DEVELOPMENT OF SMALL SCALE IRRIGATION USING LIMITED GROUNDWATER RESOURCES

RECONNAISSANCE GROUNDWATER RECHARGE STUDY: TAMWA/SIHAMBE/DHOBANI KRAALS

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EXECUTIVE SUMMARY

Background

During the past four years an extended and severe drought has placed considerable stress on the land resources of Southern Africa, and Zimbabwe in particular.

Droughts are a recurrent feature of semi-arid environments; they have always occurred, and will continue to do so in the future. Under natural conditions periodic drought poses no long term environmental threat. The flora and fauna simply die back to a density that can be sustained by the reduced precipitation, then when rain returns, the system regenerates back to its original state. But today, population growth means that pressure on land resources is greatly increased. This pressure is necessarily continued even throughout periods of drought since people still need to attempt to grow crops, graze cattle, collect firewood and draw water. Survival depends on these activities. However, when these man-made pressures are added to an environment already under natural stress, the physical characteristics of the land surface eventually become altered and the hydrological balance changed. Clearing the natural vegetation, overgrazing and poor management of cultivated land exposes the soil, causing crusting; this in turn generates increased rates of run off leading to soil erosion as well as reducing rates of infiltration and groundwater recharge. Exposing the soil can also generate increased wind erosion. The overall effect of these and other mechanisms, is a general degradation of the land surface, which if continued sufficiently long, becomes very difficult to reverse.

Accepting that these pressures will be sustained in the foreseeable future, it is essential that to prevent continued deterioration, the natural hydrological balance is maintained as closely as possible. This balance can best be achieved through the introduction of appropriate surface management techniques. However, before such techniques are introduced it is necessary to have a full understanding of the hydrological processes and inter-relationships involved.

The present project is a reconnaissance study of a 4.6km^2, semi-arid catchment, in an area of basement complex geology in southern Zimbabwe. This exploratory study is seen as the first phase of a much longer term project to identify the key factors governing the hydrological balance in a semi arid environment facing the threat of severe land degradation. A small catchment of this size is considered to represent the minimum scale at which the hydrological effects of land use and climate change can reasonably be observed.

The specific aim of this reconnaissance investigation is to describe the hydrological history and physical characteristics of the selected basin, thus providing essential baseline data for the longer term, more detailed study to follow.

Study area and objectives

The selected catchment lies about 100km WNW of Chiredzi in an area of basement complex geology along the southern fringes of the Middleveld. It has an area of 4.6 km^2, being 2.75 km long and up to 2km wide. Hills surrounding the valley are steep, and elongated parallel to the dominant NE-SW trend of underlying Precambrian gneisses. Bare, smooth rock surfaces are exposed on the flanks of many of these hills. Soils over most of the catchment are derived mainly from granulite gneiss and are light textured and grey in colour; heavier red soils are associated with the more mafic, darker gneisses; black and brown clays are found in the lower parts of the valley. Except for the steep flanks of hills, the catchment is intensively cultivated and grazed. At the time of the study the region was experiencing one of the worst drought sequences for the past 100 years.

The objective of this reconnaissance study was to:

* Identify, describe and classify the main soil types and note their location with respect to topography.

* Investigate the hydraulic properties of the various soils.

* Establish a brief hydrological history from the time of settlement.

* Monitor groundwater levels to provide baseline data for the drought period.

The work programme

Field work took place in the dry season over a 7 week period during August and September 1992. Four main activities were involved; physical description of the catchment; description and hydraulic properties of the main soil types; a summary hydrological history since settlement began and measurement and monitoring of groundwater levels.

Physical description of catchment

Aerial photographs and maps, together with detailed ground observations provided the information for catchment characterisation. Topography, geology, soil type and land use aspects have all been taken into account.

Soil types and soil hydraulic properties

The physical and hydraulic properties of the three main soil types in the area were investigated along two transects set up on opposite sides of the valley. A "grey" transect to the south was established on the lighter, grey soils; a "red" transect on the north side, covered mainly the red and grey/black clayey soils.

Six soil pits, dug to a minimum depth of 1.4m, were sited along the transects. Four were placed on the "red" transect, the remaining two on the "grey" transect. All pits were photographed and the profiles described in detail.

Hydraulic conductivity measurements were made of the crust and various soil horizons at each of the pit sites. Measurements were made using both disc and Guelph permeameters, the former proving to be the most successful. Some limited rainfall simulator studies were carried out to evaluate the process of crust development.

Hydrological history

A hydrological history of the catchment since settlement was based on the recollections of local people. Questionnaires were distributed relating to past hydrological and land use conditions in the catchment. In this way information concerning past rainfall patterns, land use changes, groundwater levels and surface run-off characteristics were obtained.

Groundwater level monitoring

Twenty five wells and boreholes were located within the catchment. Of these, twenty were monitored every few days throughout the field period. The relative elevations of two lines of wells oriented normal to the stream bed on either side of the valley were surveyed to allow local groundwater level gradients to be established.

Results

A summary of the most significant findings of the study is as follows:

* Except for the clay soils it is the hydraulic conductivity of the surface crust that provides the main control on infiltration. Thus once water has passed through the crust, there is no other <u>soil</u> layer at depth to impede its progress to deeper levels. By and large the red soils are less permeable than the grey, lighter textured varieties.

* The top surface of the saprolite (weathered rock) seems to be less permeable than the soil horizons above it, giving rise to the possibility of throughflow at the soil/saprolite contact.

* Soils with the highest hydraulic conductivity are those which skirt the base of the surrounding hills. Concentration of run-off from bare rock surfaces combined with high soil permeability makes this a region of potentially high infiltration.

* Rainfall simulation experiments suggest that crust formation takes place during intense storms, thus implying that breaking the crust by ploughing will not necessarily increase infiltration rates for very long.

* Aquifers within the catchment are variably confined and the water table/piezometric surface locally discontinuous, suggesting that flow is dominated by fractures and geological structure. Permeability and storage capacities are low throughout the catchment.

* Prior to settlement in 1953, the hills and valley were completely wooded save for small wetland areas along the valley floor. Although the main stream has never flowed throughout the year, pools would remain until June and even occasionally until September. Fish were caught during the first few years of occupation. The three small catchment tributaries were all fed by springs and depths to water in the first wells dug near the stream bed were less than 3m. Since initial settlement, however, a combination of land clearance and the recent extended drought has led to a drastic change in conditions. The wetland areas in the valley bottom and the springs feeding the tributaries have all now dried; groundwater levels in wells have declined by up to 7m in the valley bottom, and there is some recent evidence of soil erosion where contour bunds have not been properly maintained. In other words a process of dryland degradation is well under way.

This study has laid the foundation for a more detailed investigation of the catchment hydrology. A follow up project entitled "Land use and groundwater recharge in Southern Zimbabwe", which begins in 1993, will take the work forward to obtain a complete catchment balance and begin to explore some of the ways in which changing land surface conditions impact upon the process of groundwater recharge.

1. Introduction

Over the last four years many areas of southern Africa have received below average rainfall. The accumulated effect of these dry years became well publicized during 1992 as the drought began to take its toll upon wildlife, people and their environments in several of the countries including Zimbabwe. The severe environmental stress was perhaps felt most keenly in the semi-arid regions where the availability of water is a determining factor for survival.

In Zimbabwe semi-arid regions carry significant human populations. Many of the areas under normal conditions are fragilely balanced between providing adequate resources for the people and that of following the path of severe environmental degradation. Under an environmental stress, such as a prolonged drought, the current system can not provide for all that live there. The understandable needs of the human population tend to place higher and higher demands upon the available resources, resulting in a compounding of the problems and the downward spiral of desertification.

One of the measures that could help curtail such a scenario and improve the chances of sustainability is that of careful and effective control of the hydrological system, particularly so in these semi-arid areas where there is normally a substantial moisture deficit. To enable this an understanding of the hydrological sources and fluxes within the system is fundamental if an improvement to the situation is sought.

Though plenty of work has been conducted around the world upon the hydrological processes within the semi-arid environment it must be realised that direct comparisons between catchments in differing areas can seldom be made with any degree of certainty. The complexity of the environmental attributes that control the storage and passage of water inhibit it. This results in the necessity for specific regions or environments to be investigated, and only then can comparisons be made with similar areas.

1.1 THE LONG TERM OBJECTIVES

The long term purpose of this project is to establish the key factors that govern the hydrological processes in a region of southern Zimbabwe that is characterised by a basement complex topography[1].

The objective is to develop an understanding of the soil and surface processes. To be able to quantify them and provide the information necessary to help calculate: what the sustainable yield of the particular aquifer is; and whether under the present land management practises there is sufficient groundwater recharge to support a high yielding well, such as a collector well[2], or even just the existing network of hand dug wells.

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[1] This is composed of curved bornhardts, and similar exposures of rock, separated by shallow catenal soils that overlie spatially variable weathered basement aquifers. Due to the geology of southern Africa and the large scale erosion processes that have effected it these regions are relatively common. Particularly so in Zimbabwe, where many of these areas have in the past been allocated to resettlement projects.

[2] Shallow hand dug well of large diameter with horizontal boreholes drilled radially from its base to a distance of approximately 30 metres. Its design is to increase the well's yield from a spatially variable, shallow aquifer.

Having established the parameters for the initial experimental site(s) the aim is to then use these findings to provide recommendations for effective and sustainable management of catchment hydrological systems in the region and guidance for other similar areas.

To do this questions particular to this environment will have to be addressed concerning the infiltration and recharge capabilities of the system. For example large flows of water will be shed from the bare smooth rock of the bornhardts during heavy rain; what route this water subsequently takes and how sensitive it is to environmental change is not fully understood. Could this flow be utilised in a water harvesting technique? Is it prudent to manage the fringe of soil around the base of the bare rock slopes? How does the catena's gradual grading of soil particles from coarse to fine effect runoff? Such questions need to be addressed, together with those questions common to all sites concerning land-use changes, sustainability and degradation.

A clear understanding of the hydrological system would also be of great benefit in: the prevention of soil erosion, agriculture (especially with respect to rain fed cropping) and in the future for environmental impact assessments of possible resettlement projects.

1.2 OBJECTIVES OF CURRENT WORK

The objectives of the field work were to reconnoitre a typical inselberg landscape. To establish the size and scale of those parameters thought to be important to the area's hydrology and to also establish the prevailing environmental conditions. To utilise these to develop and design a work plan suitable of meeting the long term objectives.

The reconnaissance included the following:

* Identification, description and classification of the dominant soils types.

* The occurrence and extent of the soils with respect to the topography.

* A preliminary investigation into the soils' permeability characteristics using process hydrology techniques, together with some basic physical features pertaining to their hydrological properties. Special attention was given to identifying the presence of possible restrictive horizons within the soils of the catchment that would determine the rate of downward water movement. Such a "throttle layer" is important in two respects. Firstly it could determine the rate of recharge to the soil and aquifer beneath it. Secondly a throttle layer could affect the hillslope flow processes in such a way as to promote through-flow and surface runoff, which also obviously inhibits good groundwater recharge. A further consequence could be the risk of soil erosion.

* A description of the valley selected.

* To establish a brief hydrological history dating back to the introduction of settlement in the area.

* To make a rough assessment of the availability of water via the monitoring of local wells at a time when the region was suffering possibly its worst drought sequence for over a hundred years.

2. Physical setting

2.1 REGIONAL DESCRIPTION

2.1.1 Locality

The region selected as possessing the correct landscape for the investigation lies along the southern fringe of the Middleveld as it merges with the Lowveld in the south-east of Zimbabwe, (Figure 1). Proposed sites along a 100km section between Lundi (20.9°S, 30.8°N) and Lake McDougal (20.6°S, 31.6°N) were considered. The chosen site is close to Lundi.

