20	35	7.4	0.29/0.06
9	Mhatiwa School	5.0	(seismic)	6	-	8.0	0.12
10	Mhatiwa Valley	0.8	800				
		4.6	40				
		8.0	400	10	28	6.4	0.29
11	Chikore Reservoir	2.0	1100				
		2.5	5				
		27.5	150	5	-	18	-
12	Chikore Valley	0.6	150				
		1.5	35				
		21.9	245	5	15	13.6	-
13	Rungai	2.0	14				
		10.0	5	12	-	10.1	2.2

* Assumed to be regolith
\+ Assumed to be saprock

Location	Depth	VES Resistivity (ohm-m)	Drilling Decomposed*	Weathered+	RWL (mbgl)	Test Yield (l/sec)
14 Chikofa	0.3	3000				
	4.3	32				
	7.3	15				
	17.3	100	6	14	17.2	0.57
15 Sarahuru	0.2	450				
	4.6	10				
	26.6	25	30	36	20.8	0.67
16 Chikadze	0.5	900				
	3.8	9				
	12.2	90	2	17	8.0	Small
17 Madangombe	1.1	11				
	7.7	22	11	-	8.4	-
18 Maramba	0.3	125				
	2.6	19				
	11.4	60	10	-	-	-

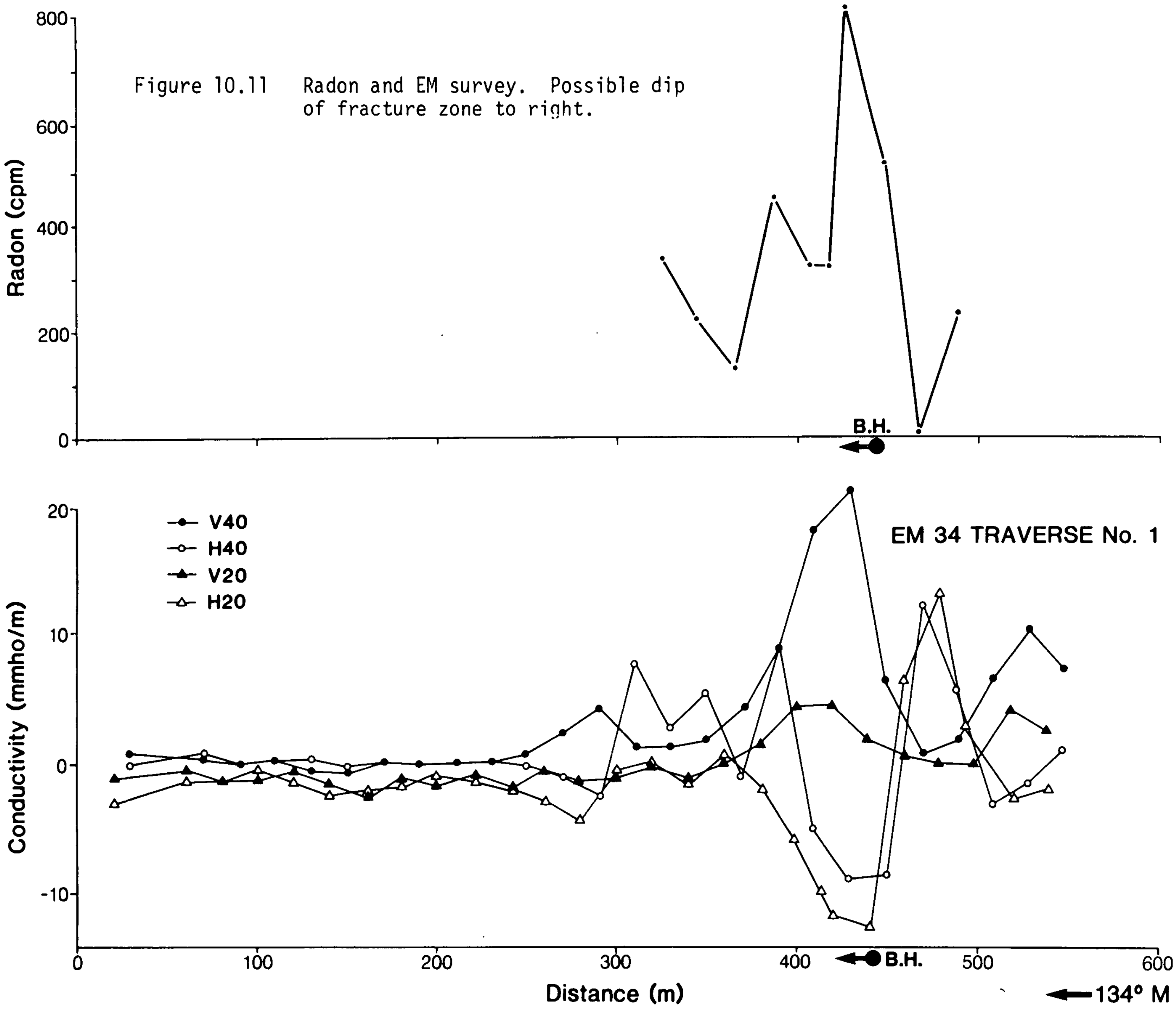
* Assumed to be regolith
\+ Assumed to be saprock



CHINAMBIRI SCHOOL SITE

Figure 10.10 Radon and EM survey. Possible dip of fracture zone to the right.

Figure 10.11 Radon and EM survey. Possible dip of fracture zone to right.



MHATIVA SCHOOL

(9) Marginal yields were obtained at sites, 3, 10 and 15. At site 3, there is a likelihood that with further development, an improved rate will be obtained. Site 10 has also a potential for further development and both 3 and 10 could be adopted as collector wells.

(10) The results show the feasbility of borehole construction at difficult sites which do not meet the Master Plan criteria. It is clear that transmissivity is the main control and with greater attention to the dip of the fracture zones and perhaps improved borehole development, the success rate could have been higher. The final pumping tests were carried out over the standard duration 5/8 hours. It remains to be seen whether the successful boreholes with thin regolith will provide a sustained yield under production.

(11) The resistivity data are not wholly consistent with yield relationships although in general the poorer yields correspond with 'unfavourable' resistivity ranges but in some cases so also do high yielding boreholes (e.g. 13, Rungai). The saprock was either not identified or grouped with the regolith (No's 12, 6, 16).

11. RESOURCE EVALUATION AND POTENTIAL, AQUIFER OCCURRENCE

11.1 <u>General Comments</u>

Basement aquifers are distinctive in that their occurrence and characteristics are largely a consequence of the interaction of weathering processes and groundwater throughflow in a fractured rock media. The heterogeneity and discontinuity of the resultant aquifers constrains both resource evaluation and development.

Because of their general low productivity by standard abstraction techniques, development is more controlled by aquifer occurrence, i.e. storage and transmissivity distribution, than by recharge. Recharge studies are important however not only as a measure of longer term potential but because of the additional information they provide on aquifer occurrence which can guide exploration and development methodology.

Abstraction from basement aquifers is mainly by handpumps or, more rarely, small motorised pumps with usage for domestic and livestock supply in rural communities. Drilling costs, rather than resource availability, are likely to restrict annual abstraction by the current methodology to little more than the 1-3 mm equivalent recharge over a basin area, even when the full 'Water Decade' requirements of 25 litres per head per day are met. Fuller development of the resource potential will only be feasible when improved abstraction techniques are developed which are both technically feasible and economic in use. The collector well studies, an associated part of this Project, are concerned with these latter objectives.

11.2 <u>Recharge and Resources</u>

There are considerable difficulties in measuring recharge rates and resource availability because of the constraints associated with the heterogeneity and discontinuity of basement aquifers. The main methods which have been used and are discussed below include:

- base flow analysis
- seepage zone discharge measurements
- chloride balance of rainfall and groundwater (in runoff and in springs, boreholes and wells)
- flow net analysis
- water level changes
- soil moisture balance or more comprehensive modelling studies

Base flow analysis has the apparent advantage of a direct identification of a groundwater component but current methodology based mainly on hydrograph separation is by no means an unequivocal procedure. Discharge also occurs by ways other than groundwater runoff, and notably by evaporative discharge from the aquifer in localised seepage zones. These are particularly common in the extensive low relief areas of the African savannah lands underlain by basement rocks. A chloride balance of rainfall and groundwater recharge provides a valuable insight into circulation and fractionation but the method is difficult to apply in an aquifer which is both compartmentalised and has composite flow systems with varying lag times. Analysis of flow net and water level changes are constrained by the variability of the basic aquifer parameters, transmissivity and storage, as well as the difficulties inherent in the measurement of these parameters.

11.2.1 Base Flow Analysis

Figures of baseflow by hydrograph analysis for the 26 catchments studied are listed in Table 6.3 and ratios of baseflow to mean rainfall vary from zero to 0.25. Some data from other sources are shown in Tables 11.1 and 11.2.

Table 11.1 Base Flow Data from Malawi Catchments.(1)

	Catchments without Dambos		Catchments with Dambos[2]		
			<5%	5-27%	21%
	n = 18*	3E3+	n = 20*	n = 11*	5D1+
Annual Average Rainfall (mm)	1292	1000	987	919	904
Base Flow (mm)	195	80	NA	NA	18
BF/AAR (%)	15	8	-	-	2

* mean values from n catchments
\+ results from single catchment
2 areal percentage dambo cover
1 Hill and Kidd, 1980

The low baseflow in catchments with high dambo cover is attributed to groundwater discharge occurring to a large extent as evaporation of seepage in the dambo periphery zones. Baseflow response seems likely to be more sensitive to the variability of dambo type than to dambo area although 'type' and area may also be correlated.

Baseflow analysis by hydrograph separation was carried out in Masvingo Province[1], southern Zimbabwe and the results are set out below.

Table 11.2. Baseflow Analysis from Masvingo Province

	Chiredzi	Mzero	Musokwezi	Lundi
AAR (mm)	818	1055	1126	797
Mean Base Flow (mm)	31	51	32	6
BF/AAR (%)	4.7	8.5	4.3	1.9

[1] Houston, 1988

The catchments in Zimbabwe have relatively low percentages of dambo cover and comparisons should therefore be made with similar catchments in Malawi (column 1, Table 11.1). On this basis, the Zimbabwe catchments groundwater runoff components would appear to be smaller, which is probably related to their occurrence on the Post-African erosion surface with thinner regolith and higher rapid response runoff.

11.2.2 Evaporative Loss from Seepage Zones

Seepage zones occur commonly on the periphery of dambos. Some approximate estimates of groundwater loss* by seepage evaporation were made on the 5D1 catchment in Malawi (Section 6). Estimated annual losses are in the range 96-152 mm of which 18 mm is the observed baseflow and the remainder by evapotranspiration. The larger estimate is comparable to the mean baseflow in the 18 catchments without dambo cover. Similar calculations on the Chimimbe dambo give a value of annual evaporative loss as 150 mm.

11.2.3 Chloride Balance of Rainfall and Groundwater

The method is based on the assumption that chloride content of recharging groundwater is determined by concentration of the rainfall chloride by evaporation/evapotranspiration in the vadose zone. Recharge is calculated on the basis of the chloride ratios, taking account of the 'effective' rainfall component (i.e. total rainfall minus rapid response runoff). Constraints to the method include uncertainties on the areal rainfall and on the rainfall chloride content but more significantly in relation to the variable groundwater flow systems which occur in basement aquifers resulting in variations in both lag times and chloride content of the groundwater in the separate systems. Although in consequence, there are uncertainties in the quantitative evaluations of the recharge rates, the chloride values do throw light on groundwater occurrence and the hydraulic characteristics of the basement aquifers.

Groundwater chloride values typically show a log normal distribution. Recharge can be calculated using an arithmetic mean but, as has been demonstrated by Eriksson (19??), it is more appropriate to use the harmonic mean. However the application of the harmonic mean has generally resulted in significantly higher recharge rates than when the arithmetic mean is used and in some cases, the rates appear manifestly excessive.

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* Seepage area and potential evaporation rates

11.2.3.1 *Chloride content of rainfall*

Rainfall samples have been collected at stations in the representative catchments during 1985-86. The samples were composite from daily rain gauges and the results are given in Table 11.3. Only wet season values were used for mean determinations, on the assumption that recharge mainly occurs during this period.

Table 11.3 Chloride Content of Wet Season Rainfall (mg/l)

	Number of Samples	Arithmetic Mean	σ	Min.	Max.
Malawi[1]	53	1.01	1.20	0.1	5.5
Zimbabwe[1]	31	2.5	1.4	0.9	5.8
Harare[2]	8	0.5	0.2	0.3	0.8

(1) Samples from representative catchments in 1985-1987. The Zimbabwe mean value excludes some exceptionally high values from the B90 station site which are regarded as contaminated.

(2) Samples collected between 1975-1985 (results provided by Dr P Wurzel of the Ministry of Water Resources and Development.

The chloride content of the Zimbabwe catchment rainfall is significantly higher than both the Harare and Malawi values. They appear higher than would be expected for continental interior rainfall and until confirmed, the results must be regarded with some caution. However, the values are lower than would be expected from contamination by careless handling and the other ion values do not suggest concentration by evaporation in the container.

11.2.3.2 *Chloride content of runoff*

Samples of runoff for chloride determination were collected at irregular intervals from the representative catchments during the 1985-87 project period. Additional chloride data were obtained during a dambo survey in the central plateau region of Malawi collected during the dry season of 1985 by students of the university of Malawi. Chloride data are listed in Lewis, Water Quality in Malawi (1987), and some of this information is also included in the tabulated data in Table 11.4. More regular samples from selected rivers were collected during 1983-84 by Lewis, and the plots of chloride data are shown in Figures 11.1 and 11.2.

Table 11.4 Chloride Content of Surface Runoff

		Wet Season			Dry Season*		
		Mean	σ	n	Mean	σ	n
I	MALAWI						
	Catchments Data	2.9	2.9	61	3.1	3.6	67
	Lewis, 1987	2.3	2.1	101	3.0	2.8	156
	'Dambo' Survey				1.7	3.1	71
II	ZIMBABWE						
	Catchments Data	3.9	-	94	4.0	-	15

* samples from July, August and September only

The first point to notice is the relatively small difference between wet and dry season chloride values. Zimbabwe runoff chlorides are rather higher than Malawi runoff chlorides which could relate to higher rainfall chlorides or lower recharge rates, or both.

A much more consistent pattern is apparent in plots of the routine sampling of the Malawi rivers carried out by the Government Water Chemist (Figures 11.1 and 11.2). Wet season chlorides are typically in the range of 0.6-1.5 mg/l with dry season peaks between 6-10 mg/l.

The higher baseflow chloride values (6-10 mg/l) are indicative of groundwater recharge rates in the range 10-20% of AAR; the lower chloride contents (c. 3 mg/l) would presuppose a higher value of recharge around 33%. For Zimbabwe and a mean Cl content of 2.5 mg/l, the baseflow chlorides would imply a recharge rate of 62% which is manifestly excessive. For a value of 0.5 mg/l (Harare rainfall), the equivalent value of recharge would be c. 13%, a rather more realistic value.

11.2.3.3 *Chloride content of groundwater*

Groundwater samples for chloride analysis have been collected from a variety of locations during the project studies. Chemical analyses from existing databases have also been incorporated and the results listed in Table 11.5. Recharge estimates are based on appropriate ratio and effective rainfall, and listed in mm over the basin area or as a percentage of mean annual rainfall (MAR).

Figure 11.1 Chloride content of surface runoff in 4 catchments overlying basement rocks in central plateau region of Malawi.

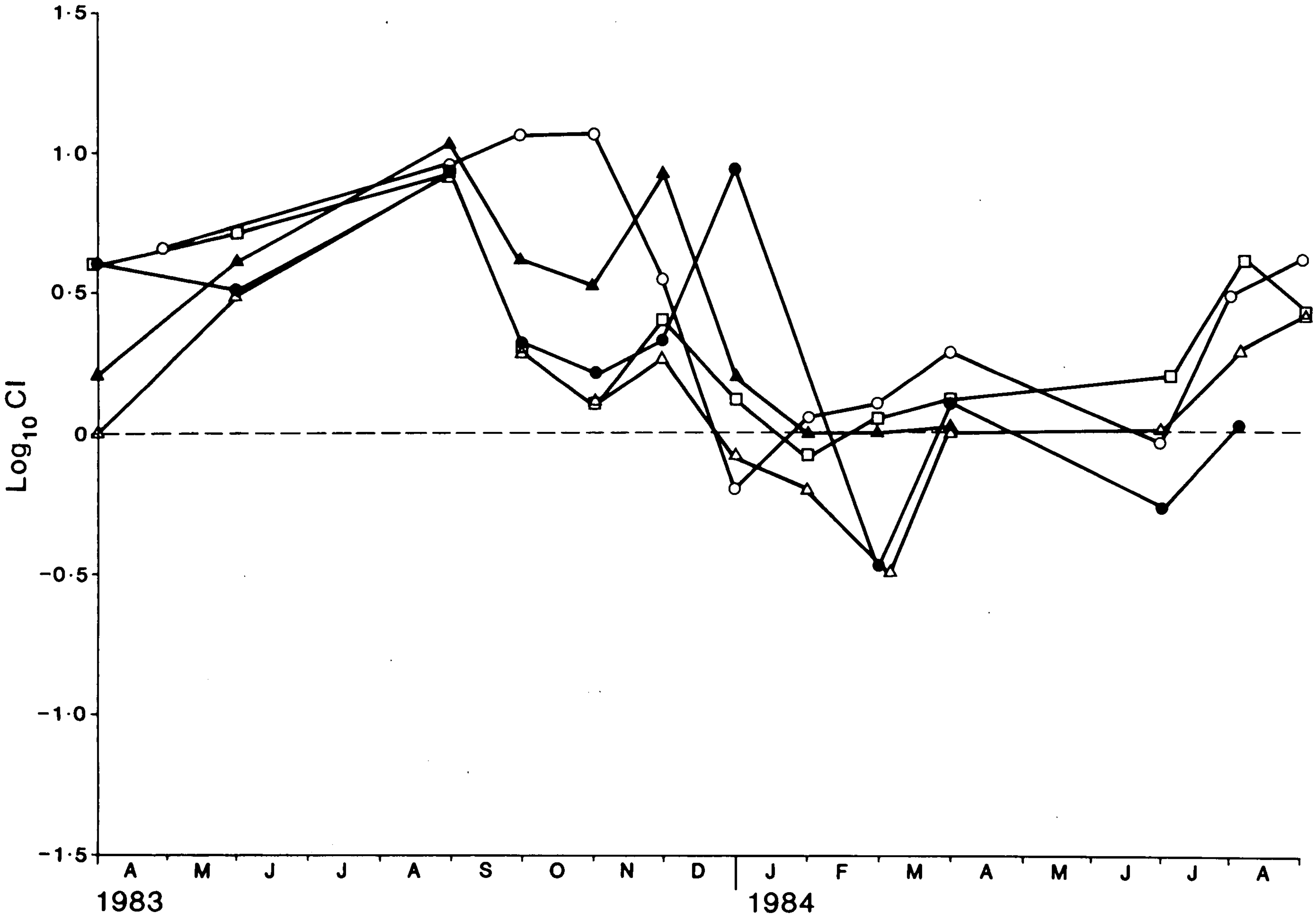

Figure 11.2 Chloride content of surface runoff in 4 further catchments overlying basement rocks in central plateau region of Malawi.