2.1.2 Geology and Geomorphology

The basement rocks of the area date back to the Pre-cambrian era. The Limpopo Mobile Belt granulite facies dominate the geology in the vicinity of the site. Granulite gneiss is the dominant rock with narrow bands of mafic granulite being commonly found in the valleys following the general south-west north-east trend of the region.

The general topography of the area exhibits the south-west north-east trend as a series of steep hills that rise in places to above 1000m from relatively flat valleys bottoms that are between 650 and 750 m above sea level. Though the hills may be several kilometres long they are generally quite narrow: usually less than 2 km wide. Some of the hills fit the description of bornhardts and whalebacks, (L.A. Lister, 1987); but many of the hills, though steep and rocky, do not obviously have these characteristics.

Pediplanation[3] is believed to be the process responsible for this landscape. The site investigated lies upon the southern most fringe of the Post-African erosion surface: a land surface developed during the Miocene period. Less than 20 km to the south lies the encroaching newer Pliocene erosion surface.

This Post-African cycle accounts for the curved bornhardts (Photograph 1), and whalebacks due to exfoliation planes, and koppies, tors and balancing rocks caused by rectangular jointing. The nature and positions of these jointing planes determine the resulting landforms, which in turn can have a profound effect upon the hydrological processes within their vicinity.

For example the case of the extensive, smooth, bare side of either a bornhardt or whaleback. The rain that falls upon this is constrained to surface flow until it either reaches a joint or the bottom of the slope. Since the rainfall in the area can be very intense this can constitute relatively very large volumes of runoff in short periods of time. Evidence for this concentration of water can be seen in dense luxuriant vegetation that rings the bottom of such hills, (Photograph 2). But interestingly there is a conspicuous lack of old established stream beds radiating out from such structures.

[3] A process that governs the destruction of older land surfaces by the method of scarp retreat caused by the gradual encroachment of a younger erosion cycle that operates at a lower elevation.

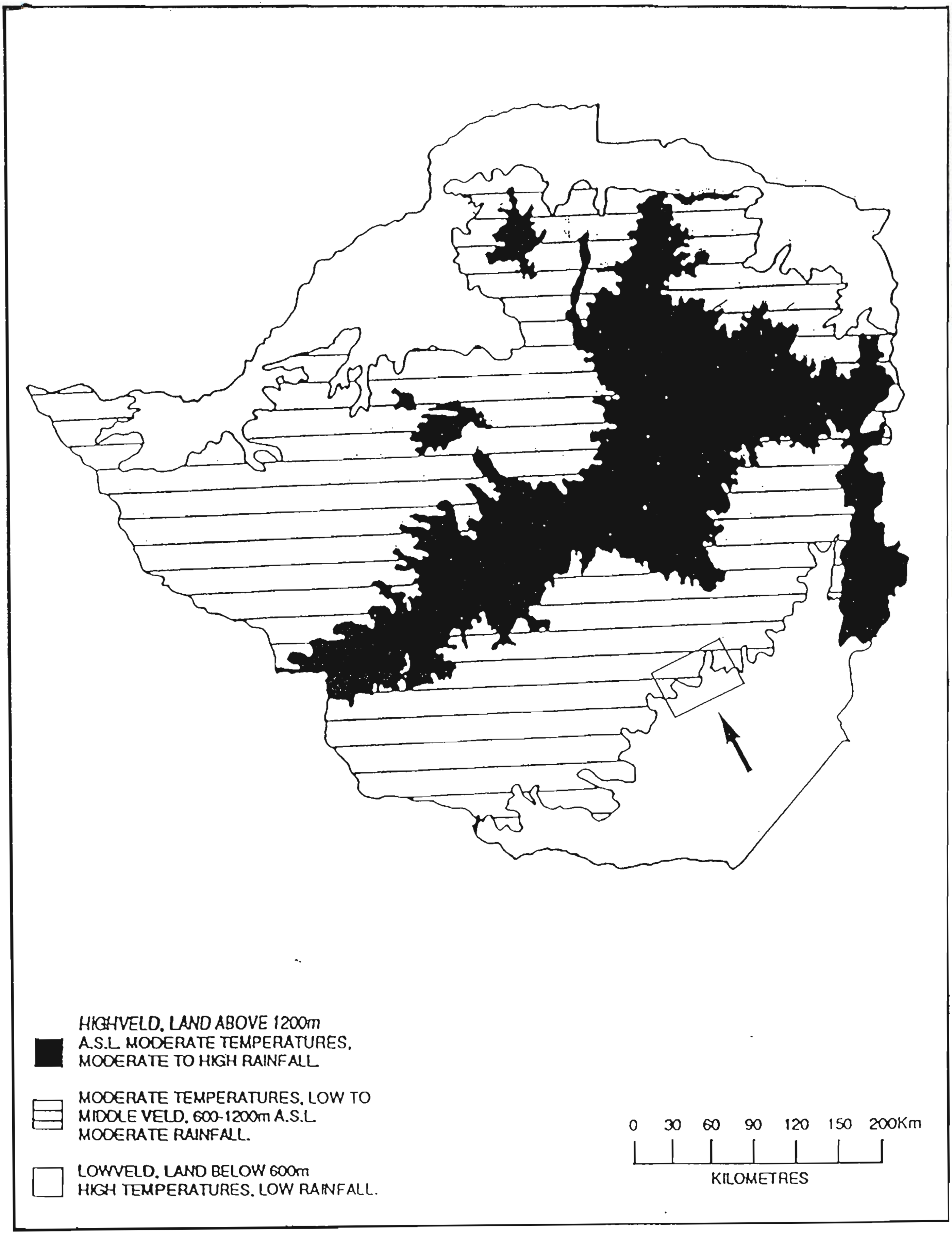
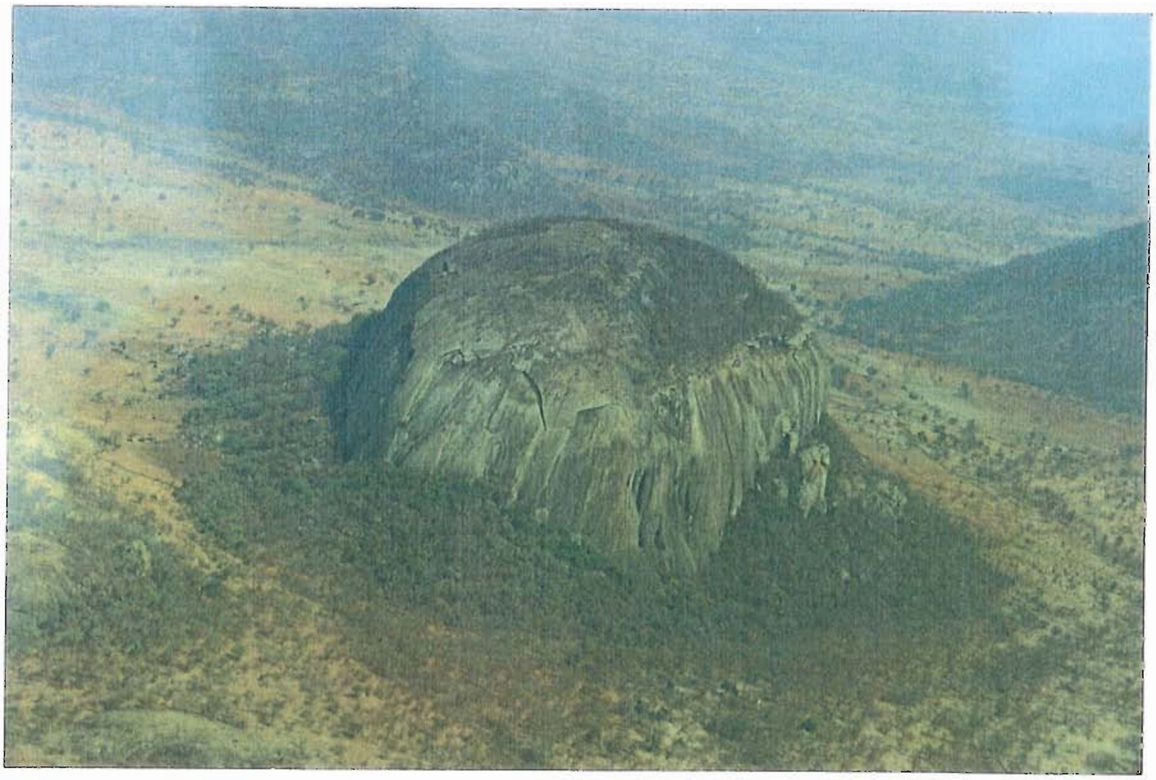


Figure 1 Location of region with respect to the three main relief regions of Zimbabwe.



Photograph 1 *Example of a bornhardt. Located 10km to the north of the experimental area.*

Photograph 2 *Luxuriant vegetation located at the base of a hill. Taken at the end of the dry season during the 1992 drought. (Location 30 km east of Tamwa).*

2.1.3 Soils

The soils reflect the granulitic nature of the geology and are usually from the "kaolinitic order"[4], though where they do occur the narrow mafic bands do produce dark, clay rich soils. The development and differentiation of the soils on a catenal[5] basis is strongly expressed in this region.

2.1.4 Climate

The region experiences a dry winter season between the months of May and September. The bulk of the rains occur in the hotter period between November and March. A significant feature of the rainfall is its lack of reliability in terms of amount and duration, giving a standard deviation upon the annual figure of up to 40%. There is also considerable spatial variability and care must be taken when extrapolating data from nearby weather stations. For example the 20 year rainfall averages for the period between 1950 and 1970 at Lundi (10 km south of the experimental site) and Chendebvu Dam (10 km north) are 715mm and 585mm respectively.

Spells of steady rain are normally associated with major changes in air masses, but most of the rainfall arises from heavy downpours during thunderstorms that are very variable in frequency and extent. The area also is characterised by invasions of cool moist air from the south-east, locally known as "guti", which can cause short spells of cool damp weather that can occur at any time of the year. Rarely does the guti provide any effective rainfall, but it does reduce evaporative losses.

Maximum temperatures, in excess of 35°C, are experienced as the first major rains are expected during the months of October and November when the mean temperature is about 25°C. The coldest months are June and July when the mean daily temperatures are about 16°C.

Owing to the high temperatures and the relatively low humidities of the region the evaporation rates are high. The average open pan evaporation rate, between 1974 and 1992 at Chiredzi Research Station in the northern Lowveld is 1976mm/year. Though probably slightly less than this on the fringes of the Middleveld it does suggest a moisture deficit of the order of 1000mm/year in the general region.

2.1.5 Weathered Basement Aquifer

Prolonged in situ weathering of the crystalline basement complex rocks in the region is thought to produce a layer of unconsolidated material with the degree of alteration generally decreasing progressively downwards until unweathered rock is reached. This is thought to constitute a relatively extensive aquifer within the area's low lands. But on a smaller scale, differences in bedrock mineralogy and structure are likely to produce significant variations in the physical properties that influence the hydrology and make the aquifer spatially variable.

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[4] Using the Zimbabwean classification scheme.

[5] A catena is a sequence of soils derived from the same parent material but differing in properties because they occupy different topographic positions.

Water abstraction from aquifers located within a similar erosion surface in Malawi, (Chilton, P.J. and Smith-Carrington, A.K., 1984), suggest that domestic water supply for relatively densely populated rural areas can be sustainably met from such aquifers. Though there was concern that increased abstraction, for perhaps agricultural purposes, may constitute water mining.

2.2 CATCHMENT DESCRIPTION

2.2.1 Location

The catchment is located in Ward 22 of Chivi Communal Area (20° 43'S, 30° 43'E), approximately 5 km west of the main Beitbridge-Masvingo road, 7 km north of Ngundu Halt.

2.2.2 Size and Shape

The 2.75 km long by 1.5 to 2.0 km wide catchment drains from east to west, (Figures 2). It has an area of 4.6 km^2. The major stream bed, located along the central axis, has only 3 established tributary streams. It drains out of a narrow gap between two hills, < 0.1 km wide. There are 3 saddles connecting the valley to other valleys. The large one to the north has an exposure of smooth rock extending along the majority of its length, possibly forming a natural boundary to groundwater movement out of the area.

The altitude varies from about 700m, where the stream exits the catchment, to just below 1000m in the hills to the south. The slopes in the valley bottom are shallow, generally < 4°, whilst the hill slopes are steep with angles of up to 30° and higher in places.

2.2.3 Geology

The hills surrounding the valley are comprised of Precambrian granulite gneiss from the Limpopo Mobile Belt. A band of Precambrian mafic granulite is found just to the north of the stream bed in the valley bottom and runs through the entire length of the valley, (Muchenga, F., 1975), (Figure 2).

Two major faults cross the western end of the valley in a north by north-west direction, dissecting the large hill to the south.

The three hills to the north-west exhibit the classic features of bornhardts/whalebacks with large expanses of smooth rock and shell like exfoliation. This is continued across the northern saddle.

2.2.4 Soils

The dominant soils of the catchment are derived from the granulite gneiss and are classified in the Zimbabwean classification system as: Kaolinitic, fersiallitic soils derived from siliceous gneisses, (III 5 P). These give rise to light textured soils in which the sand fraction is generally fine to medium. The soil forms a catenal sequence which is observed to the south of the main stream bed where the influence of the mafic rock band is not felt, (Photograph 3).

Figure 2 *Plan view of the catchment illustrating: watershed boundary, major faults (f), the location of siliceous (S) and mafic (M) gneisses, red and grey transects (RT, GT), well lines X and Y together with the numbered wells associated with these two lines.*

***Photograph** 3 Distribution of the two dominant soil types within the catchment's valley bottom.*

Where the mafic band is found it has brought about the genesis of a quite different red soil which has disrupted the catenal sequence to the north of the stream bed, (Photograph 3). Also on the northern side there are relatively small areas of brown and black clays that occur in relatively flat hollows downslope of the red soil. These probably owe their formation to a number of factors. Firstly their location at the bottom of a slope where eluviation processes tend to concentrate the finer particles. Also to the mineral rich weathering products of the mafic granulite.

2.2.5 Population

People were first settled in the valley in 1953. Before then the area had been negligibly affected by the influence of man. Three villages (known as "Kraals"): Tamwa, Sihambe and Dobani are located partially within the catchment. The houses, that home over 500, are all located in a fringe around the base of the hills.

Water is either collected from the stream or from wells depending upon the season. Though since 1991 the community has been heavily dependent upon a collector well that was installed centrally within the valley, (Chilton, P.J. and Talbot, J.C., 1992). The intensification of the drought during 1991 and 1992, together with the clean, potable nature of the collector well water has consequently drawn people from outside the valley to use the well.

2.2.6 Land use

The hills of the catchment are wooded: Brachystegia spiciformis and Brachystegia glaucescens forming the dominant species. Livestock is grazed throughout the year and trees are being

harvested heavily for fuel and timber.

All the available space in the valley bottom is cultivated. Maize, ground nuts, sunflowers, sorghum and cotton are the most popularly cultivated crops in the area under rain fed agriculture, (Lovell, C. *et al.*, 1992). The agricultural practise followed necessitates that the soil be ploughed and exposed with very little protection against the elements. Contour bunds have been surveyed in at roughly 2.5 m steps in altitude, storm drains and waterways have also been constructed and these if maintained do substantially prevent the formation of gullies and rills, as well as reducing the amount of water lost from the valley by runoff. Unfortunately many of the bunds have not been maintained and surface runoff channels are visible on both the major soil types in the valley. Small gardens are also cultivated for vegetables using hand dug wells.

Over the last couple of years the valley has benefited from the installation of a collector well that has enabled the people to not only draw domestic water but to also irrigate a large vegetable garden. Though this has been very successful the area irrigated during the 1992 dry season had to be reduced as the well began to run dry. Concern over adequate recharge of the aquifer for the next year has been expressed, especially as the rainfall in recent years has been less than average.

3. Methodology

3.1 INVESTIGATION OF THE SOILS

3.1.1 Introduction

Each of the main soil types within the catchment were investigated. The initial objective had been to investigate the hydraulic properties of the soils along a catenal sequence using regular spacings, irrespective of their visual appearance. But given the common occurrence of mafic bands in the area and the potential significance that such results could have for future work regarding water management and the collector well project it was instead decided to investigate each of the main soil types in the valley. Therefore, instead of site selection at regular intervals, areas of soil deemed representative of the major soil types were chosen.

Each of the soil types were then investigated. First the slopes along the transects were surveyed. Then soil pits were dug, samples taken and field descriptions made. Each soil horizon tested for its hydraulic conductivity and sorptivity. In an attempt to characterise surface crusts physical penetration measurements were made.

To gain further information about the soil and catchment hydrology a meeting was held with the kraal elders to discover their understanding of the hydrological processes and their observations during rainfall events.

3.1.2 Transect selection

Aerial reconnaissance permitted the selection of transects that ran downslope whilst intercepting each of the main soil types. One transect was selected within the collector well sub-catchment which incorporated soils derived from the mafic gneiss as well as those from the siliceous gneiss. A second transect was selected on the southern side of the stream where the parent rock is siliceous gneiss. (Photograph 4 and Figure 2).

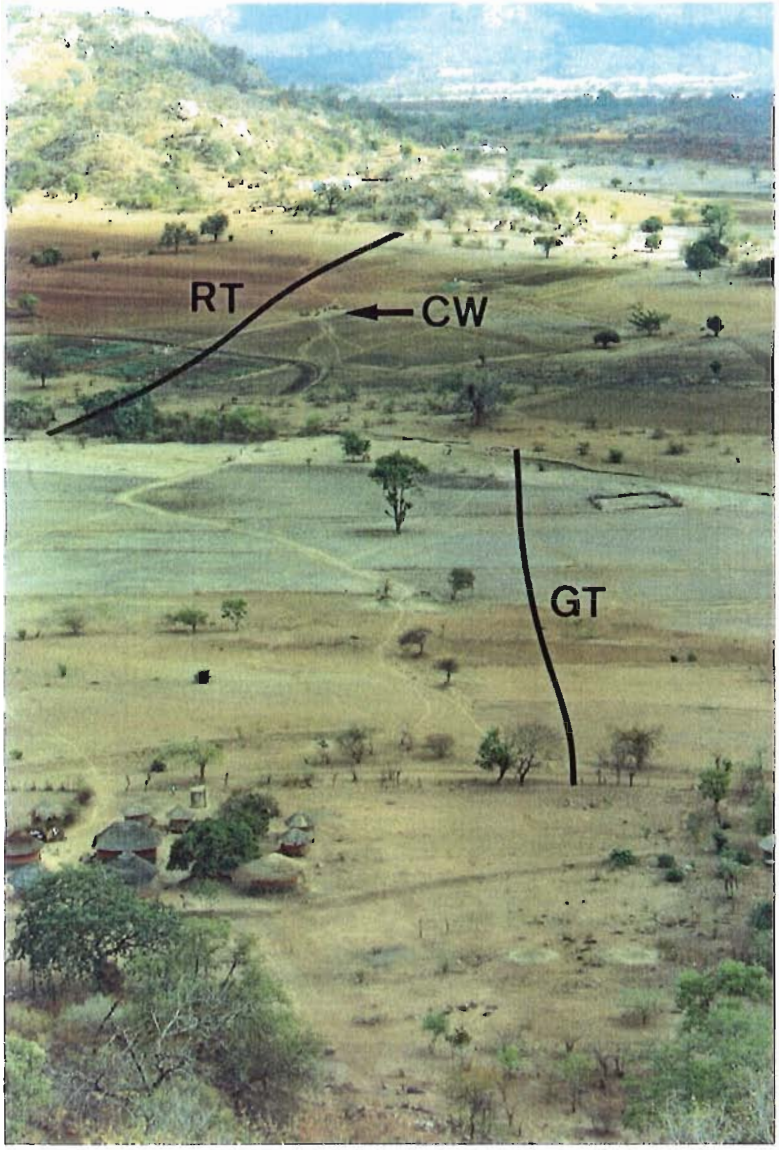
3.1.3 Soil pits

The criteria for the positioning of the soil pits and subsequent work are that:

a) The type of cultivation should be similar.

b) An equal time should have elapsed since the last cultivation was practised.

c) That the position be as close to the centre of that particular soil type yet still in close proximity to the surveyed line.



Photograph 4 *View of the two transects, looking northwards. RT = Red Transect, GT = Grey Transect, CW = Collector Well*

Once selected pits at least 1.4m deep were dug, and samples for soil classification purposes[6] were taken from each of the horizons.

Immediately after the completion of each pit a field description of the soil horizons for hydraulic purposes was made. This included: horizon depth, dry and wet Munsell colour, a rough appraisal of softness, occurrence of roots and/or evidence of disturbance by fauna, coarse texture, structure and an "other comments" section in which any other features that may effect the hydraulic properties were noted.

Hardness was measured on a scale of 1 to 5 using a medium sized (5mm wide tip) screwdriver:

1. Soft. Very easy to push screwdriver in.

2. Can push screwdriver 1cm in with little effort.

3. Push screwdriver 1cm in with effort.

4. Push screwdriver in less than 1cm with effort.

5. Very difficult to make an impression with a screwdriver.

These values are admittedly very approximate but are included if only to serve as a rough guide to the reader.

Four holes up to 21m deep were also drilled along the red transect to the north of the stream bed. Samples were collected at 0.75m intervals in order to assess the variability of this aquifer.

3.1.4 Crust Characterisation

Surface crusting of the exposed cultivated soil is prevalent within the valley. A combination of the lack of surface cover, wind and particularly the rain's intensity and the kinetic energy associated with the raindrops rearranges and sorts the surface particles. After drying this forms a brittle crust whose strength depends upon its textural composition, thickness and chemical composition.

It is an a priori assumption that the hydraulic properties of such a crust will differ from that of its parent soil, and that the specific history of its formation will also determine its nature. That is to say that the crusts formed at different times from the same parent material will not be the same. Spatial variation is also assumed.

It was therefore necessary to categorize the crustal layers upon which the hydraulic measurements were made. This was achieved in two ways:

a) Soil particle analysis of the parent material.

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[6] Classification of the soils is awaited at the time of submission of this report from the DRSS Soils Department in Harare.

b) Crustal strength test using a penetrometer.

A penetrometer had to be designed and constructed in Zimbabwe, (Figure 3). The simple design allows the incremental addition of mass in the form of steel disks. The end that contacts the soil has three circular exchangeable feet of differing area to enable a second means of increasing the pressure.

The crustal strengths were measured after completion of the other work. This caused problems in crust selection due to prior soil disturbance. At each site there was roughly a 4m radius zone of disturbance within which no reliable measurements could be made. Due to spatial variability it is important that measurements as close as possible to the hydraulic work are made. To do this a 5m radius circle was drawn around the work area and positions marked randomly around the circumference using randomly generated numbers. A grid consisting of 25 7cm squares was then carefully placed across the soil, paying careful attention to placing the grid always with the same orientation to the mark on the circle to prevent bias placement.