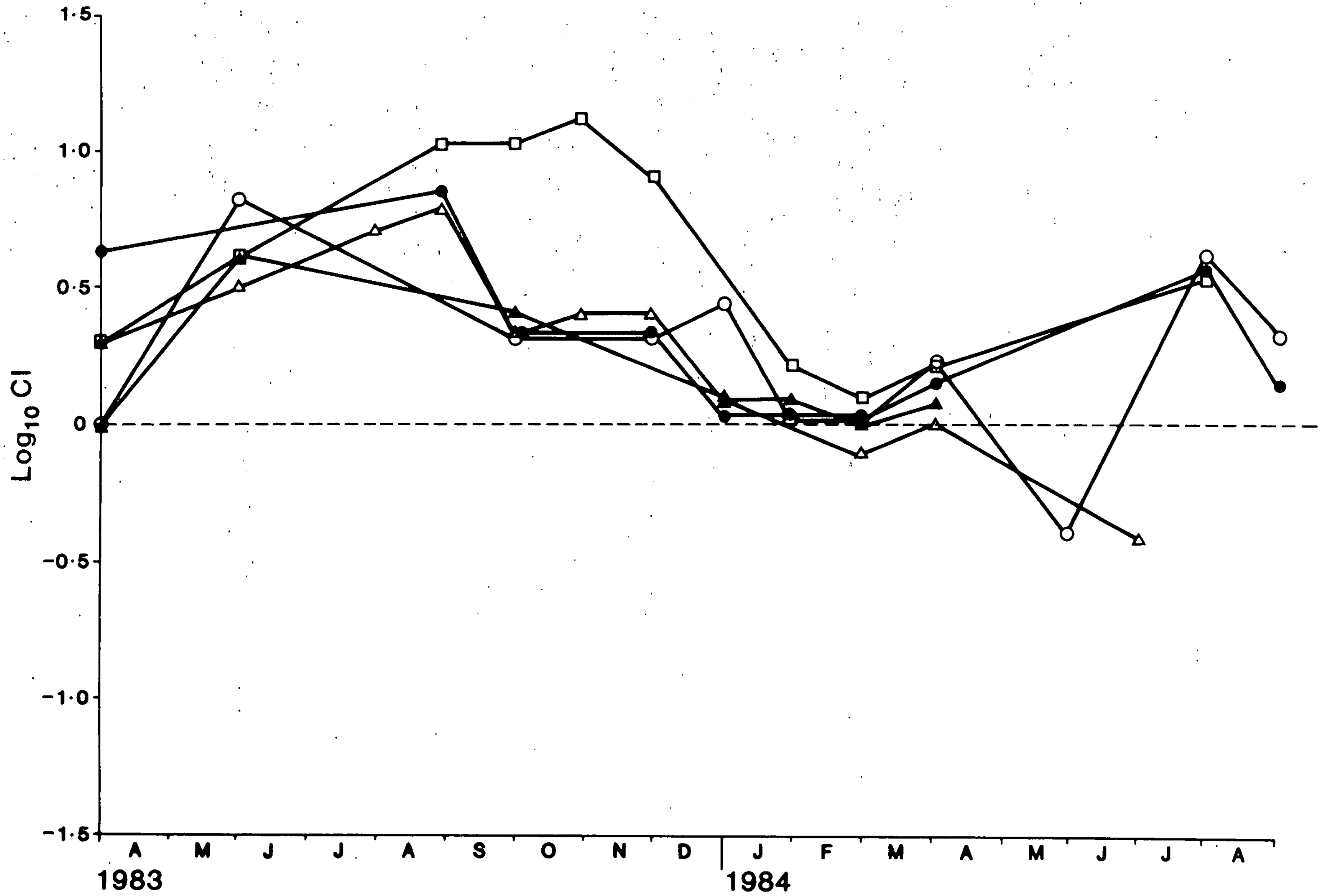

Table 11.5 Chloride Content in Groundwater (mg/l)

	Mean	σ	No. of Samples	Estimated Recharge	Recharge/MAR
Malawi [Rainfall Cl content assumed 1.01 mg/l]					
(i) Boreholes and wells in Livulezi Valley					
	7.6	7.0	169	101 mm	10%
	(0.27)[1]			(212 mm)	(21%)
(ii) Dambo Survey (auger holes/wells)					
	4.4	5.1	102	195 mm	21%
	(0.7)[1]			(598 mm)	(66%)
(iii) Lewis (Malawi Water Quality): Groundwater Unit 5D (1987)					
	11.4	-	199	75 mm	8%
Zimbabwe [Rainfall Cl content assumed 0.5 or 0.5/2.5 as appropriate]					
(i) Darwendale Tunnel Drip Samples[2]					
	4.0	-	60	85 mm	10%
	(0.3)[1]	-	-	(105 mm)	12%
(ii) EEC Masvingo Project Analyses (HydroTechnica, 1985)					
Granite Aquifers	16	30	126	135 mm[3]	10%
				28 mm[2]	3%
Gneiss Aquifers	61	59	162	36 mm[3]	4%
				7 mm[2]	<1%

(1) Harmonic Mean
(2) Rainfall chloride assumed 0.5 mg/l
(3) Rainfall chloride assumed 2.5 mg/l

11.2.4 Analysis of Flow Net and Seasonal Groundwater Levels

These analyses are rarely undertaken because of the heterogeneous nature of the basement aquifer. The method is more applicable in the regolith aquifers such as are present in Malawi for which some degree of lateral hydraulic continuity can be assumed. A study by Ruxton (1984) of the Dowa West Area (Unit 5D) demonstrates the difficulty of the analysis. Recharge estimates are in the range 4-36 mm/year although if the higher values of transmissivity derived from slug testing are used, the values rise to between 16-144 mm. Seasonal groundwater fluctuations in the same area were interpreted on the assumption of storage coefficients in the range 5×10^{-3} to 10^{-2} to give estimated recharge between 10-35 mm/year.

The flow net analysis for the Chimimbe dambo hydraulic data indicates a lateral inflow towards the dambo of c. 400 mm/a.

The results of the two sets of flow net analyses are considerably divergent and neither correspond closely with the estimated seepage zone evapotranspiration losses. These divergences are probably an indication of the difficulties in obtaining regional values of the main aquifer parameters.

11.2.5 Water Balance Modelling

No water balance modelling studies were carried out during the Basement Aquifer Project but it is interesting to compare the results of two recent studies carried out in basement aquifers, one in Zimbabwe by Houston (1988) and the second in Burkina Faso by Milville et al. (1988)*. Houston applied a soil moisture balance model using monthly data of rainfall and evapotranspiration and a root constant of 100 mm. Regional recharge values over several years of records range from 1.4-5.4% of mean annual rainfall with the latter varying from 211-1511 mm.

The more complex model developed in Burkina Faso is based on an intensive analysis of the entire hydrologic system at three widely spaced locations and takes account of the soil moisture balance, infiltration rates through the vadose zone, water level changes and flow in the saturated zone. The estimated recharge rates are in the range 24-30% of mean annual rainfall which varies from 535-1108 mm. The contrast between these two sets of estimates is considerable despite comparable climate, rainfall and bedrock/aquifer type.

11.2.6 Summary of Recharge Results

Summary results of the various recharge estimates are given in Table 11.6.

Malawi. Baseflow hydrograph and groundwater (borehole) chloride ratios give comparable results in catchments without dambos. Some baseflow chlorides are also consistent with this rate but others indicate higher values (33%). In catchments with dambos, groundwater chlorides (boreholes) analysis are comparable with the lower estimates of seepage zone losses but baseflow chlorides show much higher estimates. Flow net and water level analyses give lower values of recharge which is to be expected. General recharge rates would be expected to be in the range 10-16% of mean annual rainfall.

Zimbabwe. Data are mainly available for the southern area of Zimbabwe and the calculations are affected by a greater degree of uncertainty of the chloride content of rainfall. Baseflow chloride ratios indicate higher values of recharge than groundwater (borehole) chloride ratios, which is apparent to some extent in Malawi but significantly increased here. A wider range of chloride values is to be expected in the more compartmentalised bedrock aquifers, notably as found in the Masvingo project area and the resultant mean values are likely therefore to be higher. General recharge rates appear both more variable and lower than in Malawi in the main range 2-12% of mean annual rainfall.

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* Published in Proceedings of the Harare Workshop

Table 11.6 Summary of Recharge Estimates

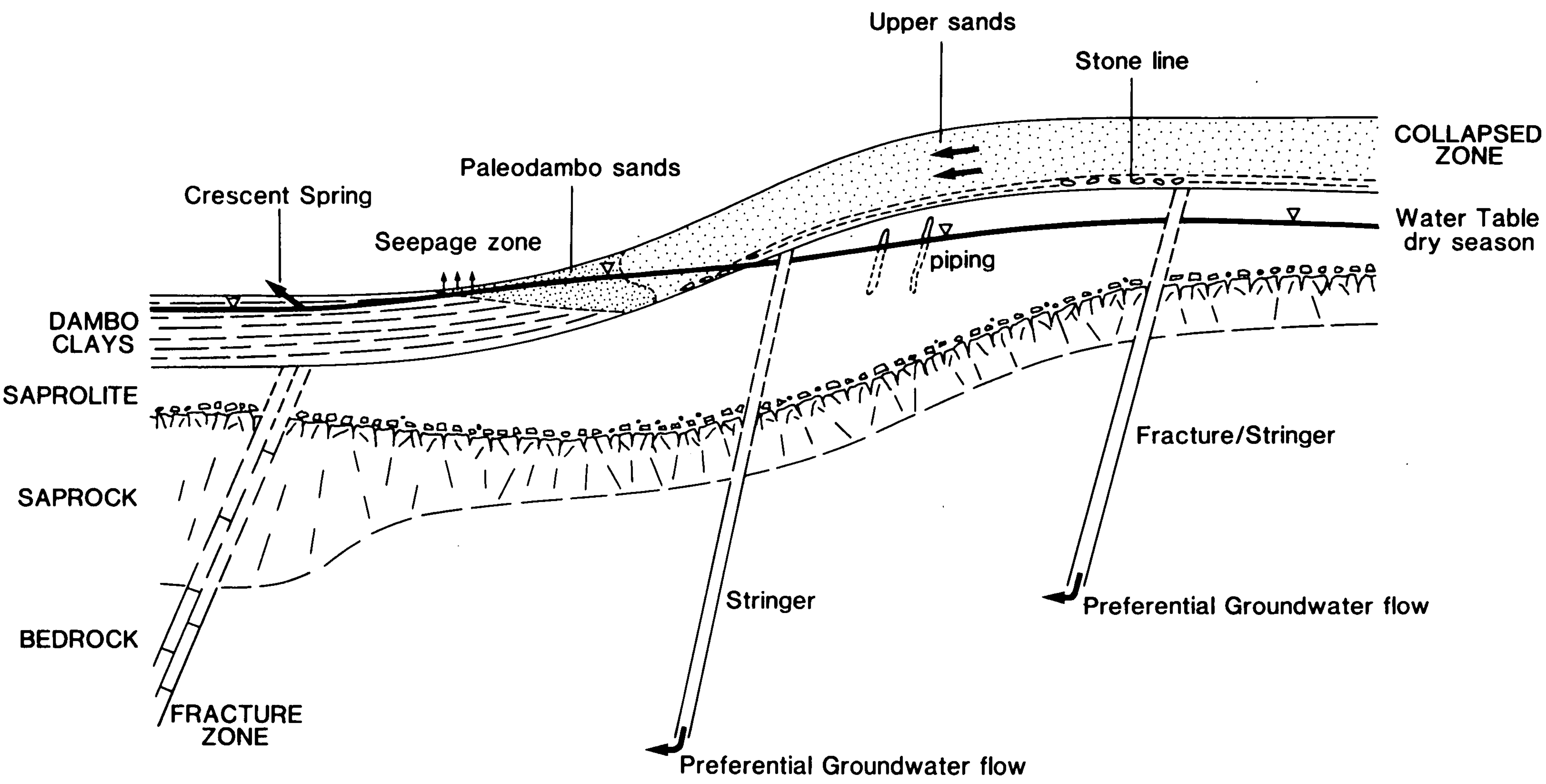
	Estimated Recharge (mm)	Recharge/MAR %
MALAWI		
Livulezi Valley (no dambos)		
(i) Baseflow by hydrograph	80	8
(ii) Groundwater chloride (boreholes etc)	101	10
Regional streams on Centre Plateau (no dambos)		
(i) Baseflow by hydrograph		15
(ii) Baseflow chlorides (Figures 11.1,11.2)		10-16
(iii) Baseflow chlorides		33
Water Resource Unit 5 - high dambo %		
(i) Baseflow chlorides in dambo survey	-	60
(ii) Groundwater chlorides (boreholes)	75	8
(iii) Flow Net	(4- 36)[1] (16-144)	(<1- 4) (2-16)
(iv) Water level changes	10-35[2]	1-4
(v) Seepage evapotranspiration	96-152	10-16
ZIMBABWE		
Darwendale Tunnel drip samples chloride content		10-12
Groundwater in Masvingo Province chloride content		
(i) Granite aquifers		3-15[3]
(ii) Gneiss aquifers		<1-4[3]
Catchment base flow chloride ratios		12-63[3]
Baseflow (hydrograph)		2-9[4]
Soil moisture balance		1.4-5.4[4]

(1) Varying estimates of transmissivity
(2) Varying estimates of storage
(3) Rainfall chloride of 0.5 or 2.5 mg/l
(4) From Houston, 1988

11.3 Groundwater Occurrence and Flow Systems

The combined evidence from lithological, hydrological and hydrochemical data suggest that there are important and inter-related features in the hydraulics of basement aquifers which include the occurrence of rapid throughflow channels operating within a composite groundwater system with three main components. There are important implications in terms of resource evaluation and development methodology. The features are illustrated in the schematic section shown in Figure 11.3.

Figure 11.3 Schematic hydrogeological cross-section (1).



11.3.1 Rapid Throughflow Channels

These are numbered from top to bottom as follows:

(i) Upper colluvial sands. These occur in the upper part of the collapsed zone and have high permeability and infiltration capacity. Their typically red coloration makes it easy to observe the lack of significant surface redistribution over adjacent lower lying land, an obvious consequence of the high infiltration capacity. The sands overlie a lower less permeable basal layer formed by illuviated clay and/or internal collapse of the sand grains. The feature has been demonstrated by packer studies in piezometers. During intense rainfall, rapid interflow is likely to occur through this shallow surface layer of high permeability and could be associated with a perched aquifer.

(ii) Stone lines may occur at the junction of saprolite and colluvium and may also promote rapid lateral flow although additionally may serve to promote downward flow into vertical or steeply dipping channelways. These zones of high lateral flow will provide interflow to surface water runoff but can also provide recharge to palaeodambo sand aquifers or to the cracked dambo clays.

(iii) Rapid downward throughflow in the saprolite zone may occur in residual fractured hard bands such as quartz veins, tree root channels and hollow pipes resulting from clay mineral illuviation by leaching.

(iv) Basal saprolite and saprock. This combined zone has high permeability and will promote lateral flow. Fragmentation and brecciation of the basal saprolite without significant associated weathering is probably associated with horizontal fractures developed in the uppermost bedrock (saprock) in consequence of erosional unloading.

(v) Fracture systems in the bedrock. These are often concentrated into planar trends, mostly vertical to steeply dipping but sometimes at shallower angles and will promote directional groundwater flow within the fissure systems which have both vertical and horizontal components.

The importance of shallow interflow is demonstrated by the absence of sheet flow (evidenced by the lack of colluvial transfer) combined with significant surface runoff during heavy rainfall. The low chloride values (1-2 mg/l) of some components of dry season groundwater flow - baseflow or seepage discharge - indicates both a reduction in the expected fractionation of recharge and a rapid transfer to locations of discharge in amounts considerably in excess of throughflow rates through the main matrix which has demonstrably low permeability. Such throughflow could occur either through the near surface fast layers (upper sands or stone lines) or via more deeply penetrating throughflow systems. Present evidence would indicate that the dry season rest water level mainly occurs within the saprolite (or locally in the bedrock) which therefore favours the latter process. The chemistry of crescent springs discharging upwards through dambo clays is able to differentiate groundwater flow associated with transfer through upper or lower saprolite zones or through the bedrock system.

The results of the student dambo survey are also significant in this respect. Samples were collected from shallow auger holes in dambos and from wells and streams. The area surveyed included Dowa West where there is a sulphate problem with evidence which demonstrates higher values of sulphate at deeper levels in the interfluve boreholes in addition to the occurrence of high sulphate in groundwater discharge areas and surface runoff. The details of the sample results are given in Table 11.7 which also differentiates locations in the Dowa West area from other areas in the central plateau region which do not have the sulphate problem.

Table 11.7 Sulphate (SO_4) Contents in Shallow Auger Holes, Wells and Streams in the Central Plateau Region of Malawi.

			SO_4 (mg/l)		
	Mean	σ	**No. of Samples**	**Max.**	**Min.**
Dowa West	671	759	73	3160	2.5
Other areas	29	61	102	324	0

Of the 73 samples from the Dowa West area, only 5 have values less than 50 mg/l of SO_4 whereas in other areas only 14 of 102 samples exceed 50 mg/l. The high SO_4 content could have been acquired by 'deep' circulation or by contamination with surface concentrations in groundwater discharge zones. The latter effect should also result in a correlative increase of chloride but only a few of the samples with high sulphate values show a corresponding increase in other ions. The conclusion therefore is that the groundwater discharge into the seepage zones and streams has penetrated to significant levels of the regolith or deeper bedrock.

The combination of evidence suggests a composite groundwater flow system with three main components.

(1) A near surface system which promotes shallow interflow through high permeability layers in the collapsed zone. Flow could occur in a perched aquifer system on some occasions. The interflow provides groundwater runoff and also recharge to shallow storage at lower levels, e.g. the palaeodambo sand aquifer or the cracks in dambo clays. Recharge could also be facilitated to dipping throughflow systems in the underlying saprolite. The chemistry of the interflow is likely to be distinctive, including low chloride and iron content, and with care it may be feasible to identify the flow component. Increased fractionation by evapotranspiration is likely to occur at greater depths in the profile.

(2) Deeper circulation which is associated either with rapid throughflow systems or more slowly through a low permeability matrix and which corresponds to the third system. The former includes both vertical to dipping channelways in the saprolite or deeper bedrock and the sub-horizontal zone at the saprolite-saprock junction. The chemistry of this intermediate system will relate to some degree to interaction with the various rock formations but may also have the low chlorides associated with the near surface flow systems.

(3) Slow matrix flow either within the low permeability medium of the weathering profile or within poorly interconnected fractures of the bedrock. The chloride content of groundwater in boreholes which penetrate this system is likely to be more variable and boreholes will probably be low yielding. Interaction will of course occur to some extent with the intermediate system dominated by more rapid throughflow channels. It is relevant to note that the chloride content of the fluid in the core samples taken at the Chikobwe dambo proved to be much higher (c. 80 mg/l) than the water in the piezometers or that associated with the marginal seepage zones. The chloride content of poorer yielding bedrock boreholes are likely to be higher than average which is consistent with the higher values in the basement gneisses (Table 11.6) of the Masvingo area. A crossplot of yields versus chloride content should help to confirm the probability. Groundwater in boreholes has in general a greater variability of chloride content and higher mean values than groundwater runoff or groundwater in seepage zones. The feature can reasonably be ascribed to the dominance of the intermediate flow system in the latter locations and the combination of the intermediate and 'matrix' flow systems associated with deeper groundwater encountered by typical boreholes.

11.4 Basement Aquifer Occurrence

11.4.1 Review

Basement aquifers can be subdivided, for convenience, into regolith and bedrock aquifers depending on which of these geological 'units' provides the more dominant control. In Malawi, regolith aquifers are the main resource unit whereas it is the bedrock aquifer in southern Zimbabwe. As shown earlier, however, bedrock aquifers do require a minimum thickness of saturated regolith (within the zone of influence of a borehole) to be effective. Regolith aquifers are more productive if boreholes can reach or penetrate the saprock.

Regolith aquifers generally form hydraulically continuous systems but perched aquifers may occur seasonally within upper layers of high permeability in the collapsed zone when overlying lower permeability formations in the basal collapsed zone or underlying saprolite.

A reasonable degree of understanding exists on the nature of the basement aquifer profile but knowledge on other essential or useful information is more limited, most notably on the areal and catenary variations of the weathered zone thickness, lithology and structure and on any correlations with surface physiographic features (including the terrain surfaces of various ages), soils and climate.

A schematic cross-section is shown (Figure 11.4) which incorporates some of the known correlations and concepts. Key factors are the thickness of the weathered overburden, the elevation of the water table and the saturated thickness of the regolith, the grade of weathering (which often correlates with permeability) and the presence of important catenary variations, local layering, residual hard bands etc. in the regolith and structural features in the bedrock which in varying degrees can control groundwater flow and associated lithological occurrence.

11.4.1.1 *Thickness of weathered overburden/regolith*

The weathered overburden or regolith includes colluvium and saprolite; the bedrock includes saprock (weathered bedrock) and fractured bedrock. Geophysical surveys may sometimes differentiate these various horizons but on other occasions, they are not resolved. The transition from saprolite to saprock is relatively sharp in homogeneous bedrock but more transitional in banded rocks such as migmatites or gneisses. In the former case it may be feasible to differentiate saprolite from saprock by resistivity differences or by drilling response particularly if the rate of penetration is recorded. It is useful to separate the two subdivisions because of critical differences in the hydrogeological responses, as discussed earlier.

Weathering thickness increases in accordance with the following (Figure 11.4):

- age of the erosion surface, being thicker on older surfaces.

- location at the foot of rock inselbergs (A) as a consequence of high runoff/recharge. Marginal colluvial fans assist infiltration.

- overlying structural zones (F), particularly if associated with stream occurrence. Bedrock lithology can also play an important role since structural features are more extensive and penetrative in some rocks, e.g. coarse granite, than in finer grained rocks.

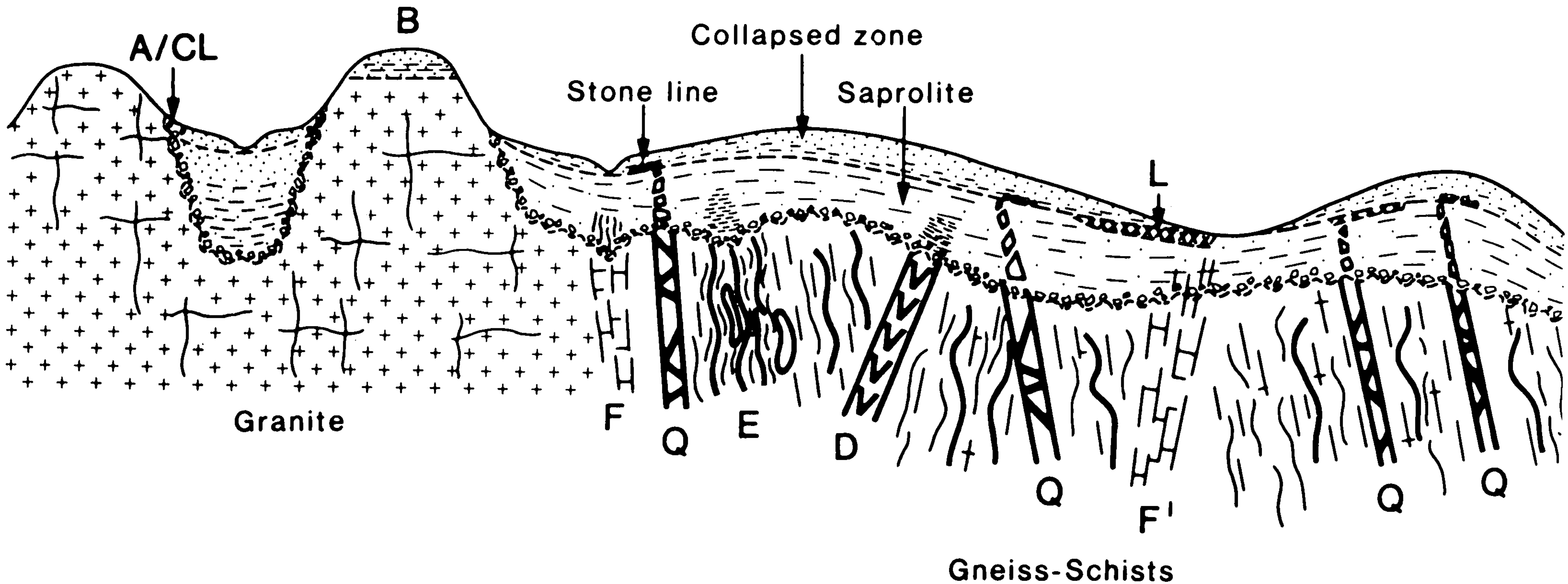
- the grain size of the rock, with deeper but less advanced weathering occurring in coarser grained rocks.

- the rock mineralogy, with the ferromagnesian minerals, particularly biotite, and the Ca-Mg feldspars being more susceptible to weathering than the quartz-alkali feldspar combination.

Weathering thickness decreases or becomes more variable in accordance with the following:

- as a result of aggressive leaching which may occur on isolated, elevated masses (B), below dambo clays due to lateral groundwater flow below the impermeable cap, and in association with rejuvenation such as the contact zone between erosion surfaces of different ages.

Figure 11.4 Schematic geological cross-section.



11.4.1.2 *Saturated thickness of regolith*

Saturated regolith thickness is a critical factor for borehole success, providing the main storage in the aquifer system. Saturated thickness tends to increase with higher rainfall and in areas of low relief. Saturated thickness tends to be reduced in the vicinity of incised or rejuvenated stream systems as a consequence of the lowering of the discharge level. Regolith and saturated regolith thickness may both tend to increase in low relief areas upgradient of transverse barrier boundaries. These barriers may range from more localised occurrences of thin dykes to major hill ranges of massive exposed bare rock. Some of the bornhardt chains of gneissic granite in southern Masvingo Province fall into this category.

11.4.1.3 *Grade of weathering*

Grade of weathering is of importance since there is often a correlation with permeability. Fragmentary brecciated rocks at the basal surface of weathering at the saprolite-saprock junction have high permeability. Grade of weathering increases upwards in the overlying saprolite with increasing proportions of kaolinite and a complementary reduction in permeability. In biotite rich rocks, an early stage of weathering is the conversion to hydrobiotite which occupies a larger volume and therefore reduces permeability. A good example of this occurrence is the collector well site at Makumba. With advancement of weathering, the hydrobiotite is converted to vermiculite which increases the permeability. Rock lithology is critical in this respect since the more basic rocks are converted to a heavy clayey, impermeable saprolite. Aggressive leaching may result in a lowering of the basal surface of weathering but also perhaps a reduction in the regolith thickness by kaolinite dissolution. Dissolution can also cause 'piping' which increases permeability.

11.4.1.4 *Structure*

Structural features are important not only for their bearing on the development of the regolith but more directly in relation to borehole locations and yields. The origin, intensity and geometry of structural features has been an important focus of study in this Project. General correlations with bedrock type and regional geological features have been identified but little information is available on more precise correlations, if they exist, with regolith thickness or the depth of fracture penetration. There appears to be no significant correlation of borehole yields with particular sets of fractures, whether by azimuth, age or apparent magnitude.

11.5 Quantitive Correlations

11.5.1 Malawi

A computerised database has been set up for the areas on the central plateau shown in Figure 3.4. Development of the Malawi basement aquifers is largely within the regolith, particularly in the integrated project studies where lightweight drill rigs are used. Drilling normally continues until the rate falls off significantly in the hard rock. Some penetration of the weathered saprock is likely.

11.5.1.1 *The Livulezi Valley*

The Livulezi valley is underlain by weathered overburden of moderate thickness, in the main range 18-30 m, and flanked by hills on either side with varying degrees of rock exposure. One hundred and thirty-five boreholes were drilled in an integrated project and with some 96% providing a yield in excess of 0.25 litres/sec.

Studies have been carried out with a view to identifying the main controls to aquifer occurrence and borehole yield. It is a common assumption in Malawi that higher yields are often associated with thicker overburden. An attempt was therefore made to ascertain whether any correlation could be made with lineament features, either as apparent in the valley or by extrapolation from the marginal hill areas. Air photographs were used for the purpose and the lineament plot is shown in Figure 11.5. It is apparent that lineament densities are considerably reduced in the valley as compared with the marginal hill areas but also that certain lineaments can be observed to extend from the hills to the valley floor. Although contoured density and frequency plots showed no recognisable patterns, it was feasible to identify zones in the valley in which a significant density of lineaments occurred or in which there was a significant lack of them (Figure 11.6).

Using digitised lineament data, matrix correlations were set up between selected features of the lineament density and distributions, and the recorded depth to water, borehole depths and yields (Table 11.8a,b). No significant correlations existed between any of the hydrogeological parameters in relation to lineaments other than a positive correlation of regolith thickness (i.e. borehole depth) with the main western fault, a correlation which diminishes when other lineament features are combined. The positive correlation can be reasonably assumed to relate to downfaulting.

Table 11.8(a) Correlation between selected features of the lineament density and distribution (A-O), and the recorded depth to water, total depth of borehole and yield, northern part of Livulezi valley.

		Depth	Water Level	Yield
A.	Lineament density	0.164	0.131	-0.045
B.	Stratification density	-0.198	-0.268	0.077
C.	Prox. outcrop	-0.042	-0.015	-0.033
D.	Prox. main fault	<u>0.542</u>	<u>0.423</u>	-0.096
E.	Prox. lineament	0.168	0.108	-0.002
F.	Zones A, B, C	0.185	0.008	-0.161
G.	Zones X, Y	0.204	0.176	-0.130
H.	Frequency level	0.147	0.176	-0.138
I.	D x F	<u>0.343</u>	0.192	-0.227
J.	D x G	<u>0.312</u>	0.258	-0.128
K.	A x H	0.080	-0.035	0.063
L.	I + J	<u>0.383</u>	0.256	-0.213
M.	D x F x E	<u>0.319</u>	0.227	-0.211
N.	D x G x E	0.269	0.278	-0.127
O.	D x A	<u>0.465</u>	<u>0.378</u>	-0.118

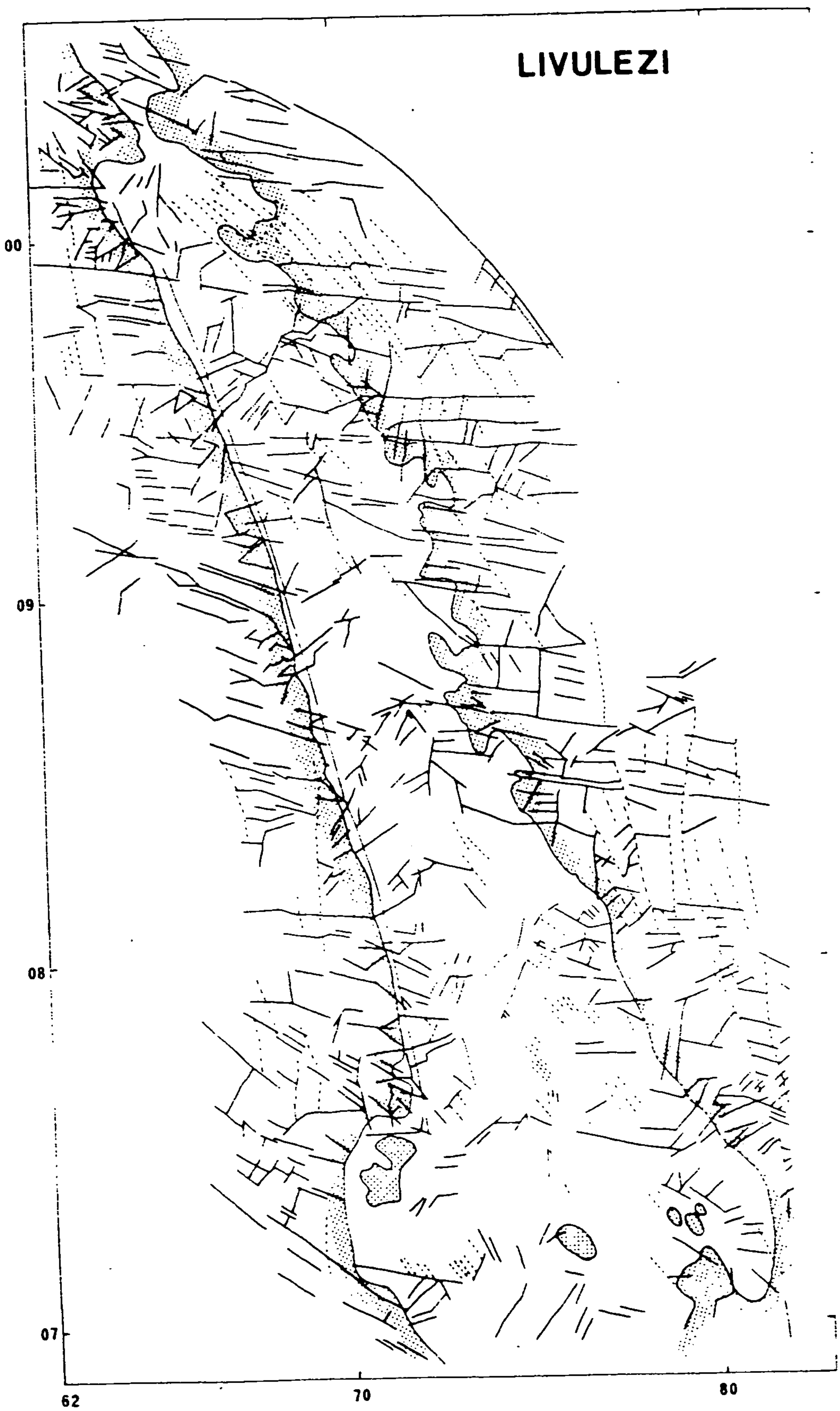


Figure 11.5 Lineament plot of the Livulezi area.
Shaded line marks the valley boundary.
Solid lines are lineaments.
Pecked lines are stratigraphy/foliation.

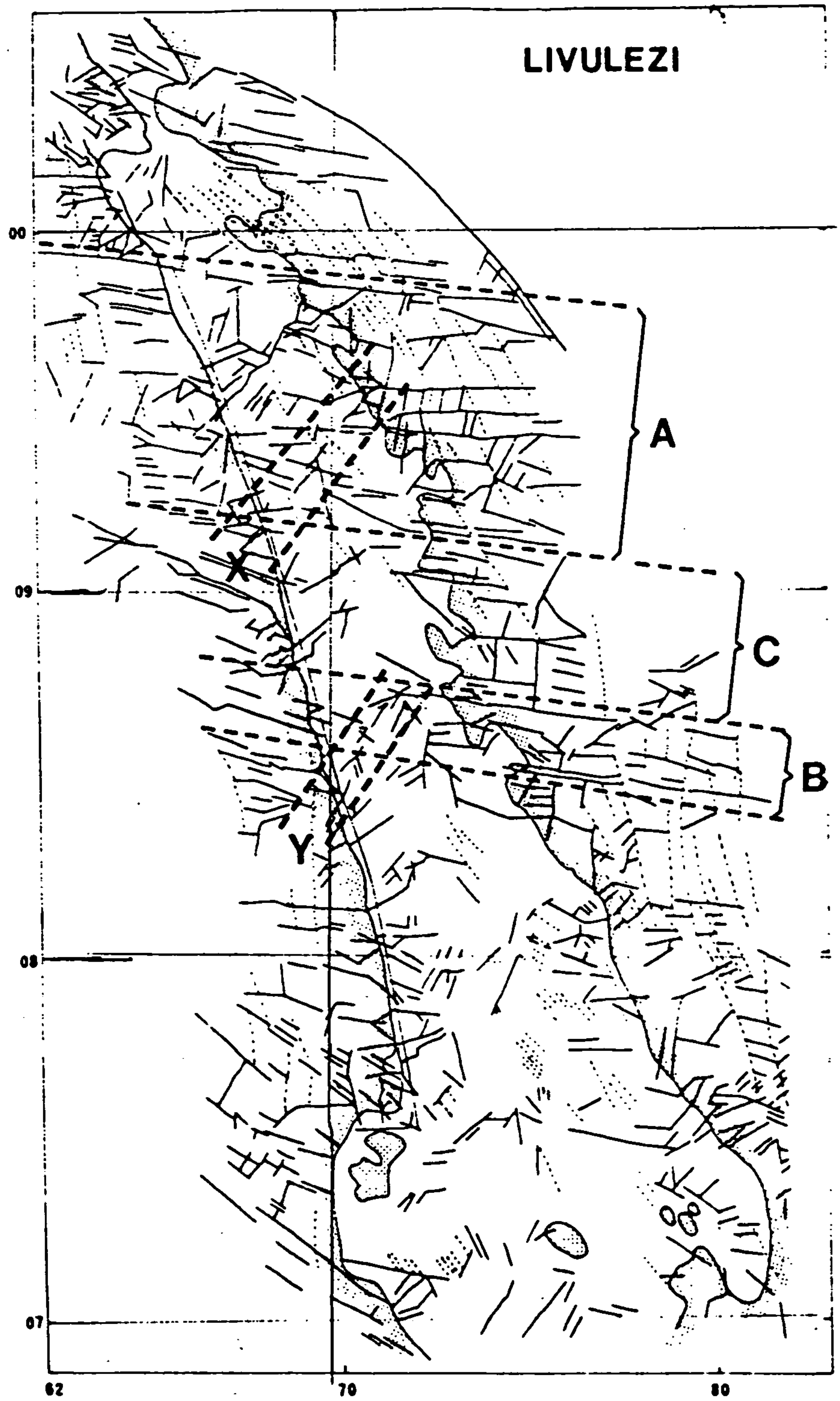


Figure 11.6 Livulezi valley area, showing zones of lineaments referred to in text.

Table 11.8(b) Correlation between borehole depth and lineament distribution, for the northern half of the Livulezi valley, measuring distances from the boundary lineament with a linear scale.

		Depth
A.	Lineation density	0.153
B.	Stratification density	-0.203
D.	Prox. to main fault	0.651
E.	Prox. to lineament	0.168
F.	Zones A, B, C	0.186
G.	Zones X, Y	0.204
H.	Frequency level	0.116

It may also be concluded that regolith thickness or borehole yield have no apparent correlation with lineament densities, either as observed or extrapolated. In the former case, bedrock lithology may well exercise a more dominant control; in the latter, the intersection of rapid throughflow channels, which are apparently unrelated to lineaments or depth, may be the main control.

The basic hydrogeological parameters were subsequently examined in more detail, using areal plots, frequency distributions and matrix correlation coefficients. There is an apparent concentration of boreholes with higher specific capacity in the south of the valley and on the eastern margins (Figure 11.7). This is, however, based on only the 66 boreholes out of 135 which had drawdown measurements to permit specific capacity to be calculated. Plotting yield, which correlates with specific capacity (Table 11.10), there is some indication that the higher yielding boreholes are clustered in small groups on both flanks of the valley, but these clusters do not appear to correlate with the zones of high and low density of lineaments (Figure 11.6). A larger group of low yielding boreholes occupies the area between the Livulezi river and the eastern interfluve at the southern end of the valley. The marginal performance of a number of these boreholes is confirmed by difficulties in meeting demand towards the end of the dry season.

Table 11.9 gives the summary statistics of the frequency distributions which show normal plots, either linear or log. Examples of the types of distribution plot are shown in Figures 11.8 and 11.9. The log/linear values were used as appropriate in the matrix correlation programme. Key figures from the frequency distributions are listed below.

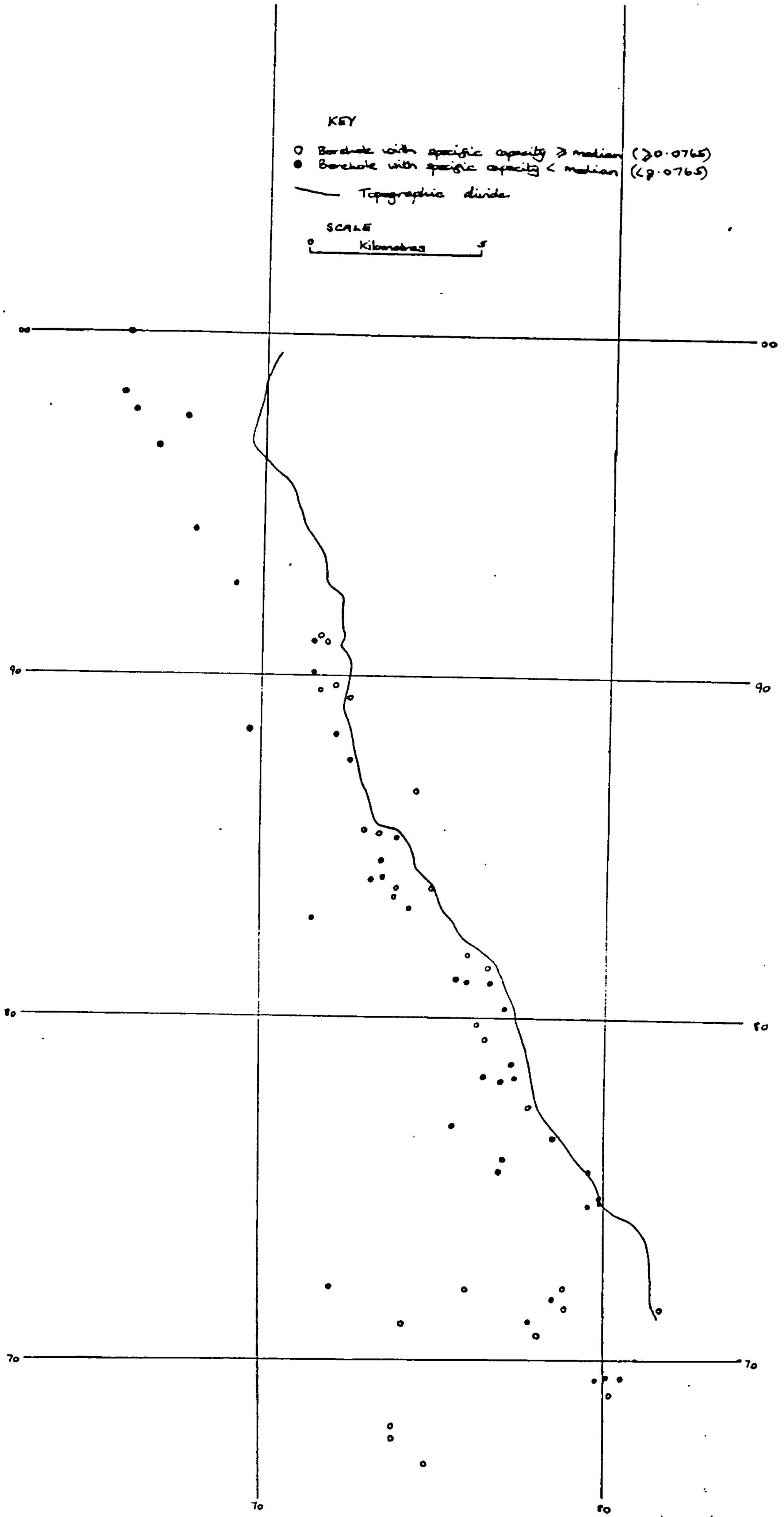


Figure 11.7 Specific capacity groupings of 66 boreholes in Livulezi Project Area, Malawi.

Figure 11.8 Log normal distribution of iron content.