The centre of each square was then tested with the penetrometer by gently lowering it on to the crust with it set to deliver the least pressure. Having tested each square and noted the number of crust failures a standard increase in weight can be made and the testing exercise repeated. This is done until all of the squares have failed, (Photograph 5). The frequency distribution is then used to characterise each crust. See Appendix 1 for further notes upon penetrometer use.

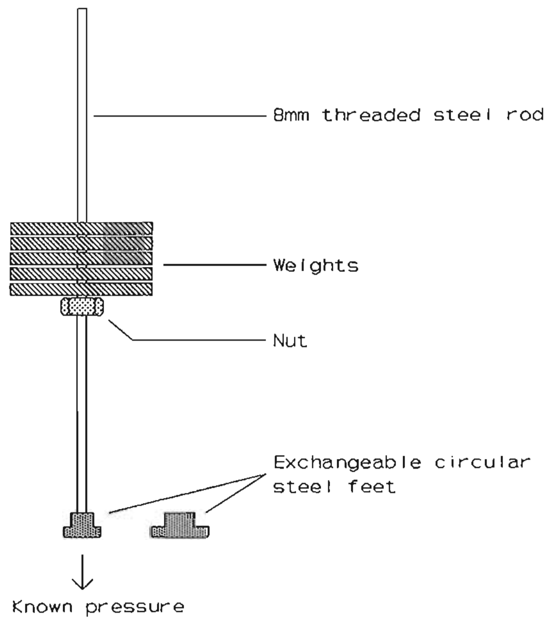

Figure 3 The penetrometer

3.1.5 Hydraulic Properties

The objective was to measure the saturated hydraulic conductivity (K) and the sorptivity (S) of each of the soil horizons in each of the soil types. Two instruments were tested: a CSIRO Disc Permeameter, (Photograph 6), and a Guelph 2800KI Permeameter, both designed to measure the in situ hydraulic properties of field soils.

The disc permeameter works on the principle of maintaining a constant head of water upon the surface of the soil and measuring the rate of infiltration[7] from a single run. From these readings, and measurements of soil moisture and density, both S and K are determined. S is calculated by plotting the cumulative infiltration per unit area of soil against the square root of time. The initial characteristics of the curve should exhibit a linear relationship from which S can be determined. K is subsequently calculated using the determined S value and the steady state infiltration rate, Appendix 2. The Guelph Permeameter operates in a similar way but, instead of the water being introduced to the surface, a hole is augered into which the water is introduced.

Both permeameters have operational difficulties. In the case of the Guelph difficulties were experienced in augering some of the coarse nodular horizons resulting in non uniformly shaped holes. Augering dry sandy soils also proved problematic. The results obtained were inconsistent indicating that the soil lacked homogeneity. The method also required a hole of at least 10 cm in depth which excluded work upon the crust and tilled soil. For these reasons this method was dropped from the work schedule.

a) Disc permeameter field procedure:

Only a brief outline of the procedure together with an outline of any necessary procedural modifications are explained here. For a more detailed discussion consult Ref.1, 1988.

The disc permeameter comprises a stainless steel cylinder that is inserted into the ground to form the vessel for the constant head (Figure 4), and a reservoir system to ensure that the head of water is constantly replenished and that the rate at which this is done can be easily monitored. The water potential is adjusted by the screws that connect to the base of the reservoir system.

A 1cm head was used for all the runs.

i) Site preparation:

One of the advantages of this method over the Guelph is that the top surface of the soil can be investigated. Of particular interest are the properties of the crust. It is generally assumed that the crust promotes runoff and is therefore less permeable. To investigate this, tests were conducted upon both intact crust and crust broken into pieces smaller than about $2cm^2$, (Photograph 7).

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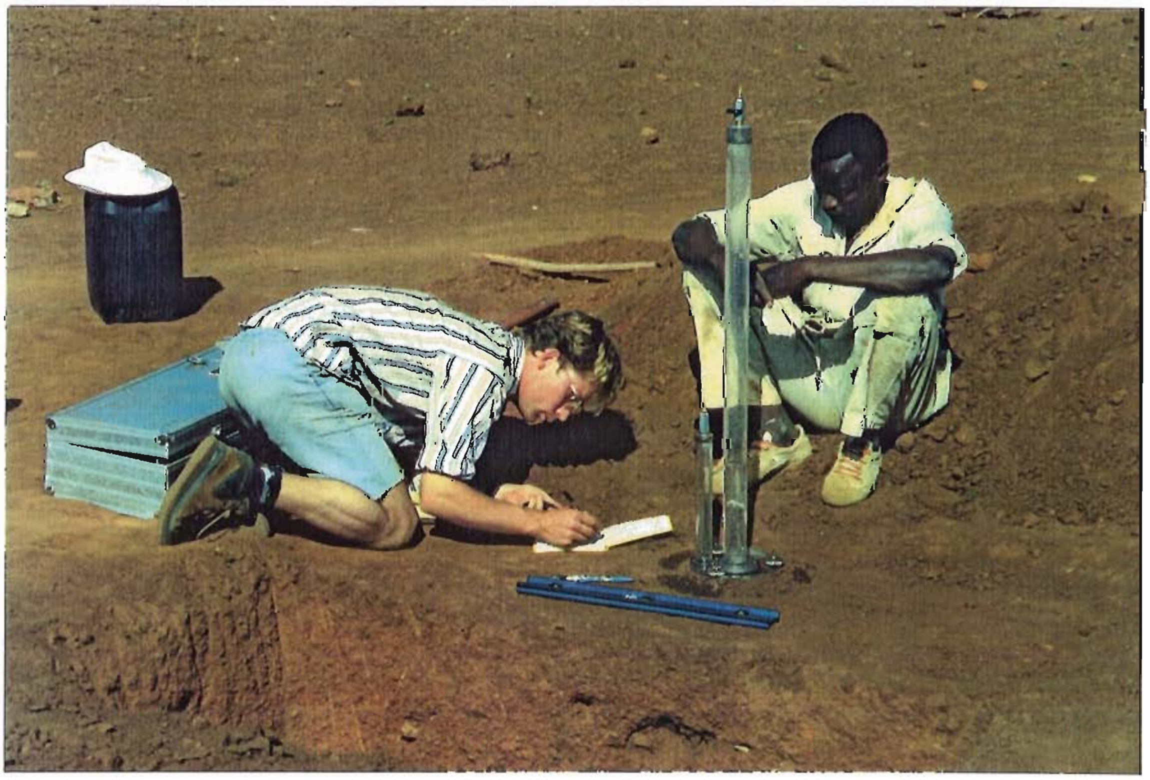
[7] This infiltration rate is that occurs from a single source of limited dimension that results in a three dimensional wetting front in the shape of a bowl. It should not be confused with the infiltration rate resulting from an extensive source that results in a planar wetting front.

Photograph 5 *Apparatus used for crustal strength measurement.*



Photograph 6 *The disc permeameter.*

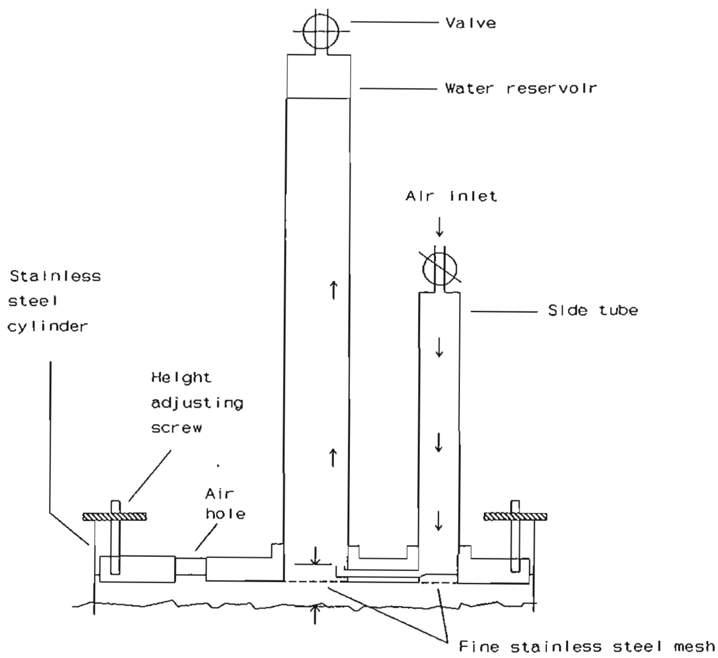


Figure 4 Disc Permeameter.

The action of pushing the steel cylinder through the crust produces an unacceptable rupture to the crust's surface that would provide easy access for the water. To seal this flour was carefully injected into the crack and gently compacted to prevent it from being washed out when the water is introduced, (Photograph 8). The permeability of flour is many times lower than that of the crust, and it effectively reduces the radius of the disc by roughly 0.5cm.

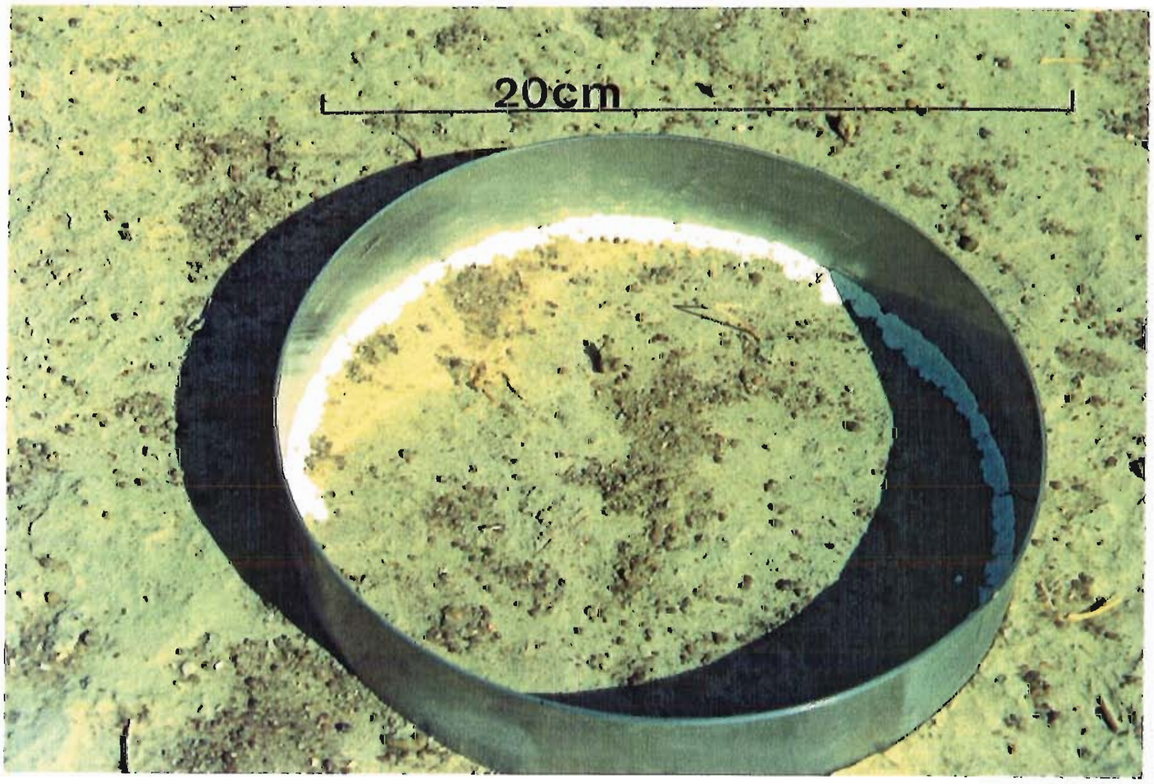
To test lower horizons requires the above layers to be removed. This was generally done along the sides of the soil pit. Care was taken to remove the above soil as gently as possible so as to not effect the in situ structure of the soil beneath. For pits about 1.5m deep with several horizons this represents a lot of work and it effectively limits the number of tests that can be managed, (Photograph 9).