- Histogram of iron concentrations for Livulezi data

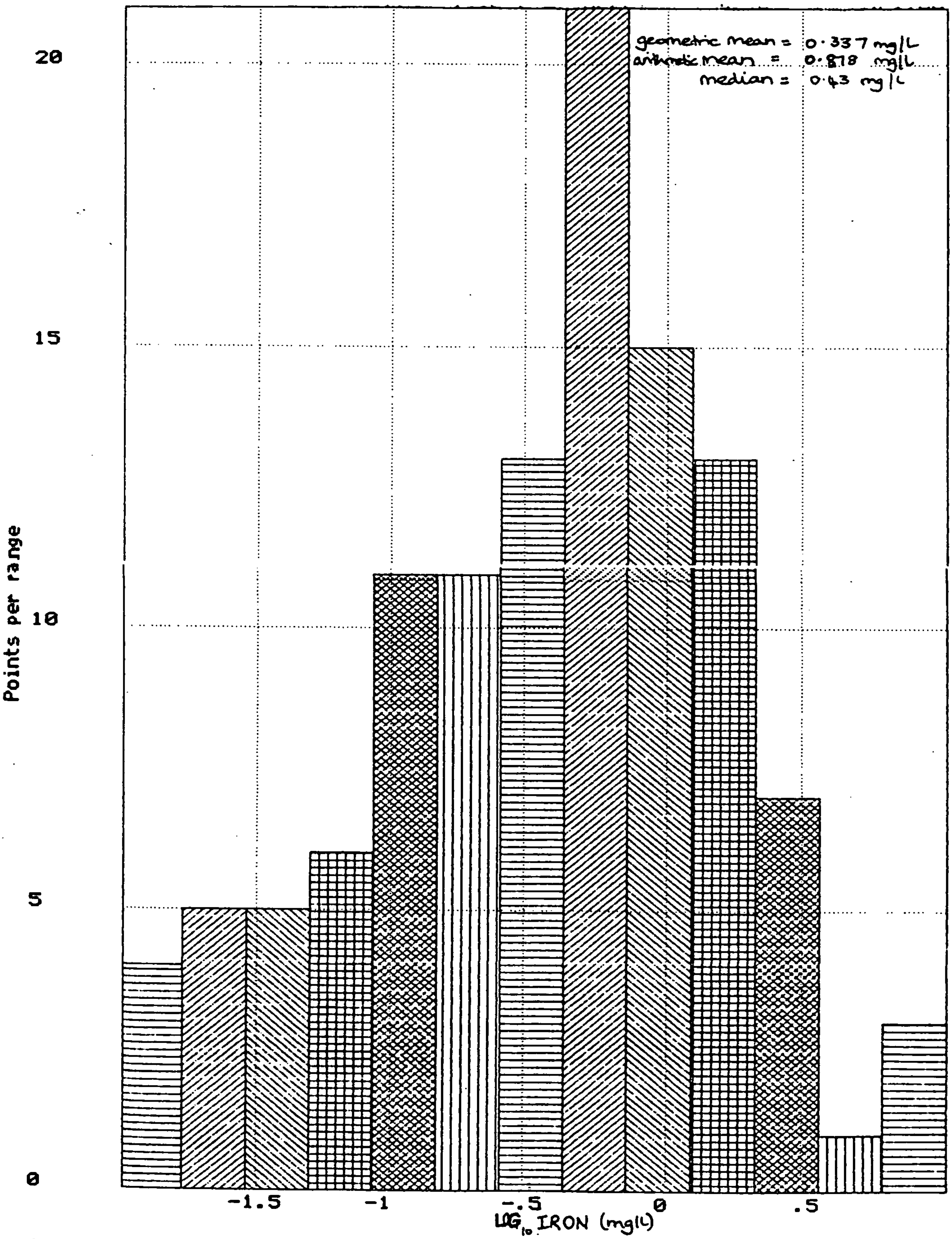


Figure 11.9 Normal distribution of weathered rock thickness.

- Histogram of weathered rock thickness for Livulezi data

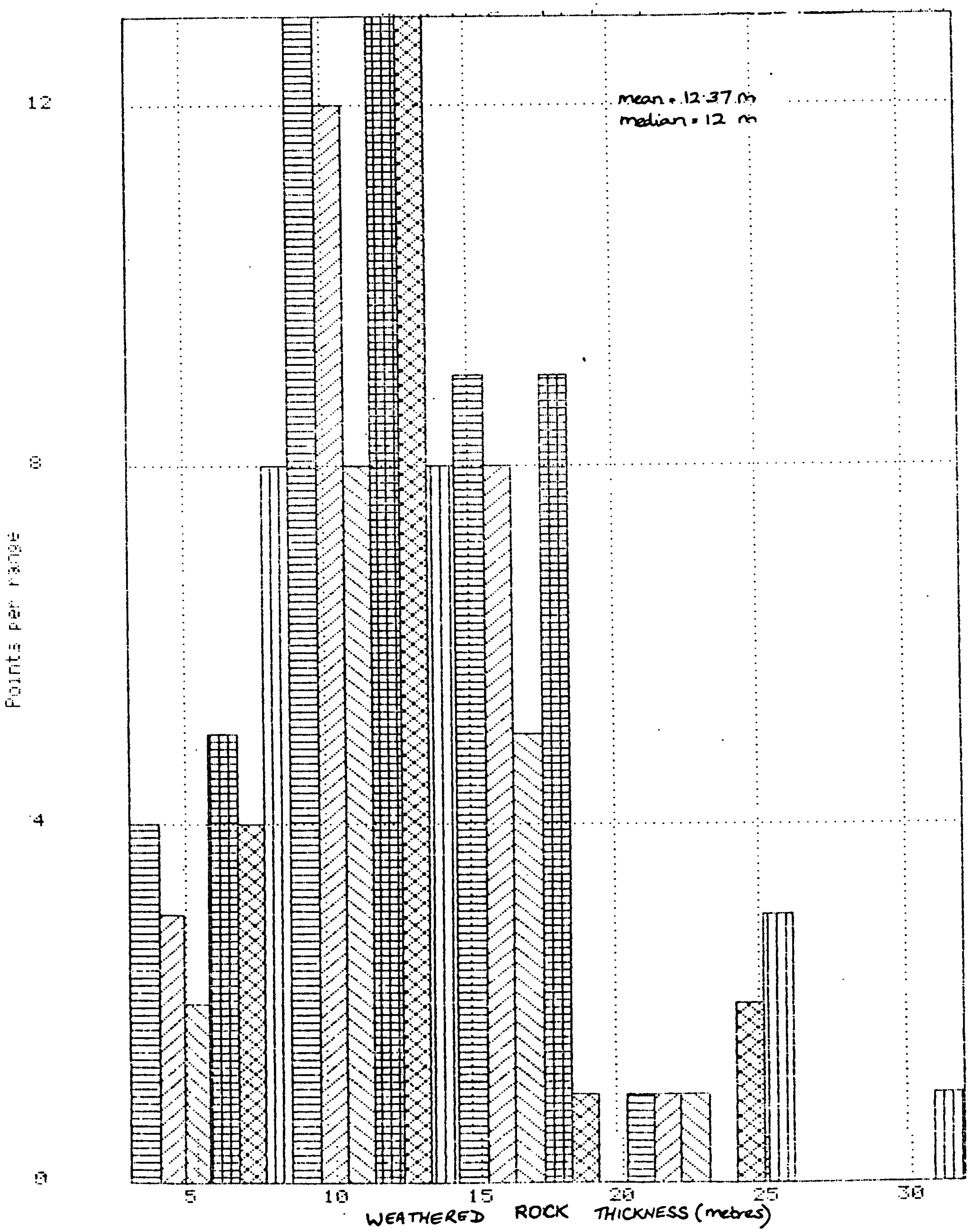


Table 11.10 Pearson's Correlation Coefficients for the Livulezi Data.

	Eastings	Northings	Clay Thickness (m)	Weathered Rock Thickness (m)	Borehole Depth (m)	Yield (l/sec)	Drawdown (m)	Depth to Water (m)	Electrical Conductivity (µmhos/cm)	Total Dissolved Solids (mg/l)	Saturated Aquifer Thickness (m)	Log_{10} Iron (mg/l)	Log_{10} Fluoride (mg/l)	Log_{10} Chloride (mg/l)	Log_{10} Sulphate (mg/l)
Clay thickness (m)	0.02	0.03													
Weathered rock thickness (m)	-0.24	0.14	-0.26												
Borehole depth (m)	-0.17	0.11	0.63	0.54											
Yield (l/sec)	-0.13	0.06	-0.17	0.26	0.06										
Drawdown (m)	-0.38	0.40	0.08	0.48	0.47	-0.24									
Depth to water (m)	0.14	-0.13	0.72	-0.16	0.48	-0.22	-0.20								
Electrical conductivity (µmhos/cm)	0.39	-0.16	0.02	-0.07	-0.06	0.12	-0.21	0.06							
Total dissolved solids (mg/l)	0.48	-0.28	0.02	-0.10	-0.07	-0.06	-0.33	0.07	0.92						
Saturated aquifer thickness (m)	-0.32	0.24	0.17	0.71	0.74	0.23	0.69	-0.22	-0.14	-0.16					
Log_{10} Iron (mg/l)	-0.23	0.28	0.13	0.11	0.19	-0.18	0.25	0.12	-0.14	-0.18	0.13				
Log_{10} Fluoride (mg/l)	0.06	0.21	-0.05	-0.16	-0.21	-0.17	0.05	-0.11	0.35	0.32	-0.14	-0.07			
Log_{10} Chloride (mg/l)	0.36	-0.17	-0.09	-0.20	-0.24	0.00	-0.18	-0.14	0.54	0.56	-0.16	-0.25	0.33		
Log_{10} Sulphate (mg/l)	0.16	0.00	-0.10	-0.14	-0.19	-0.24	-0.16	-0.01	0.28	0.26	-0.21	-0.04	0.26	0.10	
Log_{10} specific capacity (l/sec/m)	0.12	-0.28	-0.17	-0.09	-0.23	0.73	-0.73	0.01	0.02	0.17	-0.27	-0.55	-0.13	0.14	-0.11

Table 11.9

Parameter	Mean ± σ	Corresponding Range
Borehole depth (m)	24 ± 6	18 - 30
Weathered rock (m)	12 ± 5	7 - 17
Clay (m)	12 ± 5	7 - 17
Depth to water (m)	7 ± 4	3 - 11
Saturated aquifer thickness (m)	17 ± 6	11 - 23
Yield (l/sec)	0.76 ± 0.4	0.36 - 1.16
Drawdown (m)	11 ± 6	5 - 17

The lithology is compounded of 'weathered rock' and 'clay' in approximately equal proportions but it is not certain where these two lithologies are typically distributed within the profile although it might be expected that the weathered rock would be at the greater depths. It is also unclear whether the 'weathered' rock should be included in the saprolite or saprock but in view of the fact that lightweight drilling rigs were used, inclusion within the former category is preferred.

The matrix correlation coefficients for the Livulezi data set are shown in Table 11.10 and the following conclusions may be drawn.

(i) Some of the matrix correlations have medium to high coefficients in the range 0.5-0.9. They include parameter sets which are obviously correlated such as log (specific capacity) and yield = (0.73), dissolved solids content and electrical conductivity (0.92).

(ii) Weathered rock and clay thickness both correlate with borehole depth which is not surprising since they are the only two lithological components but rather surprisingly the clay thickness has only a small -ve correlation with weathered rock.

(iii) Some correlations appear hydrogeological inconsistent such as drawdown to weathered rock (0.48) and drawdown to clay (0.08). It would appear as if yields or drawdown bear no significant relation to the proportions of weathered rock or clay.

The Livulezi project area has been the subject of detailed analysis because of the high density of boreholes with good data in a relatively small area. It is unlikely to be typical of the central plateau area as a whole; the Livulezi is a downfaulted shelf, a hanging valley with a very steep western edge having high runoff creating favourable conditions for regolith development. For the larger area of the database similar correlations have been made, including attempted correlations of borehole data with the results of the very detailed terrain analysis described above.

Relative relief, stream frequency and dambo area were characterised on a map by map basis, for the 1:50,000 sheets comprising the "Malawi Strip" study area. The borehole characteristics, depth, yield, rest water level, specific capacity, saturated aquifer thickness and regolith thickness have then been correlated with these relief characteristics on a map by map basis and then compounded for the total study area, to produce both scatter diagrams and tables of correlation coefficients. As in the case of Livulezi, some high correlation coefficients occur between characteristics that are closely interrelated, e.g. total dambo area (TDA) and streamless dambo area (SDA) with percentage of very low relief. Nevertheless, there are reasonably good correlations between both borehole depth and saturated aquifer thickness and TDA, SDA and percentage of lowest relief. There is also a correlation between logarithm of yield and logarithm of TDA, SDA and percentage of lowest relief, implying that the highest yielding boreholes are associated with the lowest relief areas. There is also a reasonable correlation between yield and stream density; the best yields correlating with lowest stream densities. This is not surprising, there is a good correlation between stream density and dambo areas (TDA and SDA) and percentage of lowest relief. Thus, although this was not the case in the Livulezi Valley, on the main plateau area there is some indirect indication that higher yields are associated with a thicker weathered zone although the correlations of logarithm of yield directly with borehole depth and saturated thickness are not so good.

Analysis of borehole data, in the context of the individual kilometre squares within which they occur showed that:

(a) Mean regolith thickness increases with low relative relief (over 31 m in the lowest relative relief category, dropping to about 25 m in the higher categories).

(b) The range of regolith thickness increases with low relative relief (with 3-76.25 m in the lowest relative relief category and 9.76-46.36 m in the highest). This is inconsistent with the generalisation that incision increases the relative relief on the basal surface of weathering, that is it increases the range of regolith thickness. This may reflect selective location of boreholes in dambo-peripheral situations, where most villages are located. Further analyses would be required to examine this, but it would be consistent with the thinning of the regolith where dambo insetting is most advanced, in the areas of higher relative relief. This does not, however, alter the fact that even where the local relief is very flat, bedrock may occur at very shallow depth; an important consideration in borehole siting.

(c) Borehole yield varied with local relative relief such that the highest mean yield (72 l/min, range <1-430) occurred in the lowest relative relief category. Lower mean yields (46-64 l/min) are associated with higher relative relief. This has interesting implications. The more vigorous leaching of incised profiles might be expected to provide the regolith with higher permeability (as indeed is evident from the collector well studies, described elsewhere). These data, showing higher yield in flatter areas where regolith is thicker, appear to support the deduction that stringers within the saprolite are extremely important to borehole yield, rather than the primary permeability which is dependent on leaching aggression. That is, the thicker the regolith the better the chances of intercepting a stringer which 'collects' from saprolite with poor permeability. Earlier analysis of a limited number of boreholes in the Dowa West area had suggested that the effects of stringers on yield are such as to increase it in comparable proportion to the intersection of the high yielding basal brecciated zone of weathering profiles. However, much more extensive analysis of this is in progress.

11.5.2 Zimbabwe

The Masvingo Project has been discussed previously in Sections 3, 5 and 10. The discussion here is concerned with the statistical analyses of borehole data additional to the lineament correlations already referred to. The area of Zimbabwe for which groundwater data has been computerised is shown in Figure 3.6 but for reasons of time, discussion is restricted to the main Project Area between latitudes 19°30'S and 21°00'S, and between longitudes 30°00'E and 32°00'E. In addition to summary statistics - frequency distribution, regression analysis and matrix correlations for the boreholes in this area, areal plots have been made of relief, rest water level, regolith thickness and success rates.

The borehole structure file is listed in Table 11.11 below.

Table 11.11 Structure for files in computerised data base for Zimbabwe.

Fld	Name
001	Borehole No.
002	Grid Ref.
003	Map No.
004	Elevation
005	Well Diameter
006	Well Depth
007	Casing
008	Screen
009	Soil
010	Clay
011	Sand
012	Rock 1
013	Rock 2
014	Rock 3
015	Rock 4
016	Rock 5
017	Saprolite*
018	Geological Units
019	Fracture
020	First Water
021	Main Supply
022	RWL
023	Date
024	Test Type
025	Yield
026	Drawdown
027	Length Test
028	Use
029	Elect Condy
030	pH
031	Extra Data
032	Topography

* Base of (i.e. = regolith thickness)

Most of the field names are self-explanatory but some clarification of certain items is desirable.

- Geological Units. The full geological sequence in the Masvingo Project area is shown in Table 11.12 and the numbering alongside the geological units has been incorporated into the data base. For the purpose of statistical analysis, the subsections of groups 4, 5, 6 and 7 were combined, thus constituting the Mobile Belt Gneisses (4), the Younger Granites (5), the Older Gneisses (6) and the Greenstones (7).

Table 11.12 Geological Sequence in the Masvingo Project Area.

Data Base Unit	Description
1	Superficial deposits
2	Basalts and dolerites (mainly Karoo)
3	Great Dyke 3a Serpentinite and pyroxenite 3b Norite and gabbro
4	Mobile Belt Gneiss 4a Central zone 4b Marginal zone
5	Younger Granites 5a Batholithic granite intrusives 5b Porphyritic granite intrusives
6	Older Gneisses 6a Older gneisses and migmatites 6b Mashaba Tonalite 6c Mushandike Granite
7	Greenstone Complex 7a Greenstones 7b Serpentinite and ultramafic complexes

Other additions to the data base which had been planned but not in the event included are relief and resistivity data. A plot of relief has been made and the main features are discussed qualitatively below. The relief values in the 1 km grid squares could now readily be incorporated in the data base. A geophysical data base (mainly resistivity values of layer sequences) would have had particular value and is strongly recommended to be done. Information in the Government records is mainly in the form of basic data of profiles and soundings which would require fuller interpretation for the recommended purpose.

11.5.2.1 *Bedrock and Aquifer Type*

Bedrock and aquifer type cannot be categorised quantitatively and different data sets are therefore required for any classification. The bedrock type has been classified in the data base and statistical analysis carried out on the different data sets. There is some uncertainty regarding aquifer type. The distinction is generally made on the location of the main water strike(s) in relation to the base of the regolith, thus subdividing the aquifer into regolith and bedrock types. In Malawi, borehole completion is mainly within the regolith with most boreholes only shallowly penetrative into the underlying saprock and bedrock. The main aquifer of borehole completion can be regarded as a regolith aquifer although the evidence indicates that the main water strikes (i.e. main permeable zone) are in the transition between basal regolith and saprock. In Zimbabwe, water strikes may typically occur in both the regolith and bedrock and it is questionable whether there is generally sufficiently precise data to identify the relative proportions or indeed whether there is any value in assigning a distinction.

The EEC (Hydrotechnica) borehole data base uses the term regolith, mainly on the basis of a colour change from buff or orange (regolith) to shades of grey, pink or green (bedrock). The Japanese drilling records subdivide the weathered overburden into very weathered, weathered and slightly weathered. For the BGS data base, the EEC category is retained and the two former groups in the Japanese subdivisions are incorporated into the regolith. For the main government records with boreholes drilled by various private contractors, lithological subdivisions are minimal; the regolith has therefore been taken as the base of the cased/screened sections on the assumption that these were set opposite collapsing formations.

Other than core drilling or geophysical logging (9), the BGS studies suggest that the best method to differentiate the basement aquifer profile is a combination of samples and rate of penetration logs. There is generally a rapid passage from saprolite to saprock in the Younger Granites and a more transitional passage into migmatite or banded gneisses. The likelihood is that all the standard classifications, other than the careful analysis referred to above, are likely to overestimate the depth of the regolith.

The results of the various statistical analyses and the test drilling programmes would suggest that there is no good reason to differentiate these two aquifer types in the Masvingo Project Area but to emphasise the essential combination of regolith and bedrock components to provide sustained yields and to attempt to assess the optimum or limiting combinations and controls.

In the BGS drilling programme, out of 17 sites drilled in 5 study areas, only 4 encountered the first main water strike within the regolith and only 2 of the 4 had the greater part of the final yield derived from the regolith horizon (Table 11.13) and Figures 11.10 and 11.11.

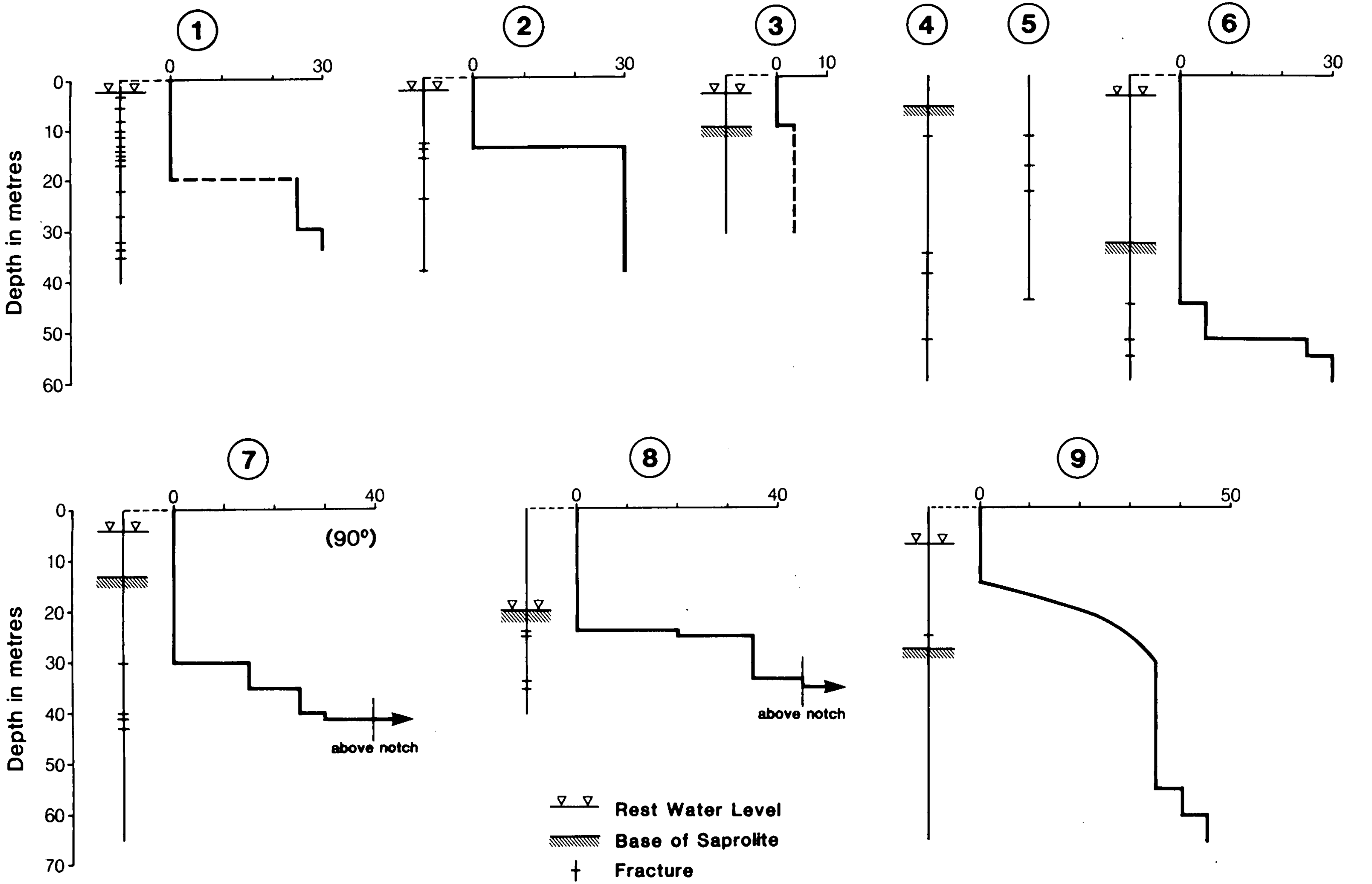


Figure 11.10 **Drilling Discharge in mm over V Notch (45° or 90°, when shown)**
Data for the BGS Drilling Programme - 1/2 Nanwi, 3/4/5 Nemarundwe, 6 Mhatiwa, 7 Zimuto B.S., 8 Zimuto Siding, 9 Chibi.

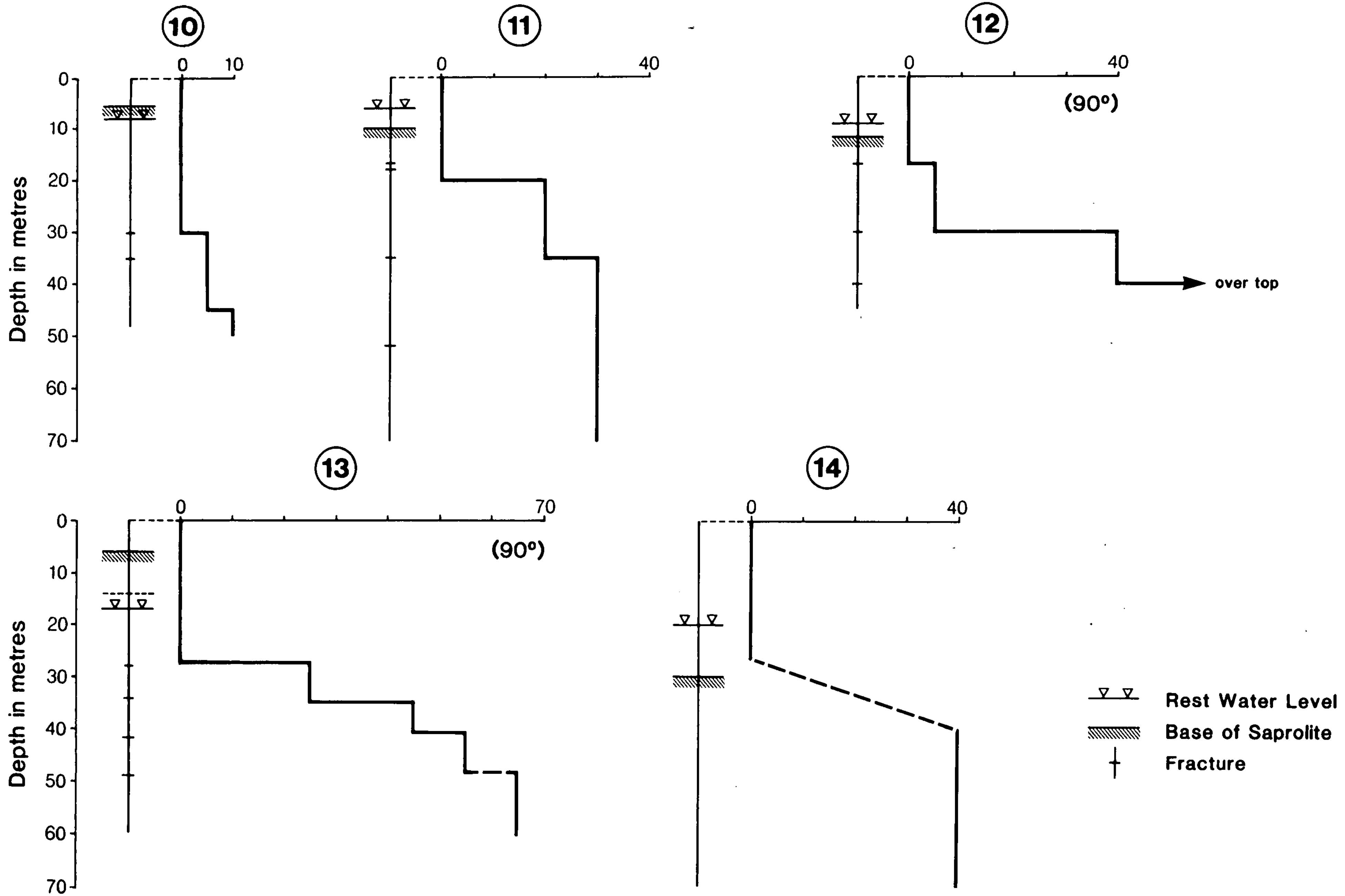


Figure 11.11 **Drilling Discharge in mm over V Notch (45° or 90°, when shown)**
Data from BGS Drilling Programme - 10 Mhatiwa Inclined, 11 Mhatiwa V., 12 Rungai, 13 Chikofa, 14 Sarahuru.

Figure 11.12 Hydrogeological units reproduced from Hindsons map (undated) for area of the Masvingo Project Study.

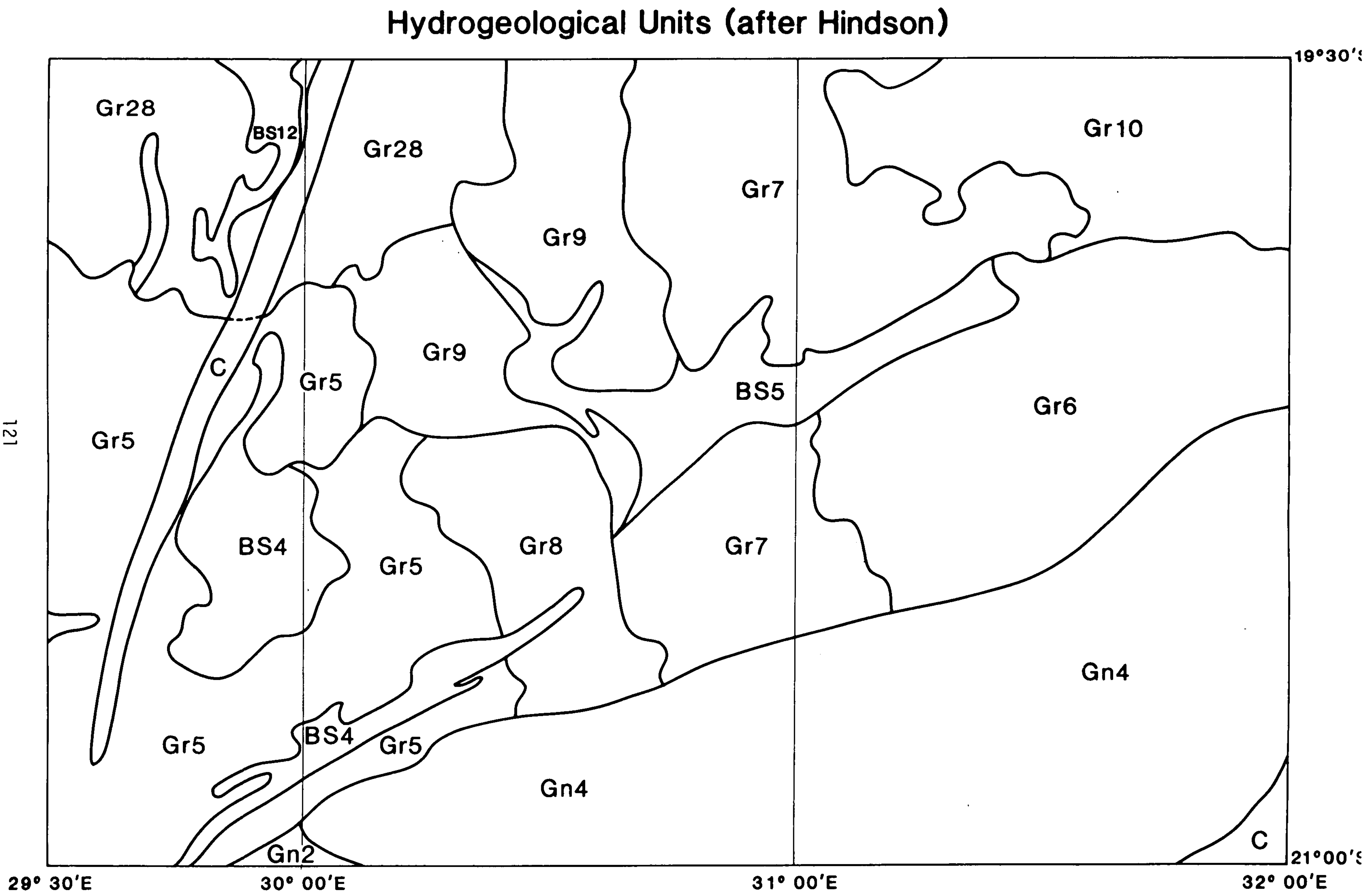


Table 11.13 **Borehole Yield and Regolith Thicknesses in BGS Drill Sites**

DRILL SITE	REGOLITH THICKNESS (m)	RWL (mbg)	FIRST MAIN WATER STRIKE (m)
Nanwi	0	2	17
Nemarundwe	10-13	3	12
Matatire	33	3	45
Zimuto Blind School	13	3	30
Zimuto Siding	20	20	24
Chibi	28	7	16**
Chinambiri Valley	20	7	12**
Mhatiwa School	6	5	20
Mhatiwa North	10	6	20
Chikore Reserve	5	17	17
Chikore Valley	5	14	33
Rungai	12	10	18
Chikofa	6-14	17	23
Sarahuru	30-36	20	28*
Chikadze	2-17	9	20
Madangombe	20	18	11*
Maramba	10	15	26

* First main strike in regolith but overall main supply deeper
** Main supply in regolith

The summary statistics in Table 11.14 (i-vii) include regolith thickness and first water strike. Both these data sets show a considerable range and standard deviation but the mean median and modal values in all except Group 7 are closely comparable which might suggest that the first strike corresponded approximately with the basal regolith. However the matrix set (Table 11.15) shows a variable and generally low correlation with regolith thickness. A more informative correlation would be with the main water strike but the borehole records are inadequately documented in this respect. Some grouped figures on main water strikes and depth range correlations have been presented in a Zimbabwe Government Report by Hindson (undated) for which the figures in Table 11.16 have been obtained. Of 279 boreholes in the Masvingo Project Area, 107 (38%) have main yields from the depth range 15-30 m below ground level and 163 (58%) from below 30 m. In relation to the mean, median and modal values in the range 16-22, for the 3 geological units concerned, these figures would suggest that the main yields are predominantly obtained from within the bedrock. The areal distribution of regolith thickness will be discussed below but it may be noted here that there is commonly a considerable range of values apparent in many of the 2½ km square units which were analysed in combination to obtain the mean 20 km square blocks. This considerable local variability in regolith thickness would reinforce the opinion that there is no valid distinction in the two aquifer types.

Table 11.14 Summary Statistics of Basement Aquifers

YIELD (l/sec)

Geology	Sample No	Mean	Median	Mode	σ	Min	Max
4	425	0.94	0.5	0	1.24	0	6.7
5	617	0.78	0.38	0	1.04	0	6.7
6	523	0.99	0.51	0	1.20	0	10.0
7	84	1.39	1.09	0	1.24	0	5.1

LOG_{10} [specific capacity]

Geology	Sample No	Mean	Median	Mode	σ	Min	Max
4	228	-1.48	-1.44	-1.98	0.59	-2.92	0.26
5	309	-1.54	-1.54	-1.27	0.58	-3.27	0.20
6	258	-1.38	-1.33	-1.78	0.59	-3.25	0.37
7	33	-1.31	-1.19	-1.28	0.74	-3.02	0.925

SPECIFIC CAPACITY (l/sec/m)

Geology	Sample No	Mean	Median	Mode	σ	Min	Max
4	228	0.086	0.036	0.021	0.20	0.001	1.8
5	309	0.072	0.029	0.054	0.14	0.0005	1.6
6	258	-	0.046	0.017	-	0.0005	2.3
7	33	-	0.065	0.052	-	0.0009	8.4

REST WATER LEVEL (m bgl)

Geology	Sample No	Mean	Median	Mode	σ	Min	Max
4	336	12.7	11.7	12	7.9	0	42.7
5	467	8	6	5	6.2	0.6	48
6	392	12	10	6	7.7	-0.7	45
7	60	14.5	12	6	10.4	0	43

REGOLITH THICKNESS (m)

Geology	Sample No	Mean	Median	Mode	σ	Min	Max
4	258	21.8	19.3	17.6	13.2	1	64
5	411	20.9	18	18	12.8	0.9	60
6	335	20.6	19	15.9	12.5	0.7	60
7	42	24.3	23	23	14.3	3	70

FIRST WATER (m bgl)

Geology	Sample No	Mean	Median	Mode	σ	Min	Max
4	221	17.9	18	18	8.0	0	48
5	228	15.1	14	15	9.0	1	90
6	240	17.9	16	15	8.4	3	56
7	37	18.2	18	9	9.3	3	38

Table 11.14 (Cont'd)

Yield categories of dry/low yielding boreholes: numbers and percentages.

Geology	Sample No	0		0 ≤ 0.1		0 ≤ 0.2	
		No.	%	No.	%	No.	%
4	425	66	16	91	21	132	31
5	618	94	15	144	23	208	34
6	524	79	15	100	19	126	24
7	84	13	16	16	19	18	21

Table 11.15 Matrix Correlations

MATRIX: GEOLOGY 5 SAMPLES 329

	Log[sp.cap]	Sp.cap	Yield	Well Depth	Reg. Th.	RWL	SWD	Sat. Reg.	FW
Log[sp.cap]*	1.00	.68	.44	-.37	.04	-.05	-.35	.05	-.19
Sp.cap.*	.68	1.00	.19	-.25	-.05	-.02	-.25	-.04	-.14
Yield	.44	.19	1.00	.14	-.005	.04	.12	-.02	.14
Well depth	-.37	-.25	.14	1.00	.16	.27	.87	.04	.21
Regolith Th.	.04	-.05	-.005	.16	1.00	-.05	.18	.92	-.13
Rest WL	-.05	-.02	.04	.27	-.05	1.00	-.23	-.44	.40
SWD	-.35	-.25	.12	.87	.18	-.23	1.00	.26	.008
Sat. Reg.	.05	-.04	-.02	-.04	.92	-.44	.26	1.00	-.28
FW	-.19	-.14	.14	.21	-.13	.40	.008	-.28	1.00

* 256 samples

MATRIX: GEOLOGY 6 SAMPLES 266

	Log[sp.cap]	Sp.cap	Yield	Well Depth	Reg. Th.	RWL	SWD	Sat. Reg.	FW
Log_{10}[sp.cap]*	1.00	.67	.41	-.31	.07	.08	-.39	.02	-.24
Sp.cap.*	.67	1.00	.11	-.18	.06	.05	-.22	-.03	-.16
Yield	.41	.11	1.00	-.07	-.10	.12	.03	-.03	-.27
Well depth	-.31	-.18	-.07	1.00	.23	.41	.73	-.005	.47
Regolith Th.	.06	-.06	-.10	.23	1.00	.24	.06	.84	.32
Rest WL	.08	.05	-.12	.41	.24	1.00	-.33	-.33	.76
SWD	-.39	-.22	-.02	.73	.06	-.33	1.00	.24	-.12
Sat. Reg.	.02	.03	-.03	-.005	.84	-.32	.24	1.00	-.26
FW^+	-.24	-.16	-.27	.47	.32	.76	-.12	-.26	1.00

* 191 samples $^+$ 152 samples

MATRIX: GEOLOGY 7 SAMPLES 28

	Log[sp.cap]	Sp.cap	Yield	Well Depth	Reg. Th.	RWL	SWD	Sat. Reg.	FW
Log_{10}[sp.cap]*	1.00	.65	.63	-.07	.11	-.07	.002	.12	-.49
Sp.cap.*	.65	1.00	.20	.15	.21	-.26	.32	.30	-.40
Yield	.63	.20	1.00	.10	.10	-.42	.37	.34	-.48
Well depth	-.07	.15	.10	1.00	.27	-.001	.69	.20	.06
Regolith Th.	.11	.20	.10	.27	1.00	-.07	.24	.77	-.14
Rest WL	-.07	-.26	-.43	-.001	-.07	1.00	-.72	-.69	-.58
SWD	.002	.32	.38	.69	.24	-.72	1.00	.63	-.37
Sat. Reg.	.12	.30	.34	.20	.77	-.69	.63	1.00	-.47
FW	-.49	.40	-.48	.06	-.14	.58	-.37	-.47	1.00

* 22 samples

MATRIX: GEOLOGY 4 SAMPLES 174

	Log[sp.cap]	Sp.cap	Yield	Well Depth	Reg. Th.	RWL	SWD	Sat. Reg.	FW
Log[sp.cap]	1.00		.47	-.33	.07	-.07	-.27	.09	
Sp.cap.									
Yield	.47		1.00	.18	-.15	-.02	.18	-.12	
Well depth	-.33		.18	1.00	.16	29	.76	.005	
Regolith Th.	.07		-.15	.16	1.00	.07	.10	.87	
Rest WL	-.07		-.02	.29	.07	1.00	-.40	-.42	
SWD	-.27		.18	.76	.10	-.40	1.00	.28	
Sat. Reg.	.09		-.12	.005	.87	-.42	.29	1.00	
FW									

Table 11.16 **Main Water Strikes and Depth Data from Zimbabwe Government Records (Hindson, undated - see Figure 11.12)**

UNIT	TOTAL NUMBERS OF BOREHOLES	NUMBERS IN EACH DEPTH CLASS (m) <15	15-30	>30	APPROXIMATE BEDROCK DEPTH (m)* Mean	Median	Mode
1. Older Gneiss Complex							
Gr 5	55	1	28	26	21	18	16
Gr 9	37	1	16	20			
Gr 8	17	0	6	11			
Gr 28	40	2	11	27			
2. Younger Granite							
Gr 7	23	1	9	13	21	18	18
Gr 6	45	3	19	23			
3. Mobile Belt Gneisses							
Gn 4	62	1	18	43	22	19	18
Totals	**279**	**9**	**107**	**163**			

(*) From summarised statistics, this report

11.5.2.2 *Summary Statistics*

These are given in Tables 11.14 and 11.15 and additional data in various figures and plots.

Of the parameters analysed, specific capacity shows a log normal distribution (Figure 11.13) whereas the others, yield (Figure 11.14), rest water level, regolith thickness and first water strike exhibit normal distributions, sometimes skewed to the left of the mean. The areal plots have been constructed on 2.5, 5, 10 and 20 km square units, depending on the density of the date points. The final plots as shown in the Figures with this report are on a 1:1M scale and in 20 km square units. A transparency of the geological map on the same scale can be overlain and the more obvious patterns and correlations observed.

Yields and boreholes failure rate: The mean, median and modal values are comparable for the geological units 4 and 6, somewhat lower in 5 and significantly higher in 7. A success rate in Zimbabwe is officially regarded as a yield ≥0.25 litres per sec although many boreholes with test yields lower than this are equipped for production. For comparative purposes, the percentage categories of yields from 0 to ≤0.2 are shown in Table 11.14 (vii). Dry holes have a comparable percentage in all four groups but with the failure rate decreasing in the higher yield categories in groups 6 and 7. These comparisons and essential comparability are apparent in the frequency and probability plots (Figures 11.15 and 11.16).

Figure 11.17 shows a distribution plot of percentage of dry to low yielding (≤0.2 l/sec), which attain values in excess of 50%. The highest failure rates occur in a belt trending WSW-ENE with intermediate values to the SE and lower values to the NW. A possible correlation of the lower failure rates with higher rainfall is a possibility (Figure 11.18). There is also a possible correlation with areas of lower relief.

Rest water levels: These show a normal distribution with mean, median and modal values comparable and in the general range of 6-12 mbgl. Despite the small range of variations there is a correspondence apparent in the distribution plot (Figure 11.19) with the rainfall map. A correlation with relief is also to be expected.