Most of the lower horizons were too hard to insert the cylinder into, so clay was used to seal the cylinder into place and prevent leaks.

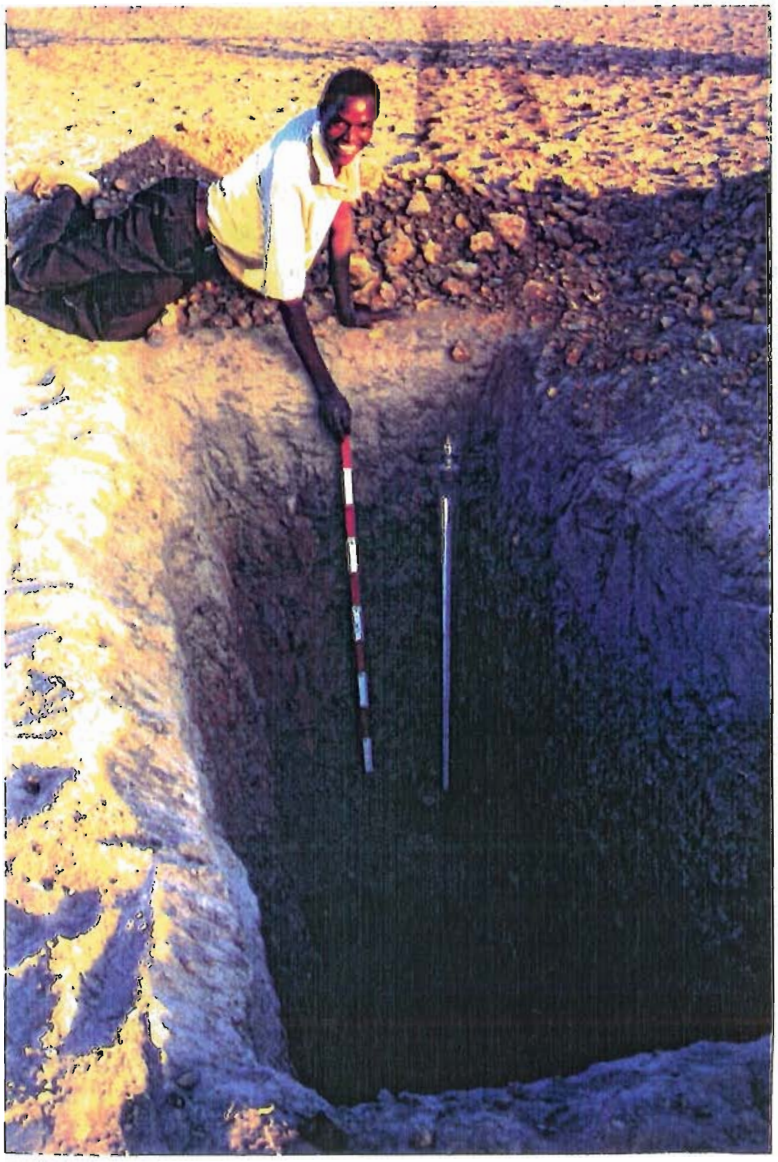
One set of measurements was made within the top of the saprolite layer. The excavated surface exhibited smearing that would have effected the infiltration rate; so once the surface was levelled a knife was used to prise the top smeared layer off.

Once the cylinder has been positioned the reservoir unit can be gently placed on top. The side tube reservoir is emptied into the cylinder, which it should fill, and the timing started as soon as it empties. The rate of infiltration is then monitored upon a graduated scale located down the side of the main water reservoir.

Photograph 7 *Site preparation for a broken crust test.*



Photograph 8 *Unbroken crust preparation using flour to block the rupture caused by the insertion of the disc.*



Photograph 9 *A soil horizon over 1 metre down being tested with the disc permeameter.*

The permeameter runs were limited to relatively short times for two reasons:

1. Many of the horizons are quite thin, therefore the wetting front may penetrate into the next horizon which is likely to have different hydraulic properties. This will affect the infiltration rate.

2. It is vital to reproduce point measurement tests as many times as possible in order to achieve a reasonable understanding. It was therefore decided to increase the number of runs at the expense of their duration, regarding the error on the steady-state rate as being acceptable.

ii) Rainfall simulation:

Though the lower horizons may receive a low energy saturated water flow during a rainfall event, the crust on exposed soil does not. It is subjected to raindrop impaction and sorting. Tropical rainfall can be very intense, with kinetic energies associated with the drops being over 4 or 5 times of that that could be expected in the UK, and the overall rainfall intensities up to an order of magnitude higher than in the temperate zone (Lal, R., 1977).

It was therefore realised that a better test of the hydraulic properties would be to examine the crustal conditions after a rainfall event. This was achieved by suspending a shower 2m above the ground and directing the jet at a constant rate around a marked circle upon the ground so that the selected experimental area and a rain gauge received a steady simulated rainfall. Circling the jet of water also helped prevent ponding upon the surface. The surface's infiltration was then tested as above.

To estimate the raindrop energy the size and the velocity of the drops are required, (Appendix 3). The average size of the droplets was calculated from the projection of slide photographs of the water jet.

3.2 HYDROLOGICAL STATUS OF CATCHMENT

3.2.1 Introduction

The catchment has only been inhabited by people for 40 years. Yet within that comparatively short period the environment has been radically changed. The natural vegetation from the lowland that was specifically adapted to the conditions has been largely cleared. Taking its place are crops which are not as capable of withstanding the unreliable rainfall conditions. To compensate for this the farmers tend to cultivate large areas whilst also herding goats and cattle. This, together with the increasing population, has meant that the natural vegetation cover has been degraded and soil erosion could more easily occur. Some corrective measures were and are taken: contour bunds and contour ploughing but only with limited success.

Many trees have been felled upon the hills for timber and fuel. These hill slopes are also heavily grazed by the livestock. Again the once natural cover has been altered.

These changes to the ground cover and the soil's composition and structure are very likely to change the hydrology of the system in some way. A hydrological history over the last 40 years was therefore sought using the recollections of the local people.

Land use change due to man is not the only environmental stress felt by the region. A prolonged drought, possibly the worst in a 100 years, has occurred in the late 1980s and early 1990s. Obviously this also greatly affects the hydrological state. To investigate this and possibly help in the understanding of some of the drought processes, all the wells within the catchment were studied.

3.2.2 Local information

The objective of questioning the locals about the hydrology and environment of the catchment is to try and gain information upon changes to the hydrological system. It is assumed that their earliest recollections, dating back to when they were initially moved to the valley, will reflect the hydrological state before it was disturbed by man. This equilibrium situation, assuming very gradual or no long term change in natural environmental controlling factors, will have developed over a considerable length of time compared to man's recent introduction, and, if man had not been introduced would still be the present state.

From their recollections and observations it should be possible to gain some understanding as to how the hydrological processes and the mechanisms that convey the water through the environment work and how they have altered. If the alteration has been detrimental it should give some indicators as to what management practises would return the area to a healthier state.

Their knowledge also has the added benefit of providing support for field work results and conclusions. This will be of particular relevance to confirming crustal infiltration rates for different soils.

Emphasis within the survey is placed upon how the living components within the environment have reacted and hence reflected the hydrological situation. An obvious example of this would possibly be the inability of a rainfed crop to continue growing in a certain area due to a reduced supply of water. Man is also included; and how he has reacted may also reflect the hydrological state. For example an obvious example could be the gradual deepening of wells throughout the settlement period.

Questions upon the following were asked:

1. What the environment was like when they first arrived, with emphasis upon the vegetation and occurrence of water.

2. Rainfall patterns.

3. A historical record of the types of crop that have been grown in the valley.

4. The occurrence, depth and use of wells.

5. How the steep hill slopes and the various valley soils react to rainfall events.

Only one formal meeting was held, to which about 15 elders were invited. An alternative plan was to visit them individually but, due to time constraints and the hope that a discussion would help them recall more clearly, just the single gathering was arranged. All the questions were translated into Shona via an interpreter, and the answer translated back. This was despite the fact that roughly half the men could speak English, but it was felt that all discussion and answers should be made in Shona so that a consensus of opinion could be met.

Care was taken in the formation of the questions. Questions that included a suggested answer were not used in case this influenced their answer. For example the question, "Does the water flow upon the soil surface and drain into the stream?" would not be used. A better way for determining the fate of the water would be to simply ask, "What happens to the water once it has hit the ground?".

3.2.3 Monitoring the wells

All the wells within the catchment were located, marked with datum lines, and a dipping routine established. The relatively slow recovery rate of many of these hand dug wells necessitated a depth measurement being made before the first water was drawn in the morning. The wells were therefore monitored between 05.00 and 06.00 hours. If there was any reason to believe that water may have been drawn then the reading was not included in the final results.

Two sets of wells positioned in roughly straight lines down the slopes on either side of the main stream bed were surveyed in so the surface of the groundwater could be assessed, (Lines X and Y, Figure 2).

4. Results

4.1 SOILS

Soil analysis data is presented in Appendix 4.

4.1.1 Transect Surveys

The two transects are named after their dominant soil colours. Hence the transect to the north of the stream bed that passes close to the collector well is known as the "Red Transect", (Figure 5), and the transect to the south as the "Grey Transect", (Figure 6).

4.1.2 Soil cultivation history

Non of the soils within the valley have been deep ploughed (depth $\approx$ 60cm) during the last 30 years. The last normal ploughing by the farmers to a depth of 12 to 20cm was:

Soil Pit 1	February 1991.
Soil Pit 2	March 1991.
Soil Pit 3	February 1991.
Soil Pit 4	1988. (month unknown)
Soil Pit 5	March 1992.
Soil Pit 6	1990. (month unknown)

4.1.3 Soil Pits and Drilled Holes

These are described and illustrated in Figures 7 to 14.

Soil particle size analysis[8] was performed upon the surface layers of soil pits 1, 2, 3 and 6. (Table 1).

[8] Performed at "Soil Survey and Land Research Centre, Silsoe, Bedfordshire.