Regolith thickness (Figure 11.20): Normal distribution with comparable values of mean, median and mode in a range from 18-23 m. The standard deviation values are substantial (12-14 m) and there is considerable variability on a local scale (2½ km grid units) which can most likely be related to structural rather than lithological features. The regolith is generally supposed to be thinner on the younger granites (geological unit 5) which is not apparent in the statistical summary but possibly more evident on the areal plot. The belt of lower regolith thickness which extends diagonally from SW-NE also corresponds approximately with the area of highest borehole failure rate. There is no apparent correspondence with rainfall.

Specific capacity: Log normal distribution and fairly comparable values of specific capacity in the three main quartz and gneiss groups. The modal value of the Younger Granites (group 5) is appreciably higher than the other two but is otherwise comparable.

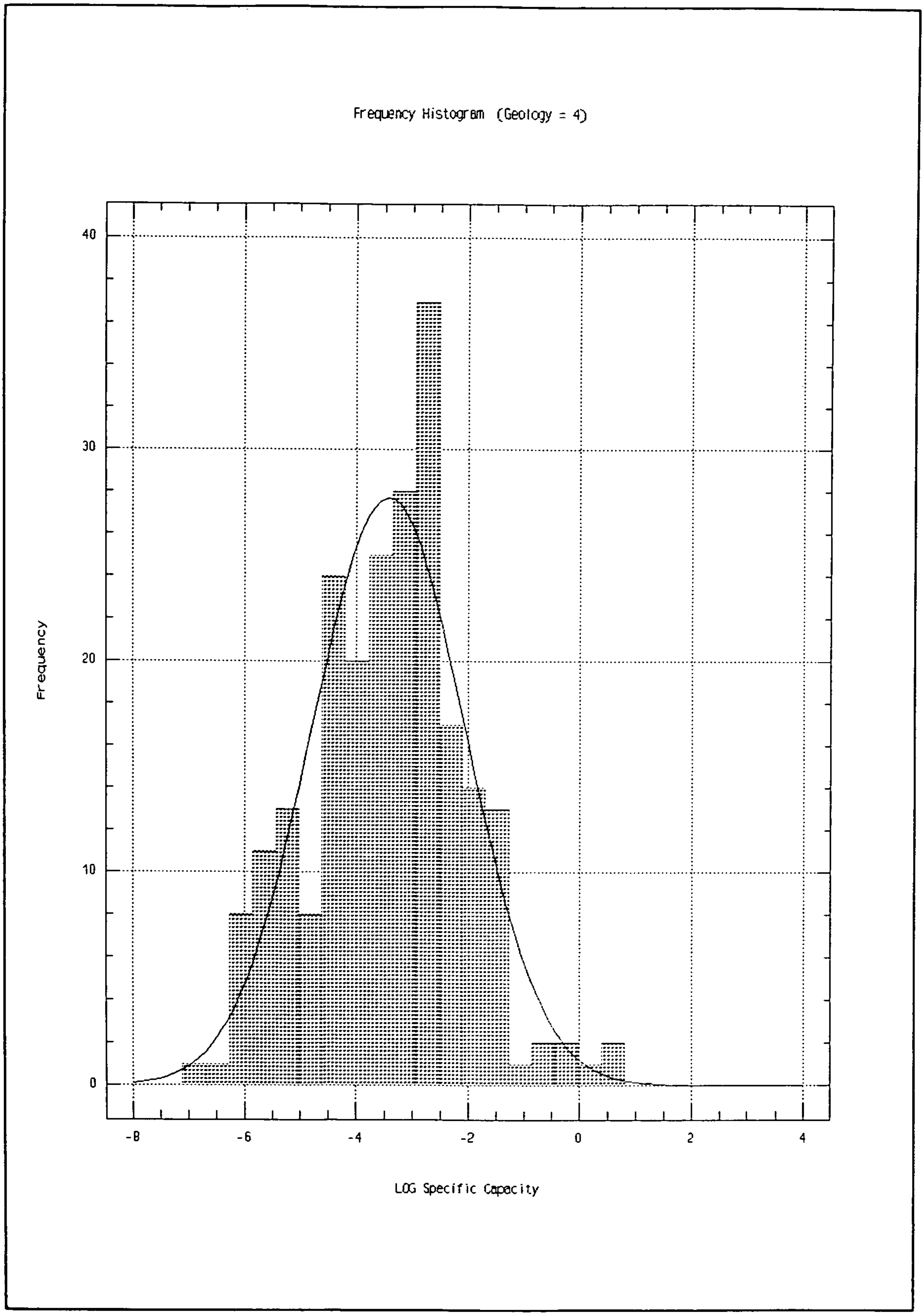


Figure 11.13 Specific capacity data for mobile belt gneisses.

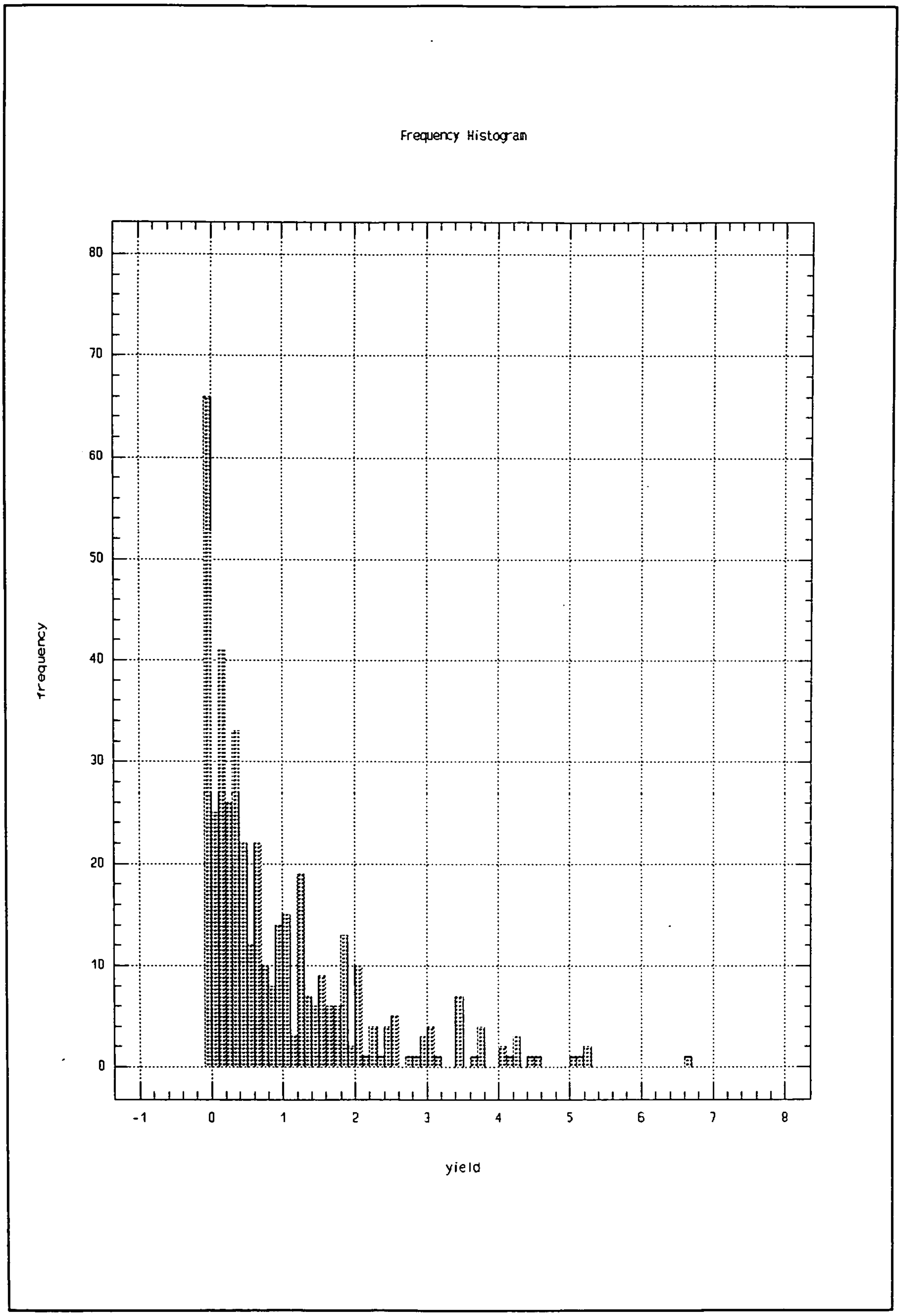
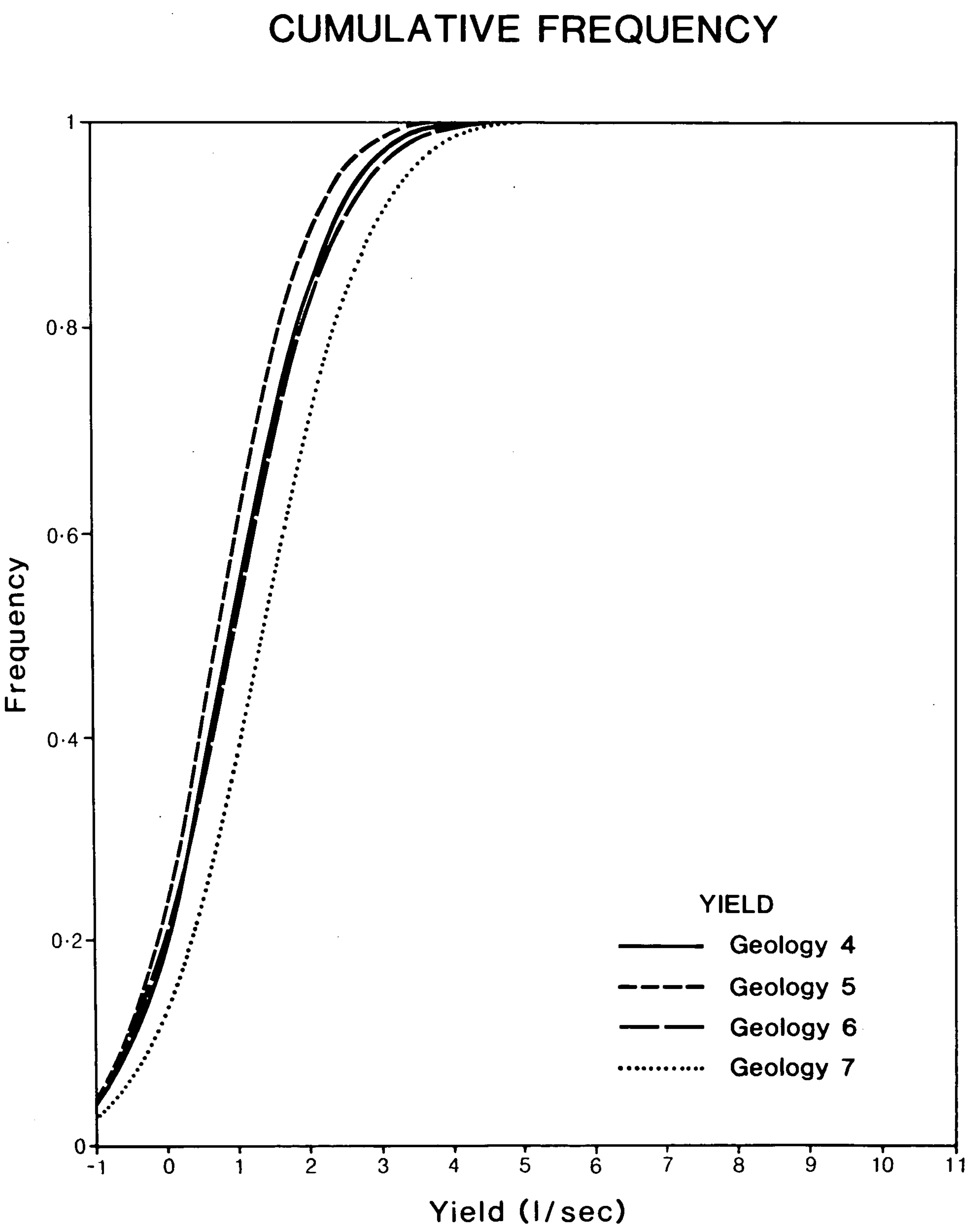


Figure 11.14 Yield data for mobile belt gneisses.



CUMULATIVE FREQUENCY
Frequency
0
0·2
0·4
0·6
0·8
1
-1
0
1
2
3
4
5
6
7
8
9
10
11
Yield (l/sec)
YIELD
Geology 4
Geology 5
Geology 6
Geology 7

Figure 11.15

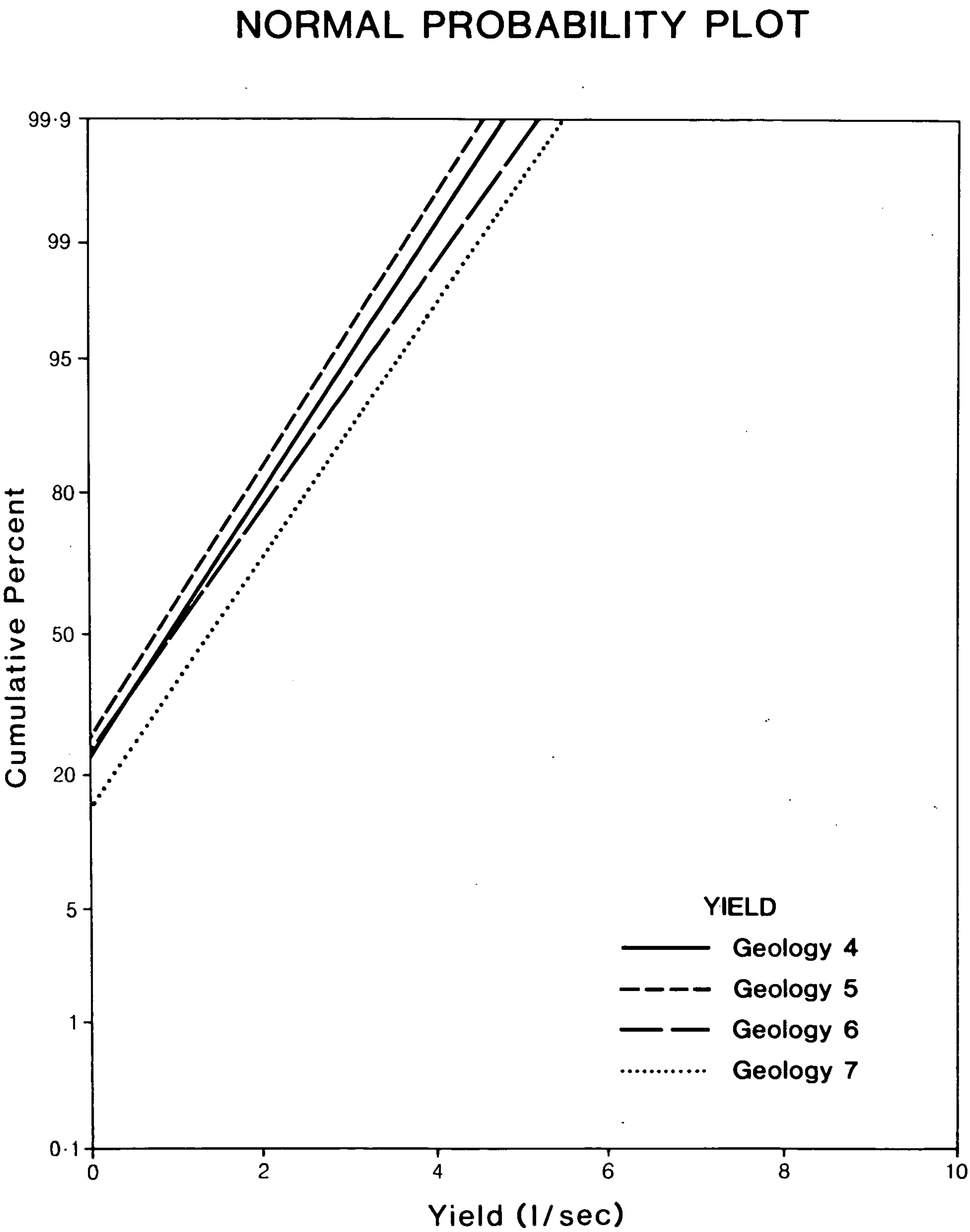

NORMAL PROBABILITY PLOT
99·9
99
95
80
50
20
5
1
0·1
Cumulative Percent
0
2
4
6
8
10
Yield (l/sec)
YIELD
Geology 4
Geology 5
Geology 6
Geology 7

Figure 11.16

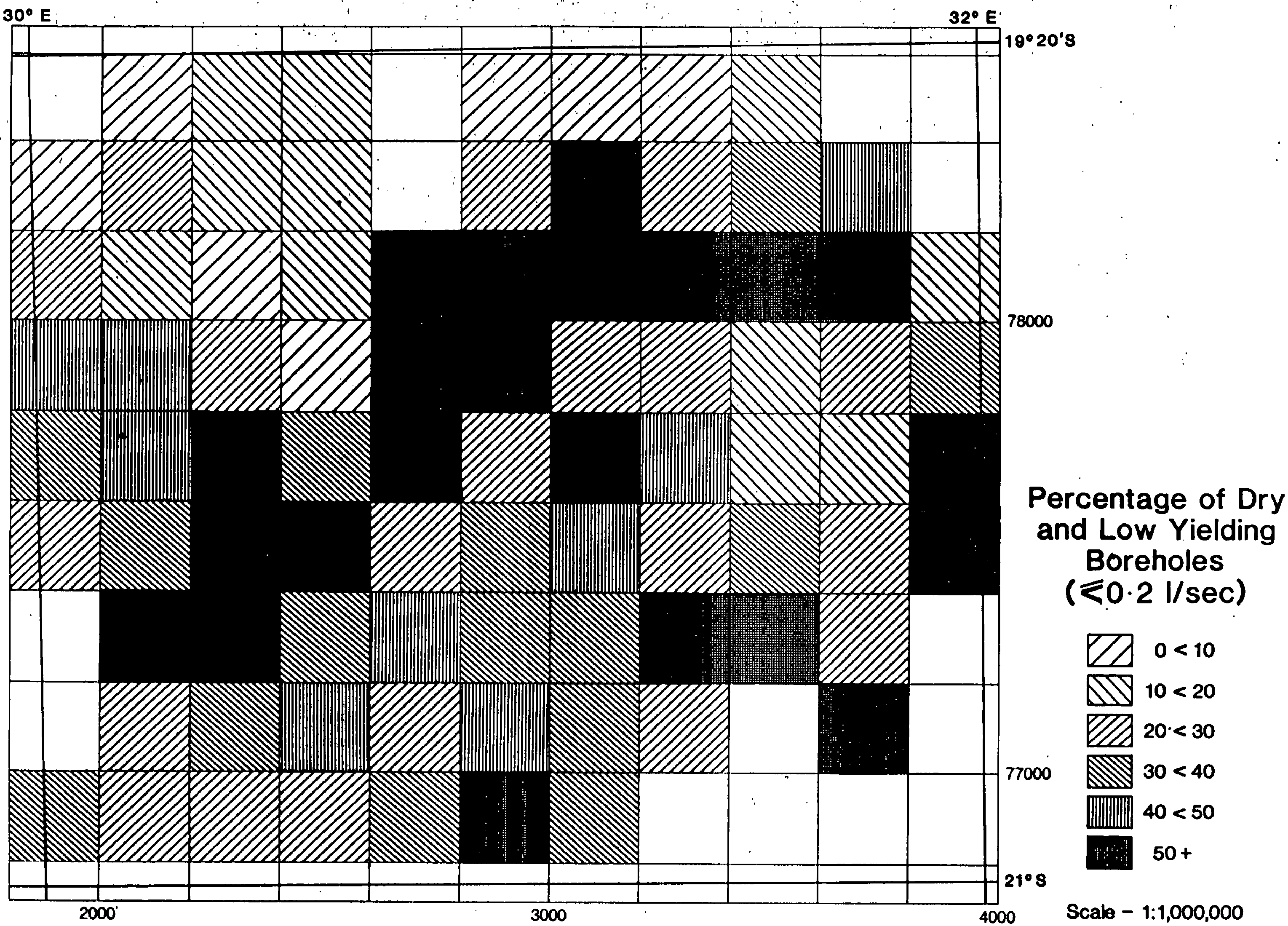
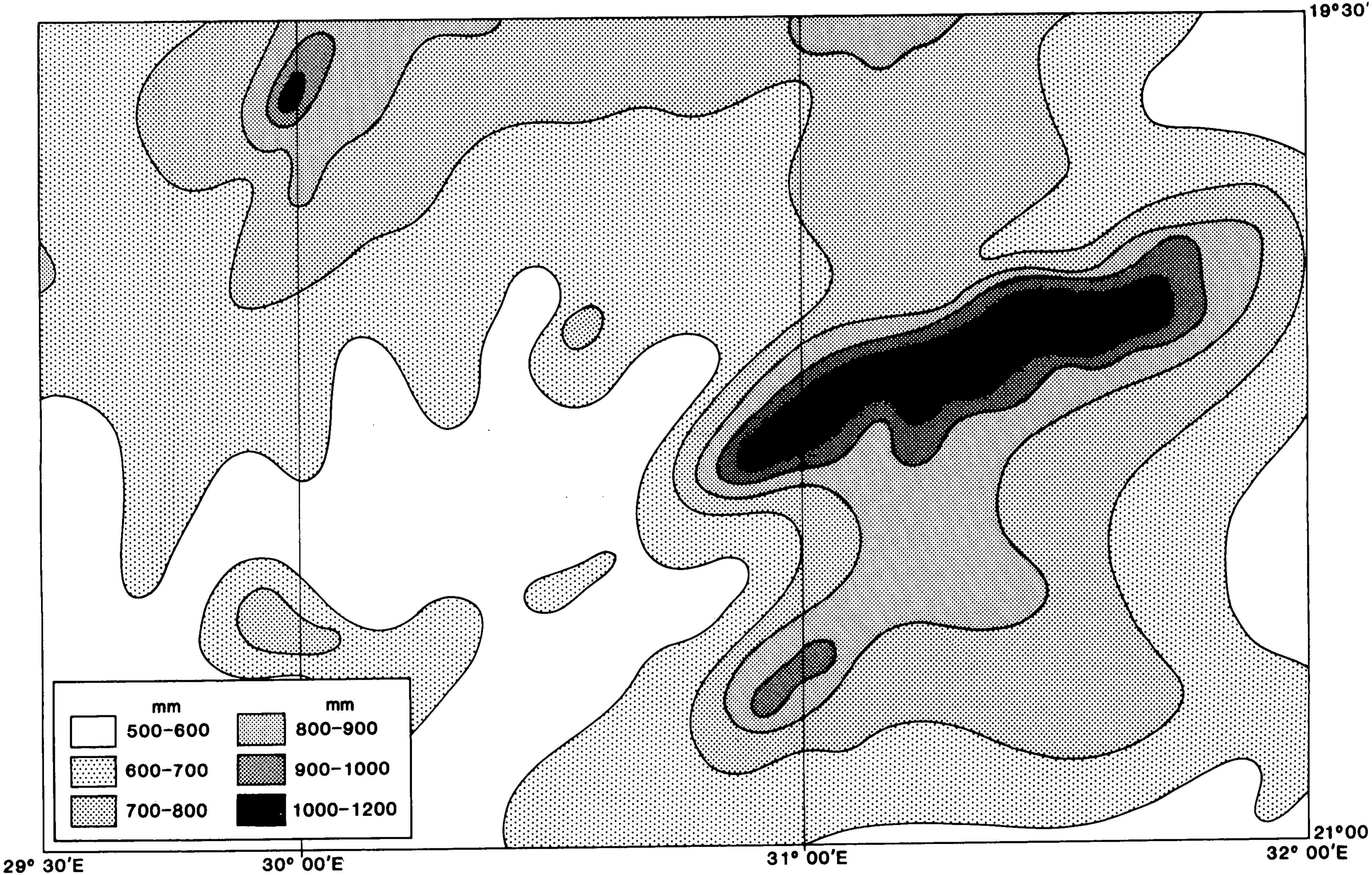

30° E
32° E
19°20'S
78000
77000
21°S
2000
3000
4000
Percentage of Dry and Low Yielding Boreholes (⩽0·2 l/sec)
0 < 10
10 < 20
20 < 30
30 < 40
40 < 50
50 +
Scale – 1:1,000,000

Figure 11.17

Figure 11.18

Mean Annual Rainfall



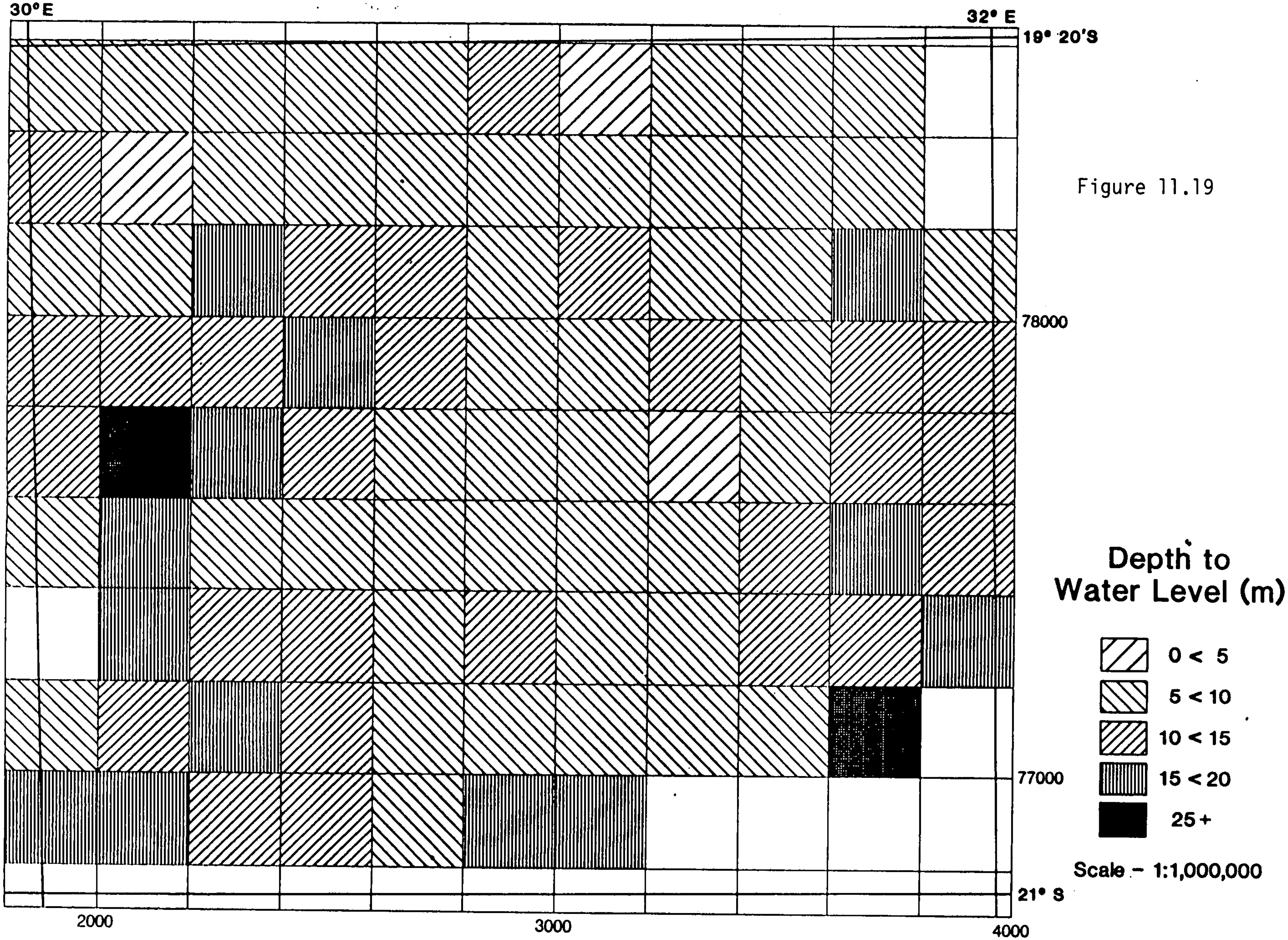
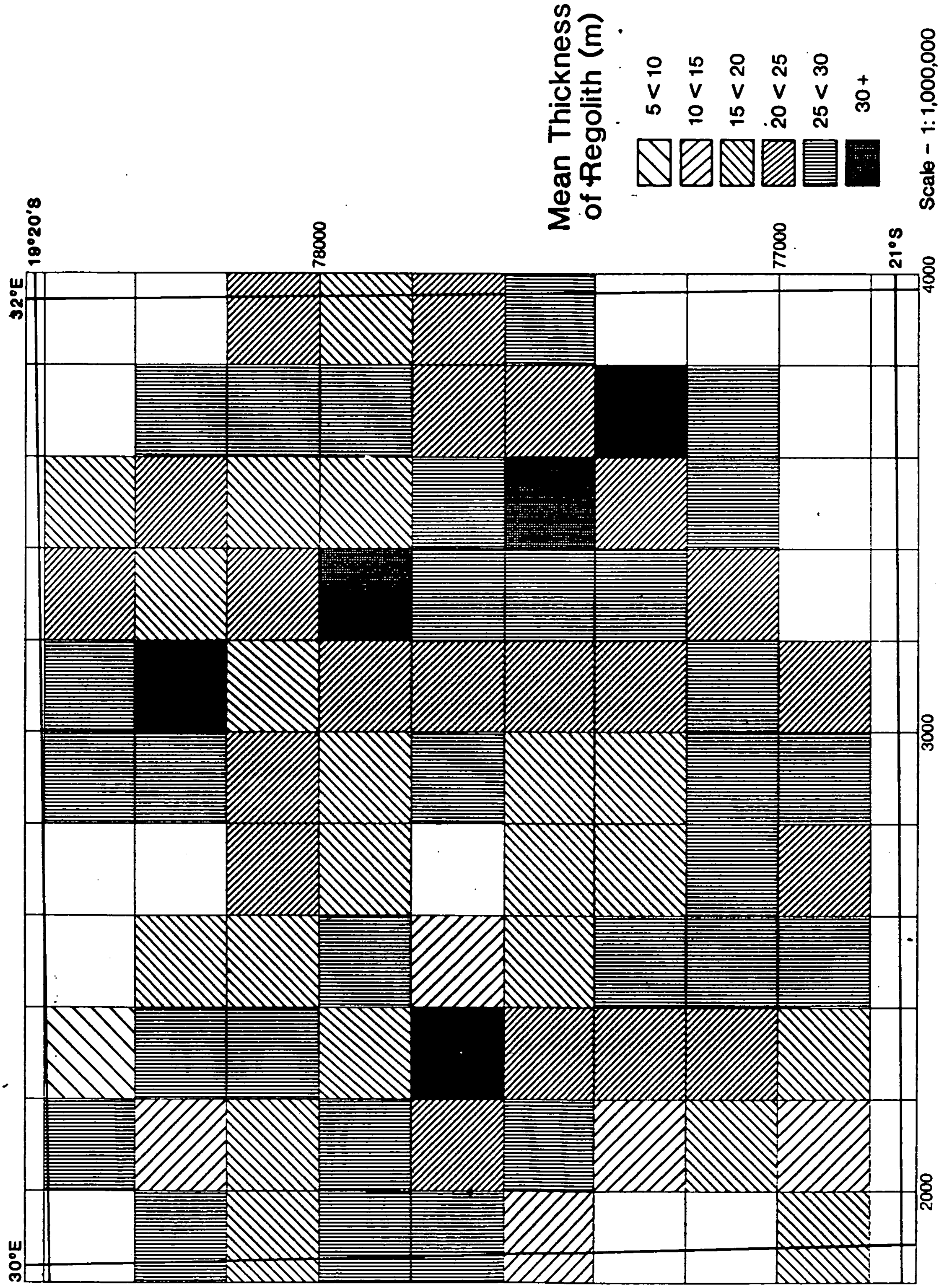

30°E
32° E
19° 20'S
78000
77000
21° S
2000
3000
4000
Depth to
Water Level (m)
0 < 5
5 < 10
10 < 15
15 < 20
25 +
Scale - 1:1,000,000

Figure 11.19



Mean Thickness of Regolith (m)
5 < 10
10 < 15
15 < 20
20 < 25
25 < 30
30 +
Scale - 1: 1,000,000
19°20'S
21°S
32°E
30°E
78000
77000
4000
3000
2000

Figure 11.20

Regression analyses:

(i) Yield and specific capacity. These correlate fairly closely (Figure 11.21) which makes it feasible to use either parameter for matrix correlations (other than 'dry' boreholes).

(ii) The plots of incremental yield (yield/m saturated aquifer) against depth is commonly used to categorise basement aquifers and show a negative correlation. No such correlation was found in the data sets for the Masvingo Project aquifers (Figure 11.22).

Matrix correlations: These are shown in Table 11.15 and the following points may be noted.

(i) Log specific capacity is negatively correlated with borehole depth, saturated depth and first water and the correlation is apparent in the three main geological units (4-6). Its absence in unit 7 can almost certainly be attributed to the small number of samples. The correlation appears reasonable on the assumption that drilling is extended when yields are low in the hope of striking additional water. The true relationship must be of dual type, positive at shallow levels and becoming negative later.

(ii) There is no apparent correlation of log specific capacity with regolith thickness, rest water level or saturated regolith, despite the obvious control which these parameters must exercise. This control must be masked by other factors. A correlation with resistivity layering in combination with regolith and structural associations (i.e. distance to lineament) may be anticipated but the essential data to assess this possibility are not at hand.

12. EXPLORATION AND DEVELOPMENT

Development considerations are restricted to boreholes since wells/collector wells have already been discussed in detail in the Final Collector Well Report (Wright et al., 1988).

Studies on recharge have demonstrated an order of magnitude which is considerably greater than current development planning and methodology is likely to exploit. In the central plateau region of Malawi, recharge appears to be in the range of 10-16% of mean annual rainfall. In southern Zimbabwe, present estimates are lower, in the range of 2-12% of mean annual rainfall although future modifications are more likely to upgrade than to reduce this estimate. Further studies on groundwater discharge calculations by imagery analysis are recommended and also a more careful sampling programme for chloride determination on rainfall, river baseflows and seepage zones. Integrated modelling studies would obviously be appropriate but more difficult and costly to set up.

Borehole exploration and development methodology should continue to maintain a flexible approach which takes account of the significance of high local variability. Regional models (altitude, rainfall, bedrock type, terrain and erosion surface) are able at present only to provide general guidelines but which may be able to identify where the local surveys require to be more detailed. Borehole depth models developed for local conditions and areas should assist in optimising depths of drilling.

Figure 11.21 Plot of specific capacity against yield for mobile belt gneisses.

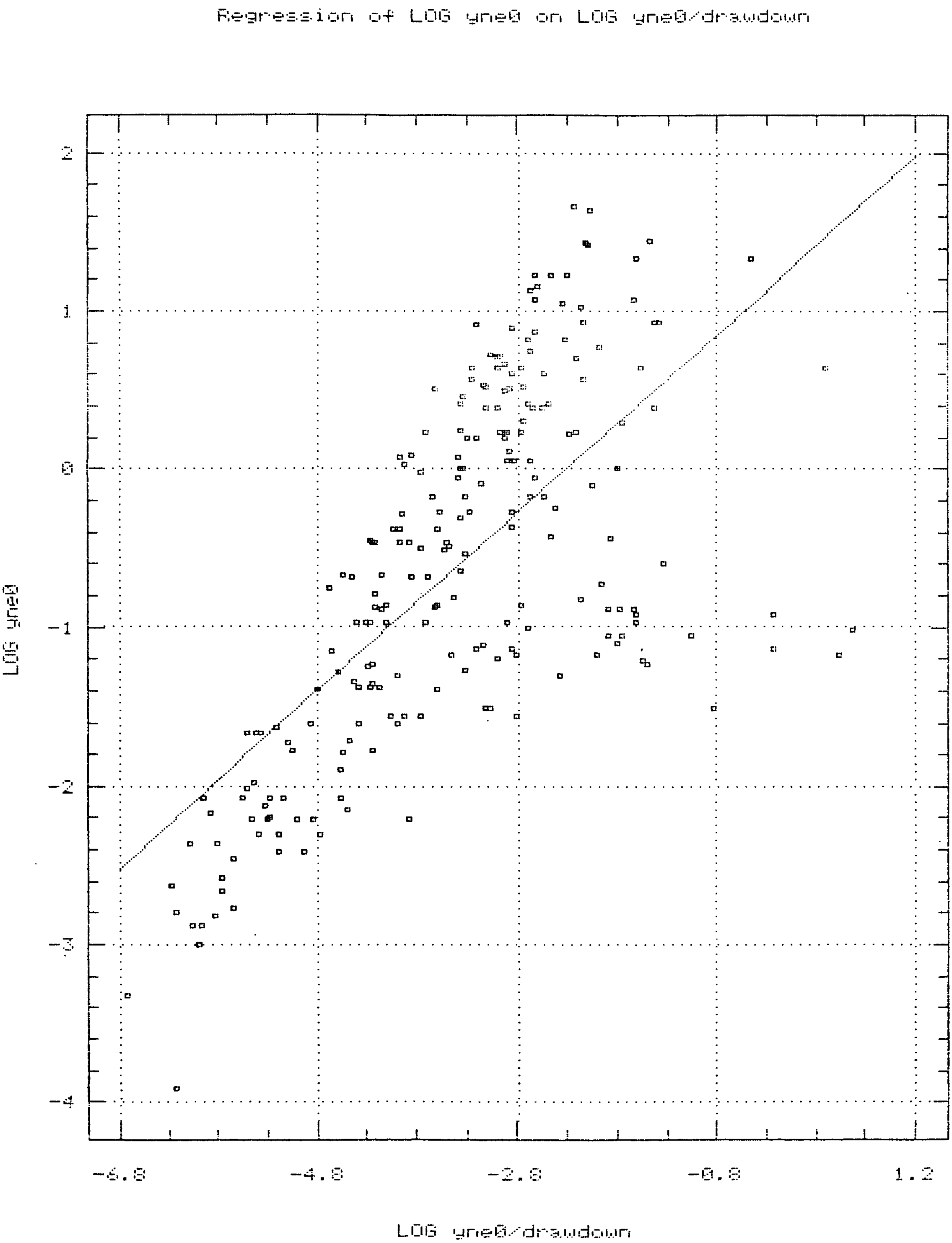
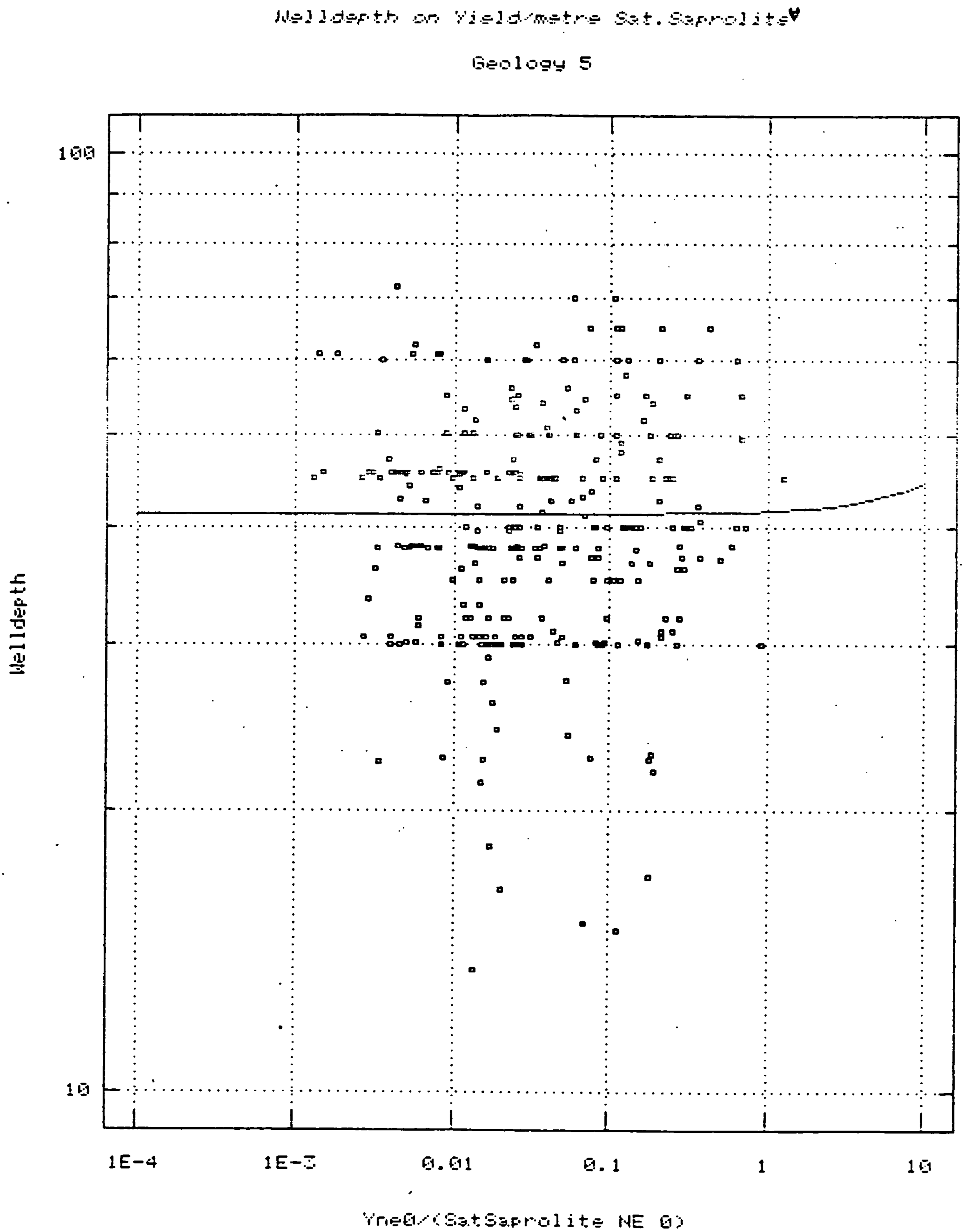


Figure 11.22 Incremental yield with depth for younger granites.