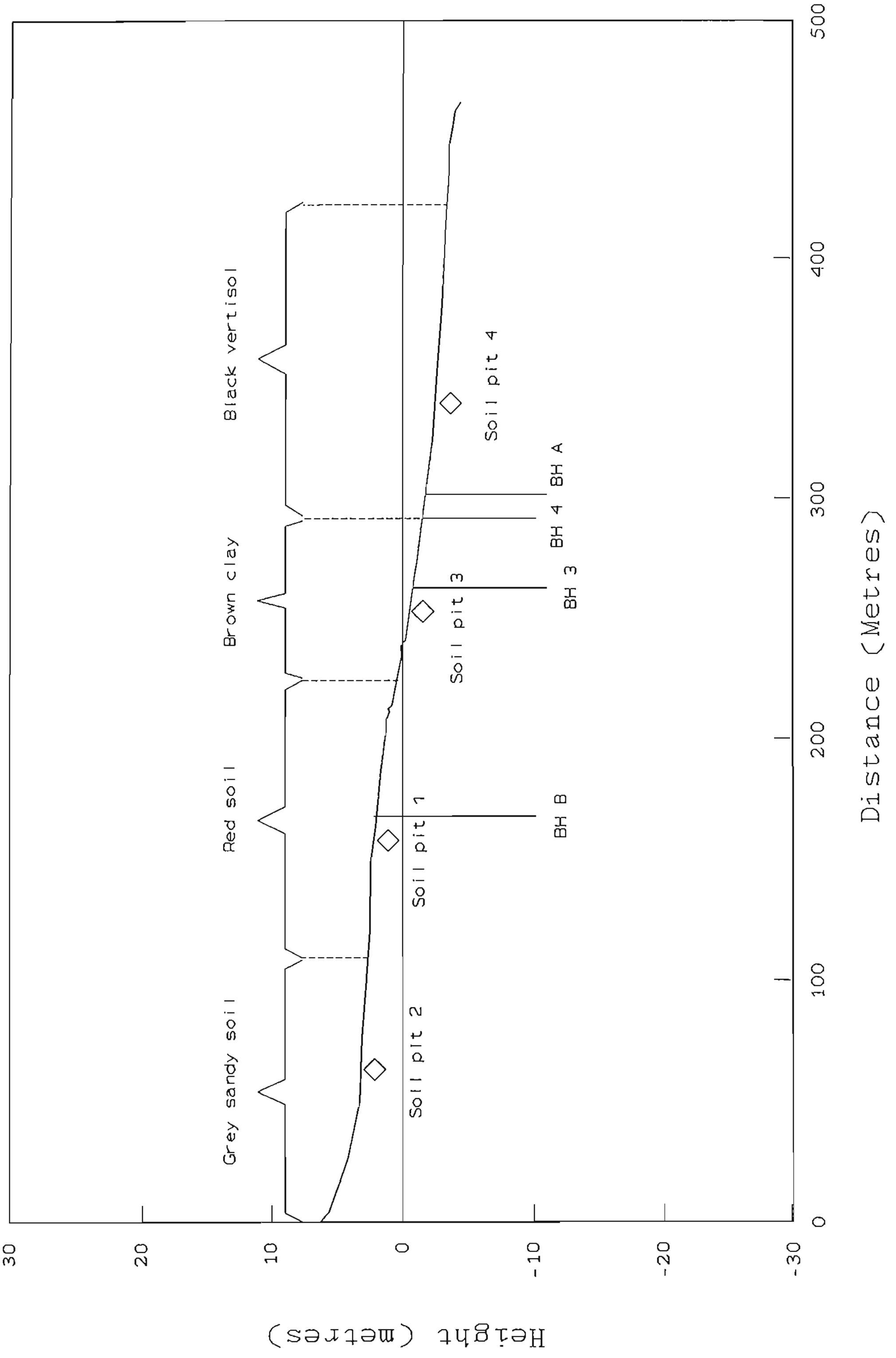


Figure 5 Cross-section of the red transect

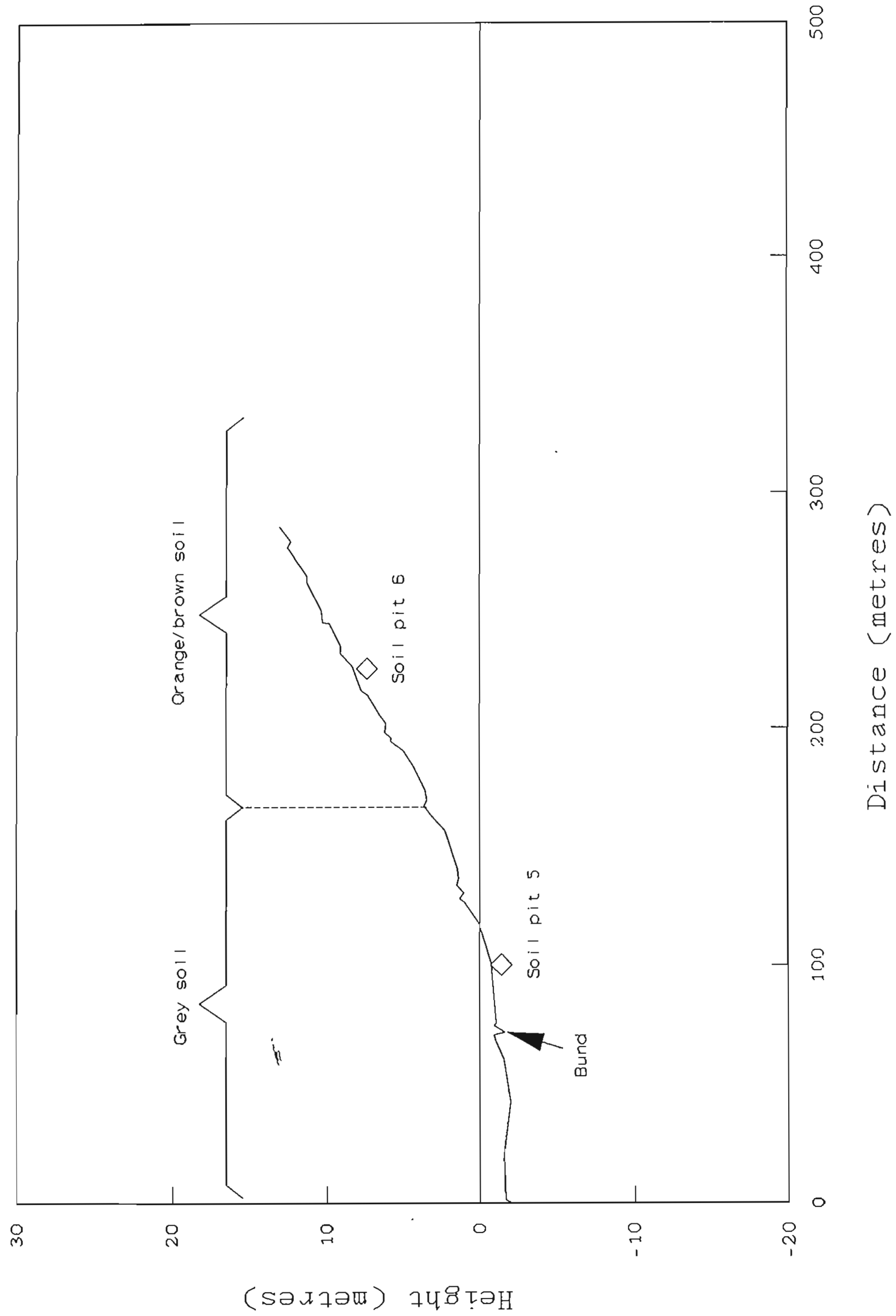


Figure 6 Cross-section of the grey transect

Figure 7 Soil pit 1.

SURFACE

12 cm

HORIZON 1
Munsell colour. 10YR 4/4 (dry), 7.5yr 3/3 (wet) Hardness 1
Flora & fauna: Roughly 40 roots per 100cm^2. Root diameter < 0.5mm
Texture: (Awaiting lab. classification) Mainly fine, nodules < 1cm common
Structure: No visible cracks, v. poorly defined medium subangular blocky
Surface crust, about 1cm thick
Comments: Ploughed layer.

45-50 cm

HORIZON 2
Munsell colour: 7.5YR 4/4 (dry), 7.5YR 3/2 (wet) Hardness 3
Flora & fauna Few roots, <10 roots per 100cm^2 Diameters < 0.5mm
Texture: Mainly fine plus nodules < 1cm common
Structure: Nil.
Comments: Hard pan

90-100 cm

HORIZON 3
Munsell colour: 5YR 4/6 (dry), 5YR 3/4 (wet) Hardness: 4
Flora & fauna: Nil.
Texture. Majority is nodular < 2cm.
Structure: Nil
Comment: Slight cementing, yet easily broken.

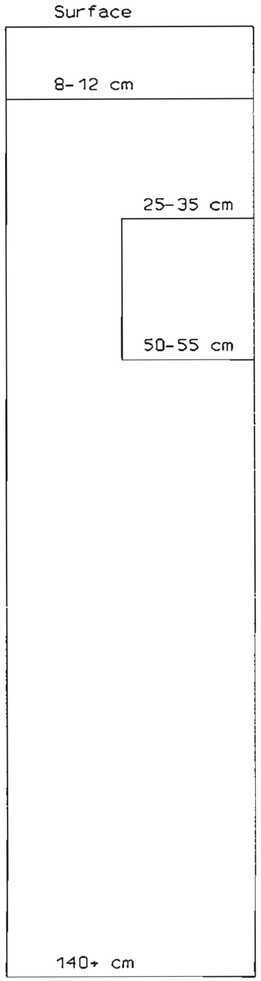
140+ cm

HORIZON 4
Munsell colour: 5YR 5/6 to 5/8 (dry), 5YR 4/4 (wet) Hardness 4
Flora & fauna Nil
Texture: Similar to horizon 3 but nodules less well defined
Structure: Nil
Comment. Slightly damp.

Figure 8 Soil pit 2.

Surface – 12 cm	HORIZON 1 Munsell colour: 10YR 5/2 (dry), 10YR 4/3 (wet). Hardness: 1. Flora & fauna: Many fine roots, <0.5mm. Several 100 per 100cm^2 Texture: (Awaiting lab. analysis) Mainly sandy, few nodules < 5mm. Structure: 1 cm thick crust. Comments: Ploughed layer.
60-70 cm	HORIZON 2 Munsell colour: 2.5Y 6/2 (dry), 2.5Y 3/2 (wet). Hardness: 2. Flora & fauna: Roughly 1 root per 100 cm^2. Most > 1mm thick. Probable termite activite in the form of holes. Texture: Sandy and finer. Structure: 3 to 4 vertical cracks per metre, that run from top to bottom. Round holes, running in all directions, about 1mm diameter, about 10 per 100cm^2. Comments: Hard pan. The progression into the lower layer is gradual
100-110 cm	HORIZON 3 Munsell colour: Matrix 10YR 8/2 (dry). Nodules from the YR charts. Hardness 3 Flora & fauna: Few very fine roots,<0.05mm. 1 or 2 per 100cm^2. Texture: Orange/brown nodules,< 2cm, set in a fine matrix. Occasional rounded crystalline stone. Structure: Trace of above cracks from horizon 2. Obvious feature: gaps up to 8mm across, irregular shape, between the nodules, nearly as common as the nodules themselves. Comments: Notable for high porosity.
200 cm	HORIZON 4 Munsell colour: Mottled. Matrix 10YR 7/2 plus orange, red & brown mottles/particles. Hardness: 2 Flora: Very few fine roots. Texture: Majority is fine with crumbly nodules/particles. Structure: No cracks. Irregularly shaped gaps, < 155mm, common Comments: Notable for high porosity
200+ cm	SAPROLITE

Figure 9 Soil pit 3.



HORIZON 1
Munsell colour: 2.5Y 4/2 (dry), 10YR 3/1 (wet). Hardness: 1
Flora & fauna: More than 50 roots per 100cm^2. Mainly fine roots < 1mm.
Texture: (Awaiting laboratory analysis) Predominantly very fine.
Structure: Slight cracking but no clearly defined internal structure There is a crust, about 1cm thick, that has developed some fine cracks.
Comments: Ploughed layer.

HORIZON 2'
Munsell colour' 2.5Y 5/2 (dry), 10YR 3/1 (wet). Hardness: 2
Flora & fauna: Limited no. of roots, < 5 per 100cm^2. But locals say rhizomes favour this soil.
Texture: Sandy plus particles < 0.5cm common.
Structure: Fine vertical and horizontal cracks, about 5 per metre The soil is honeycombed with small circular holes. Possibly of termites origin.
Comments: This soil is regularly found in the clay areas, usually several metres in extent. It is noted by the locals as producing the best crops.

HORIZON 2
Munsell colour 2.5Y 3/2 (dry), 10YR 3/1 (wet) Hardness' 4
Flora & fauna: Only fine roots, < 0.5mm thick, found in the top 40cm. Roughly 15 roots per 100cm^2.
Texture: Dominantly clay. Orange particles, <1mm, and stones, <10mm, common.
Structure: Very course prismatic, especially near the top. Some cracks are up to 1cm across and extend down to 140cm below the surface.
Comments' Very shiny surfaces when sheared. The lower soil is damp.

Figure 10 Soil pit 4.

Surface

9-12 cm

65-75 cm

130-135 cm

140+ cm

HORIZON 1
Munsell colour: 5Y 2.5/1 (dry), 2.5Y 2/0 (wet).
Hardness: 2 (impliment passes between the angular blocky structure)
Flora & fauna: Thick grass roots, <3mm, about 10 per 100cm^2
Over 50 fine roots per 100cm^2.
Texture: Predominantly black clay. Some stones < 5mm.
Structure: Fine to medium angular blocky. No crust.
Comments: Ploughed layer.

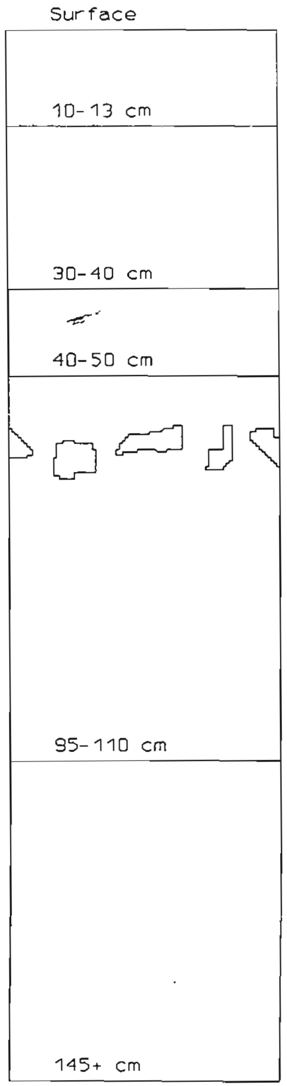
HORIZON 2
Munsell colour: 5Y 2.5/1 (dry), 5Y 2.5/1 (wet). Hardness: 5.
Flora & fauna: Few fine roots, <10 per 100cm^2.
Texture: Clay. Few small stones plus occasional carbonate concretion.
Structure: Very course prismatic. Vertical cracks dominant, up to 3 cm across
Comments: Layer slightly moist at bottom.

HORIZON 3
Munsell colour: 5Y 3/1 (dry), 5Y 3/2 (wet). Hardness: 2
Flora & fauna: Only very fine roots, <5 per 100cm^2.
Texture: Clay. Occasional carbonate concretion, < 2cm across.
Structure: Peds not seen. Occasional vertical cracks, up to 1cm across.
Comments: Moist.

HORIZON 4
Munsel colour: 5Y 5/3 (dry), 5Y 3/2 (wet). Hardness: 2
Flora & fauna: No roots
Texture: Clay
Structure: Difficult to tell. If cracks occur then very fine
Comments: Moist.

Figure 11 Soil pit 5.

No photograph available



HORIZON 1
Munsell colour: 10YR 5/1 (dry), 10YR 4/2 (wet). Hardness: 1
Flora: Roots up to 1mm thick, >100 per 100cm^2.
Texture: Fine sand and finer.
Structure: Nil apart from surface crust
Comment Ploughed layer.

HORIZON 2
Munsell colour: 10YR 5/1 (dry), 10YR 4/2 (wet). Hardness: 3
Flora: Roots up to 1mm thick. <10 per 100cm^2.
Texture: Fine sand and possibly finer material.
Structure: Occasional thin vertical crack 1 crack per horizontal metre
Comment: Plough pan with numerous root holes, <1mm

HORIZON 3
Munsell colour: 10YR 5/1 (dry) for the matrix, a range of oranges reds, browns and purples for the particles. Hardness: 4
Flora: Roots, <2 per 100cm^2. Thichness about 1mm.
Texture: Densely packed layer of spherical nodules, <1cm Sand matrix
Structure: None observed.

HORIZON 4
Munsell colour: 10YR 6/1 (dry) for matrix. The particles cover a range of reds and oranges. Hardness: 3/4
Flora: Very few roots.
Texture: Vague stoneline at 60 -70cm. Rest is crumbly particle material.
Structure: Occasional thin vertical crack. About 1 or 2 per metre.

SAPROLITE
Colour There are 3 major bands of colour grey, yellow & orange
Hardness: On average about 3. (Variable).
More roots than above layer, variable thickness
Texture: Texure within the vertical colour bands resembles rock.
The grey banding much more similar to clay than other two
Structure: Nil
Comments: Slightly moist.

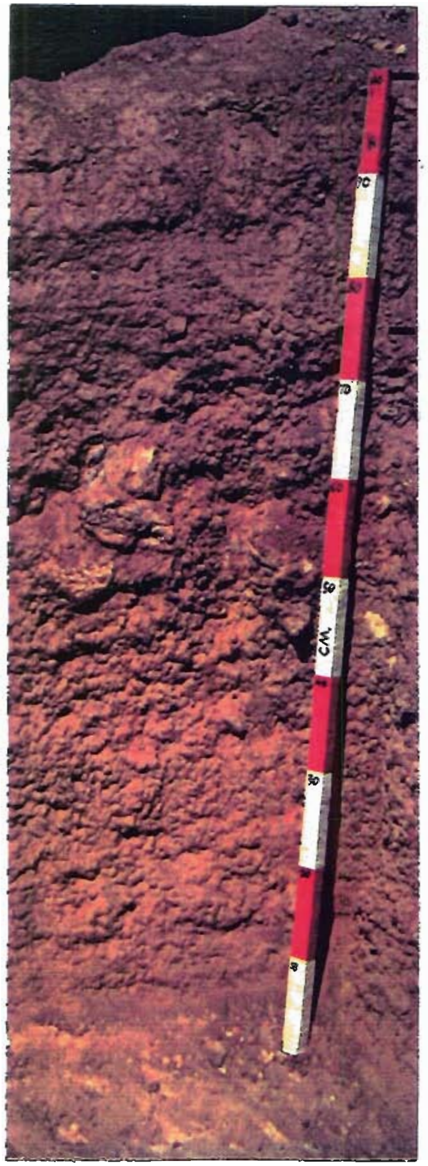
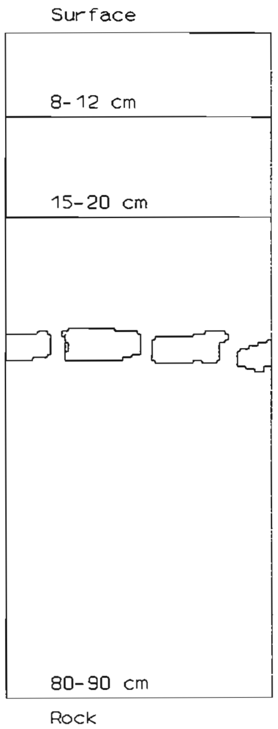


Figure 12 Soil pit 6.



HORIZON 1
Munsell colour: 10YR 5/3 (dry), 10YR 3/3 (wet). Hardness: 1
Flora: Roots <1mm, about 10 to 30 per 100cm^2.
Texture: Generally fine with stones <5mm common.
Structure: Only a 1cm crust on the surface.
Comments: Ploughed layer.

HORIZON 2
Munsell colour: 10YR 5/3 (dry), 10YR 3/3 (wet). Hardness. 2
Flora: Roots <0.5mm very common, 100 per 100cm^2.
Texture: Generally fine plus stones <5mm common.
Structure: Nil.
Comments: Plough pan.

HORIZON 3
Munsell colour· 10YR 6/4 (dry), 10YR 3/3 (wet). Hardness· 3
Flora· Roots throughout, common, <1mm in thickness, 10-100 roots/100cm^2
Texture: Particles up to 20mm very common, dominates, plus a fine matrix
There is a stone line at 30-60cm. Very similar to the under lying rock and the stones seem to be oriented in similar fasion to the rock.
Structure: Nil.

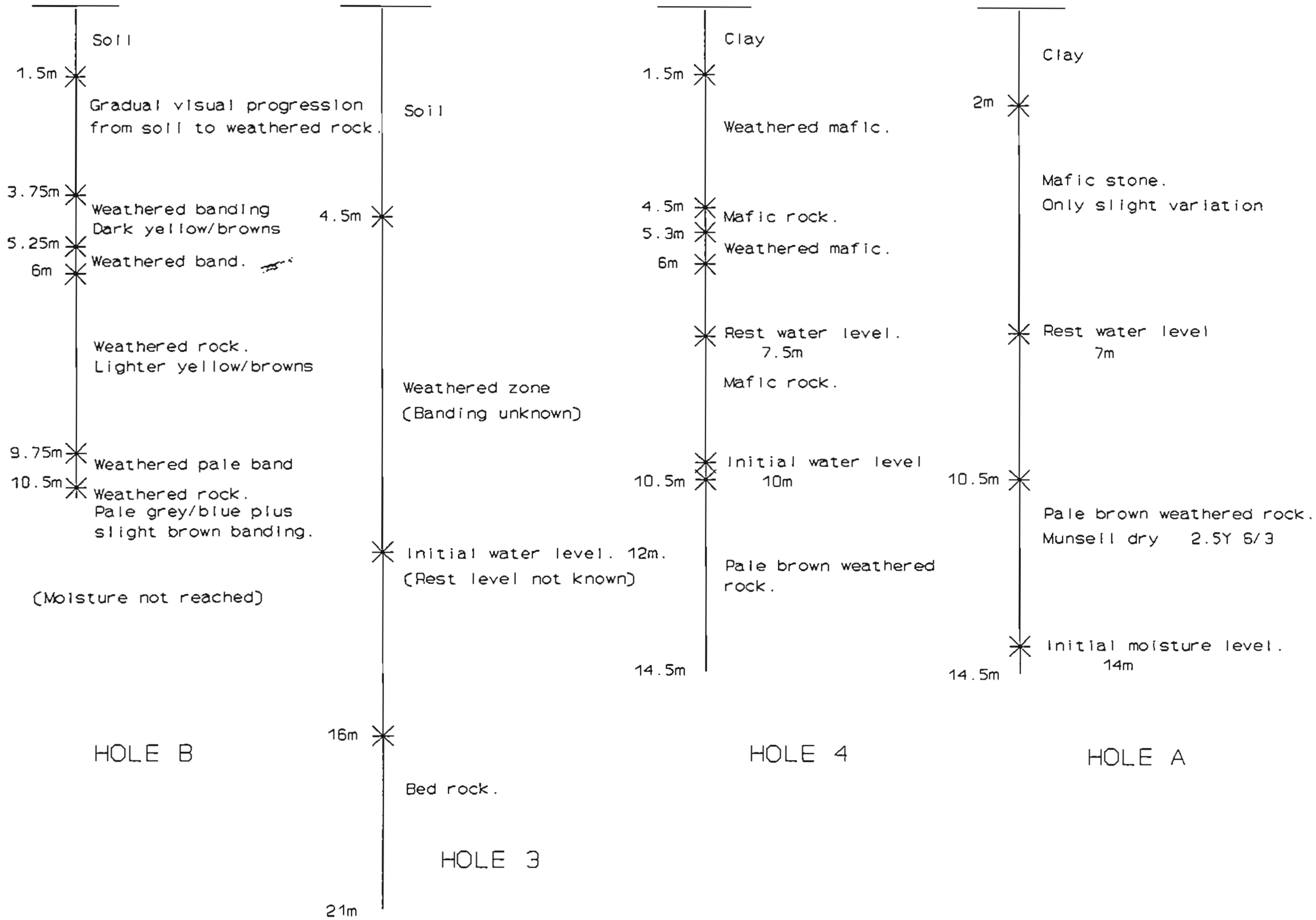


Figure 13 Descriptions of the boreholes.