12.1 Malawi

The basement aquifer in Malawi has its main development in the weathered overburden (regolith/saprock). Main yields in boreholes completed in this formation are likely to be derived either from rapid throughflow channels in the saprolite which, since they tend to be steeply dipping, are more difficult to intersect by vertical boreholes, and, more generally, from the high permeability zone in the basal saprolite and saprock. The former features cannot be identified by existing geophysical survey methods and appear to bear no general correlation to overburden thickness or bedrock lineament occurrence. Identification of the latter zone and a possible correlation of the thickness and hydraulic properties with geophysical parameters may be feasible although the zone appears to be generally too thin to be resolved as such. More detailed drilling logs which identify the location of water yields more precisely (air drilling yield tests, more frequent bailer tests) would assist in making these correlations.

Higher yielding boreholes will require to tap fracture zones in the bedrock and there are difficulties in identifying such zones below a thick cover of regolith. The feasibility of using dambo features in this context needs to be evaluated.

Local water quality constraints exist, notably for example the high sulphate content of groundwater in the Dowa region. Since a regional flow system appears to exist in the aquifer of the weathered overburden, the identification of the source of such occurrences should be feasible from the chemistry of river baseflow and seepage zones. Collector wells at higher elevations would probably be of value in these conditions since water quality is likely to deteriorate with depth, although will obviously require deeper construction than at lower elevations.

12.2 Zimbabwe

The basement aquifer in southern Zimbabwe and possibly over much of the country obtains its main yields from either the basal weathered zone and/or the fractured bedrock. There is not, in general, sufficient evidence in the existing data to demonstrate precise relative proportions but in southern Zimbabwe, it would appear that the fractured bedrock provides the greater component. Boreholes are typically cased through the collapsing section, largely coincident perhaps with regolith, and open hole or slotted casing below. In only the EEC project has more effort been made to screen regolith and to use a gravel pack.

The degree of weathering in the regolith of southern Zimbabwe is relatively little advanced with only minor amounts of secondary clay minerals. Effective porosity seems likely to be high and with a significant thickness of saturated regolith, there should not be a major constraint of available storage on boreholes yields. The occurrence of dry and low yielding boreholes with a wide range of values of both total regolith and saturated regolith (Figures 12.1 and 12.2) is suggestive of a critical control by the more permeable sections, either in the basal overburden (saprolite-saprock transition zone) and/or fractured bedrock.

The results of the experimental drilling studies have demonstrated the feasibility of obtaining adequate yields from boreholes at sites with variable regolith down to negligible or zero values, provided the borehole

Figure 12.1 Yield versus regolith thickness for Younger Granites group.

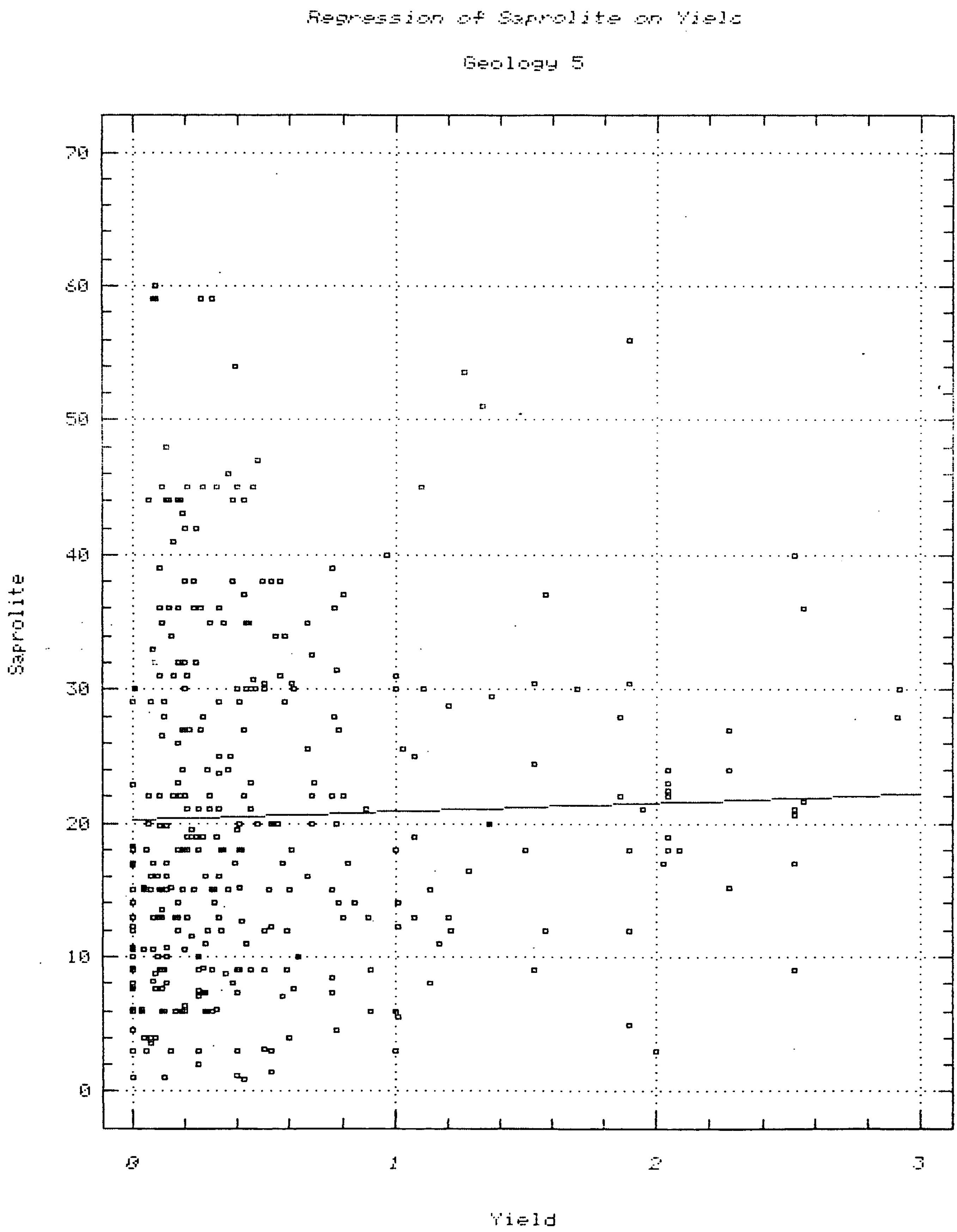
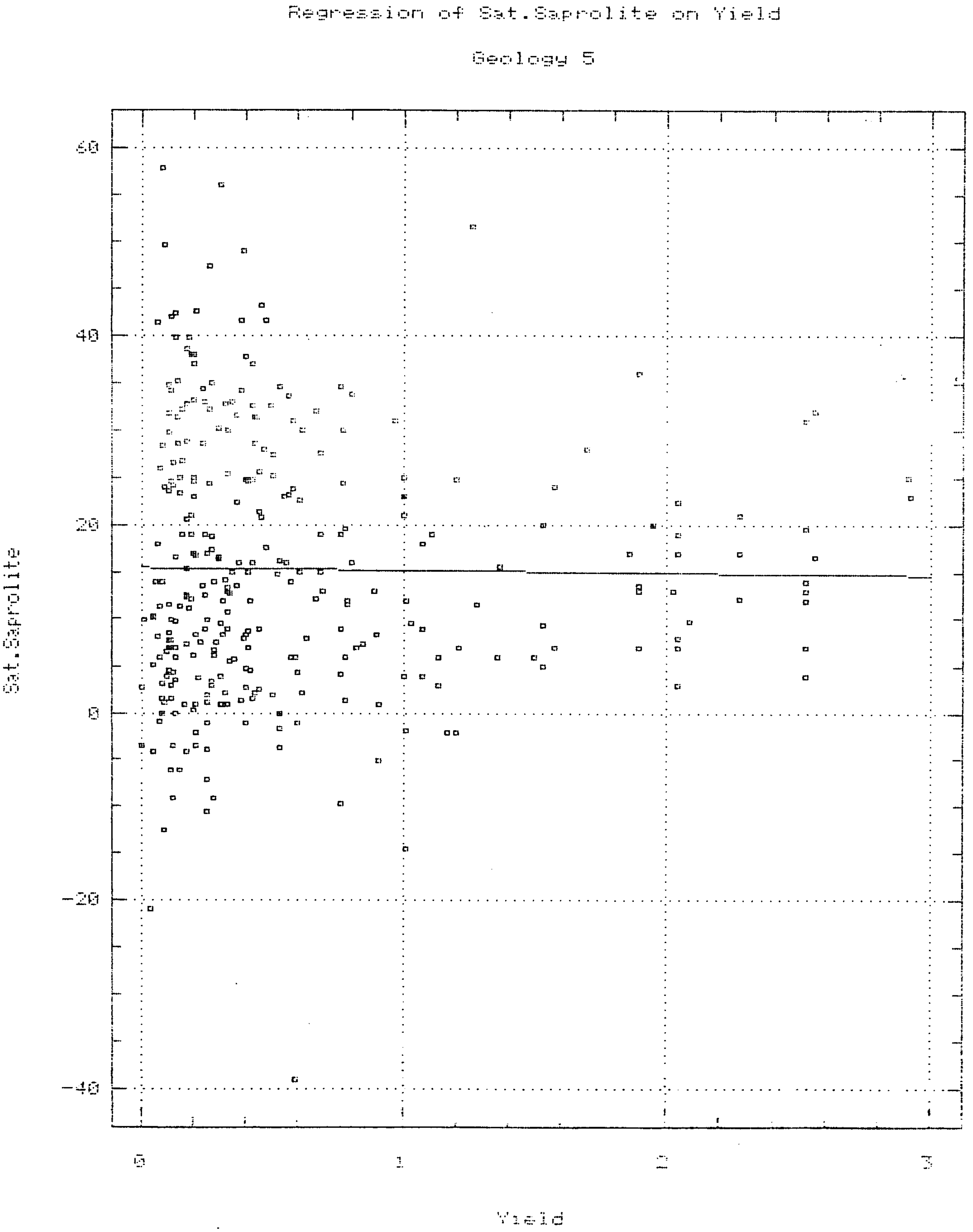


Figure 12.2 Yield versus saturated regolith thickness for younger granites group.



intersects a fracture zone of significant transmissivity. The siting becomes increasingly critical with decreasing width and/or the dip of the fracture zone since the borehole is required to intersect this below the water table. Every effort should therefore be made to establish the direction and if possible the angle of dip. Fracturing is likely to extend to greater depths in the main fracture zone than in adjacent less fractured rock, and the dip of the zone might well explain the common occurrence, referred to by Hindson in an unpublished Zimbabwe Government Report, of boreholes which were drilled through thick sections of massive, fresh and unfractured rock before reaching a productive fissure.

Radon gas surveys have shown a close degree of correlation of fracture zone occurrence identified by other geophysical, mainly EM, surveys. Radon anomalies should firstly serve to confirm the existence of a transmissive fracture zone and the scale of the anomaly might correlate with its magnitude. The offset between the radon and EM anomaly probably indicates a dipping feature although precise correlation have yet to be obtained and other features such as surface clays and recent surface runoff can affect the results. The majority of the unproductive experimental sites showed neither an EM nor a radon anomaly. Radon might also assist in detecting productive fracture systems adjacent to dykes which tend to mask the usual fracture response characteristics. In the Masvingo Project area, boreholes adjacent to dykes have had a relatively low success frequency.

Rest water levels are difficult to identify by geophysical survey, particularly where more clayey regolith occurs. The precise location becomes more important where the regolith is thin or at sites of high relative elevation away from valleys. Dry holes at peripheral bornhardt sites with thick regolith are probably a consequence of the water levels occurring below the saprock or fresh bedrock surface. Water level maps can be useful in these circumstances to allow extrapolation or interpolation.

Water quality constraints are fairly rare in the basement aquifers of Zimbabwe but appear more common in gneissic rocks, possibly because the transitional features in the basal weathered zone result in a more compartmentalised occurrence of the aquifer.

The present methodology has a moderate degree of success in borehole siting but the failure rate is sufficiently high to justify additional studies or modifications to methodology. The success rate could almost certainly be improved by more detailed and extended surveys, as has been demonstrated by the BGS experimental drilling results. Regional statistical models, as and when these are developed, may help to provide general guidelines to development, in particular to identify difficult areas where more detailed studies are needed for an improved success rate. Some correlations are to be expected with factors such as rainfall, runoff, groundwater chloride, bedrock type, relief/altitude, etc. but present evidence suggests that the relationship is likely to be complex with many factors interacting.

Detailed remote sensing and geophysical/geochemical surveys are likely to be justified in most cases but studies leading to suitable models are needed to assist these surveys and clarify the controls of permeability and storage and the relative influences of saprolite, saprock and fractured bedrock. A major dependency appears to exist in southern Zimbabwe on main inflows from the fractured bedrock below the regolith. Where fracture occurrence in the fresh bedrock is unlikely, deep wells/collector wells could be a viable alternative for development of the weathered zone. Borehole data should therefore routinely identify the locations of main inflows, either via drilling yield records or by subsequent flow logging.

12.3 <u>Optimum Drilling Depths</u>

The emphasis so far in the discussion of exploration and development has been on aspects of optimum siting of boreholes. Optimum drilling depths are determined by economic factors in relation to success rates and yields. Expressed in alternative ways, optimum drilling depths can be either:-

(i) The minimum depths at which an adequate yield can be obtained and with a specific capacity which keeps pumping and maintenance costs to a minimum.

(ii) The depths at which unsuccessful boreholes should be abandoned so as to give the lowest average cost per successful borehole. Capital and maintenance costs need also to be included in the analysis.

Pumping costs (capital and recurrent) for motorised pumps can readily be related to specific capacity, i.e. drawdown. Maintenance factors in the same context are not well understood although it is believed that handpumps are significantly affected when required to operate continuously at maximum heads.

A major control to yields is the permeability of the transitional zone from basal saprolite to saprock and of the productive fracture systems in the bedrock. For the development of regolith aquifers, it is generally necessary to drill through the regolith and into the saprock. Borehole completion in the regolith only has the advantage of the capability in use of lightweight drilling rigs or cable tool rigs (which are economic in use but excessively slow in harder rocks). Some flexibility is possible by selecting sites with optimum thickness of regolith and if rapid throughflow channels are intersected (e.g. exsolution piping or quartz veins), drilling may occasionally be discontinued above the bedrock surface. These drilling depths can be targeted by geophysical survey methods and there is a possibility that a correlation may exist between borehole yields and the longitudinal conductance of the regolith. The rapid throughflow channels cannot be resolved by geophysical surveys as presently practiced. Predicted thicknesses and even permeability might perhaps be capable of some degree of prediction from surface terrain analysis and some of the results obtained in this programme have given an indication of this possibility.

Where higher yields are required or lower specific capacities desirable, than can be obtained from a regolith aquifer, drilling has to be continued into the bedrock, and the situation changes significantly. Lightweight or cable tool rigs are less economic in use and bedrock fracture systems cannot be targeted directly by geophysical survey techniques. This is the situation which occurs typically in Zimbabwe. Although storage is still derived from the saturated regolith, the main water inflows are derived from productive fractures in the saprock and bedrock. Because of the variability in regolith thickness, successful sites can be obtained even when the immediately underlying regolith is of small to negligible thickness, provided the transmissivity of the intercepted fracture system results in a cone of depression which is able to draw on sufficient storage at a distance. Surface indications of fracture zones are apparent from remote sensing data and ground observations. Although the fracture systems at depth are unlikely to be resolved by current geophysical survey methods, some resolution may be feasible if the zone is reflected by differential weathering. If the width of the fracture zone is small, precise location in relation to the width and dip may be critical to the borehole location. Radon surveys may assist in assessing potential productivity.

Fractures are expected to reduce in frequency and aperture size with depth which could be an explanation for the negative correlations which occur between specific capacity/yield and boreholes depth (Table 11.15). Rather surprisingly however, the regression of incremental yields and depth do not show the negative correlation, as is common in fissured rocks generally and would be anticipated from the matrix correlation obtained. This is apparent in all four geological units, an example of which is given in Figure 11.22. It is possible that in the context of borehole drilling to c. 70 m, the precise location of the fracture system in that depth range is more critical than significant closures or frequency reduction of the fissures.

Few detailed studies on fracture frequency or fracture productivity in basement aquifers are known to have been carried out. In the EEC drilling programme, the fracture frequency showed an exponential fall off from a maximum of 28% immediately below the bedrock surface to effectively zero at 40 m. Borehole frequency at these greater depths is also reduced (Houston and Lewis, 1989). A similar trend was apparent in fractures measured in a number of cored boreholes in Sri Lanka, the only difference being that the uppermost saprock (4/5 m) was described as completely fractured whereas below that depth, individual numbers of fractures could be measured. The distribution of the fractures in the boreholes drilled in the Project programme (Figures 11.10 and 11.11) did not show this type of distribution, either obvious reductions in depth or a concentration immediately below the bedrock surface. The latter concentration is usually attributed to horizontal fracturing due to pressure release stresses and these would be expected to reduce with depth. It may be significant that the fractures in the Sri Lanka cores were mainly at shallow angles. The fracture systems which are being targeted by the Zimbabwe boreholes are mostly with steep dips and attenuation with depth is more difficult to assess..

Optimum drilling depths in crystalline rocks in the published literature shows a wide range of values from less than 10 metres (Summers, 1973) down to 200 m (Afrodisis, 1979) with many values in between. These depths have probably been obtained from observed yield-depth relations but the range does point to the regional variability of controls which are unlikely to result in a simple depth correlation. Many authors stress the values of intersecting fracture systems and Summers (1973) has attempted to quantify this by assuming that specific capacities are related to the number of contributing fractures penetrated and that the number of fractures diminishes linearly with depth. He derives the following relation:

$$S_c = \frac{Q}{s} = B\left(\frac{-bz^2}{2E} + bz\right)$$

where S_c is the specific capacity, Q is discharge, s is drawdown, B is a constant, b is fracture frequency at the land surface, z is depth and E is the maximum depth of fracturing (100 feet in Wisconsin). Fracture density maps were prepared for the the detailed study areas in the Masvingo Project and initial analyses show no significant correlation with specific capacity although there is the usual -ve correlation with depth.

The BGS project has not been able to obtain sufficient data on down-hole fracture occurrence on yield relations. However a more pragmatic approach has been adopted using known drilling and borehole completion costs and relating these to critical depth relations. The analysis could be refined and generalised.

(i) Drilling rates to 35 m : 57 Z$/m
Drilling rates below 35 m : 80 Z$/m

(ii) Successful borehole to 50 m = 5650 Z$ . . . . SC_1
Successful borehole to 70 m = 7250 Z$ . . . . SC_2
Dry borehole to 50 m (drilling +300) = 3495 Z$ . . . . . DC_1
Dry borehole to 70 m (drilling +300) = 5095 Z$ . . . . . DC_2

When a borehole has reached 50 m and is dry, the decision has to be made whether to continue drilling or to abort and drill elsewhere. The decision can be based on the success rates in these depth ranges and the following equation will apply:

$$\frac{ySC_1 + (1-y)\,DC_1}{y} = \frac{ySC_1 + (1-y)\,xSC_2 + (1-y)(1-x)\,DC_2}{y + (1-y)x}$$

where y is the success rate in the 0-50 m range and x is the success rate in the 50-70 m range.

With a given value of y, the x value is the success rate for which a break even economic rate is obtained.

The equation has been applied to the three main geological units in the Masvingo area and using a criterion of a yield >0.2 litres/sec as successful. The results are shown in Table 12.1 below.

Table 12.1 Observed success rates in the depth ranges above and below 50 m and the break even value for the below 50 m.

Geological Unit	Success Rate % <50 m	Minimum Success Rate at >50 m	Observed Success Rate at >50 m
4	72	33	60
5	72	33	48
6	84	38	50

These results show that the deeper drilling to c. 70 m has been justifiable. The results are only approximate since standard depth values have been chosen. The method could be extended by computerisation to use the actual drilling depths and would give a more precise answer.

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Appendix 1

SOME NOTES ON IN SITU STRESS IN SOUTHERN AFRICA

A number of in situ stress determinations have been reported in Southern Africa covering a depth range from 20 metres to 2.5 km. Gay (1975; 1977; 1980) reports that in Southern Africa the average horizontal stress is generally greater than the vertical stress at depths less than about 500 m. Commonly this means that the vertical component of stress is minimum which could give rise to surface-parallel sheeting on exfoliation. The only determination in Zimbabwe was at Shabani Mine (van Heerdeen, 1968) where the ratio of the average horizontal to vertical stress was 1.45 at a depth of 350 m.

Directions of the two horizontal principal stresses average E-W to NW-SW and N-S, though the greater of these two is not consistent. At Shabani the maximum principal stress is directed NNE-SSW which might lead to opening of NNE-SSW fractures, other things being equal. However, the present-day stresses are probably not tectonic and their magnitude is unlikely to greatly affect any one fracture direction.

Descriptions of the surface stress regime by Gay (1975; 1977; 1980) and Price (1966) provide a detailed explanation as to why the surface region shows a greater horizontal than vertical stress. Changes that occur during gravitational unloading include the following:

(1) changes in the horizontal component are small compared with the reduction of the vertical stress due to removal of lithostatic pressure;

(2) uplift on a sphere causes horizontal tensile stresses that may be as large as half the change in the vertical stress;

(3) temperature changes due to the geothermal gradient also produce tensile stresses.

Where the total tensile stresses exceed the tensile strength of the rock fractures and joints form on existent fractures open. Thus, the presence of fractures provides an explanation for why tensile stresses are not preserved in the surface zone as might have been expected.

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