Table 1 Particle size analysis of surface horizons.

	SOIL PIT			
PARTICLE SIZE[9]	1	2	3	6
600μm - 2mm %	12	7	6	16
200μm - 600μm %	22	34	11	24
100μm - 200μm %	29	27	13	28
60μm - 100μm %	11	11	7	13
2μm - 60μm %	11	15	20	12
< 2μm %	15	6	43	7
	Sandy loam	Loamy sand	Clay	Loamy sand

4.1.4 Crust strengths

The strength of the surface crusts at pits 1, 2, 3 and 6 were investigated, (Photograph 10). A subdivision of the crust occurring around soil pit 2 is made: crust approximately 10m from a large ill defined termite mound was tested as well as the crust surrounding the soil pit.

In Figure 14 the frequency distributions are illustrated together with the mean and median values.

4.1.5 Soil Permeability

The hydraulic properties of the horizons in the six soil pits were investigated with a few exceptions. The surface layer at soil pit 5 was too rough to site the permeameter due to the relatively recent ploughing. Both horizon fours in pits 1 and 2 and the saprolite layer in pit 2 were omitted from the investigation due to their in accessibility. In pit 4 the third and fourth clay layers were also left out as it was felt that their hydraulic properties were not vital since they are covered by an impermeable clay layer.

Figure 15 illustrates a typical series of measurements for the different soil horizons in soil pit 1. An impression of the relative infiltration rates is conveyed by such a diagram though single point measurements must be treated with care due to spatial variability.

Figure 16 displays this data in an appropriate form for the analysis. From the cumulative volume (Q/AREA) versus time graphs it can be seen that the steady state infiltration rate is being approached. But the graph of the cumulative volume versus the square root of time does not form a straight line as anticipated. This was repeated for the other horizons in the other soil types, though some runs did more closely conform to the expected shape, these were the exception rather than the norm.

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[9] Equivalent spherical diameter.

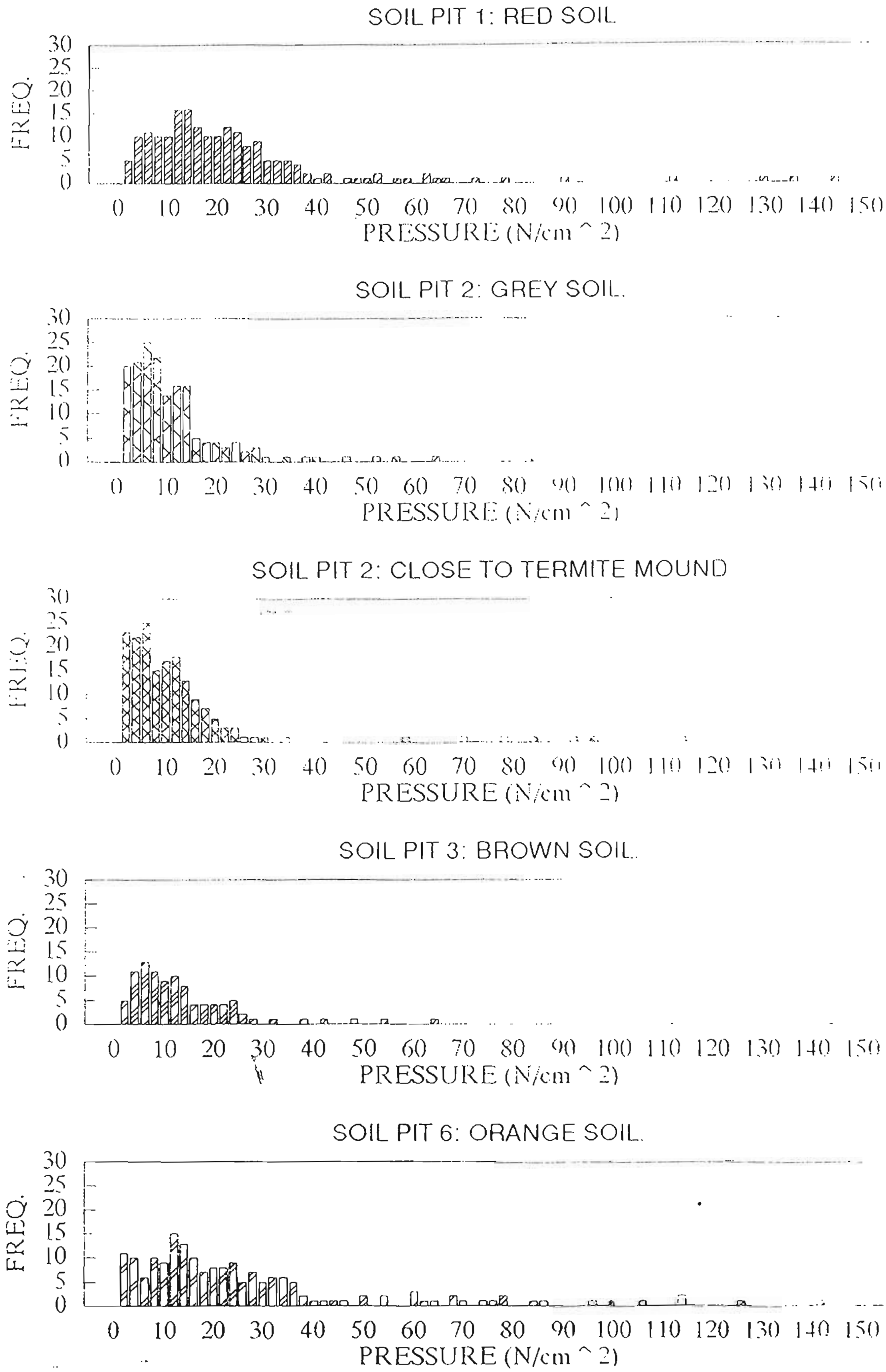


Figure 14 Crustal strengths.

Photograph 10 *Pieces of crust collected from soil pit 1 (left), 3 (centre) and 2 (right).*

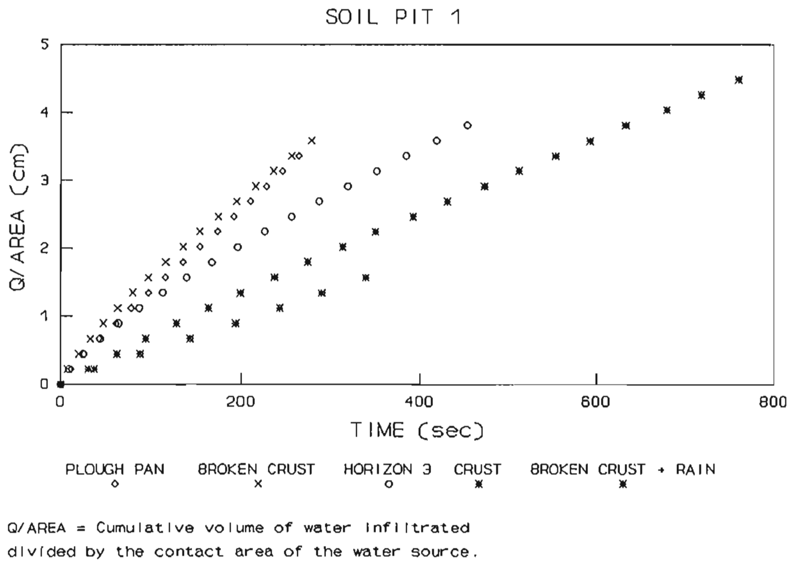


Figure 15 *Typical set of permeameter readings for soil pit 1.*

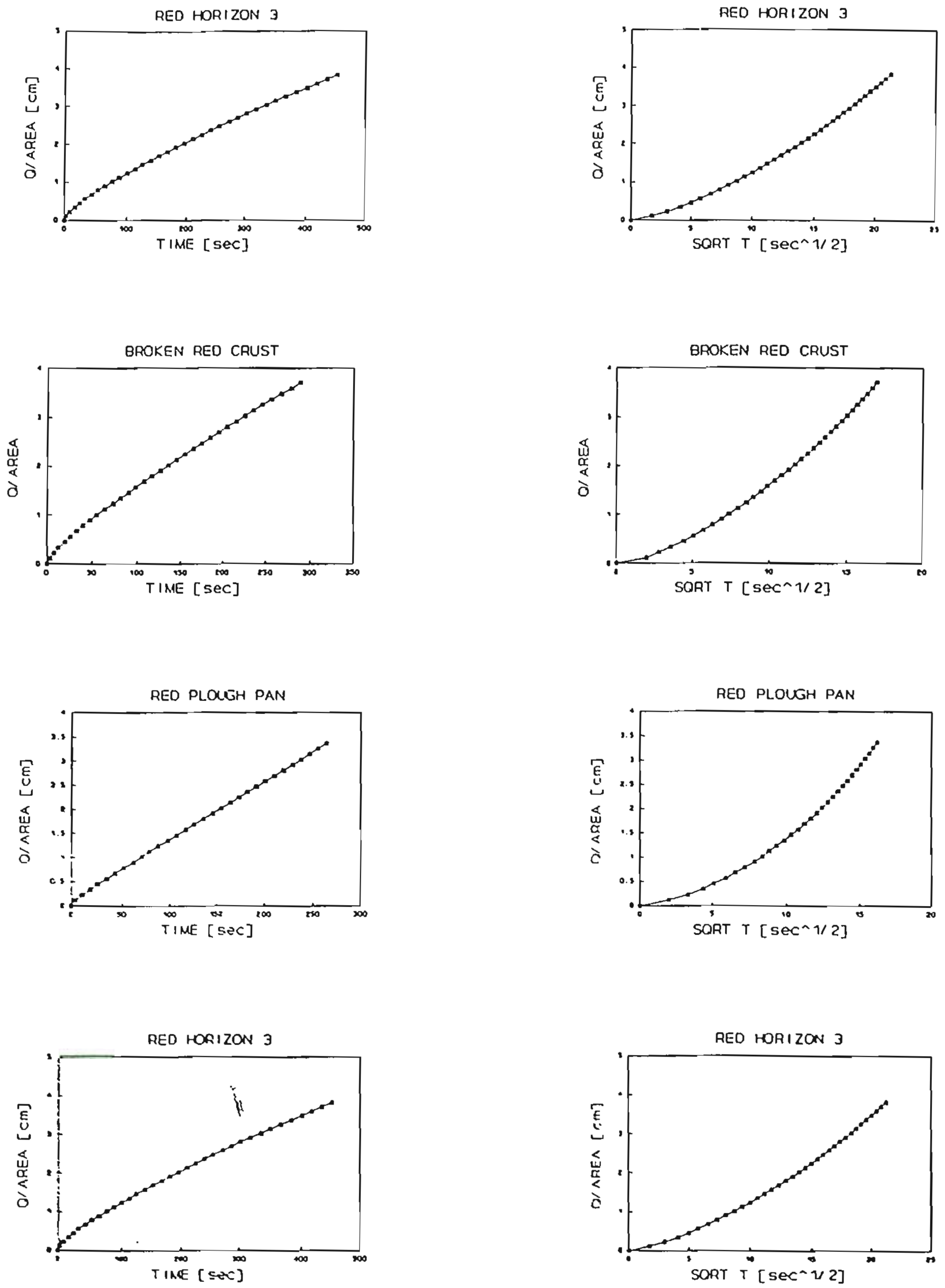


Figure 16 A set of typical infiltration results for soil pit 1. The graphs on the right show the data plotted with the square root of time along the x axis.

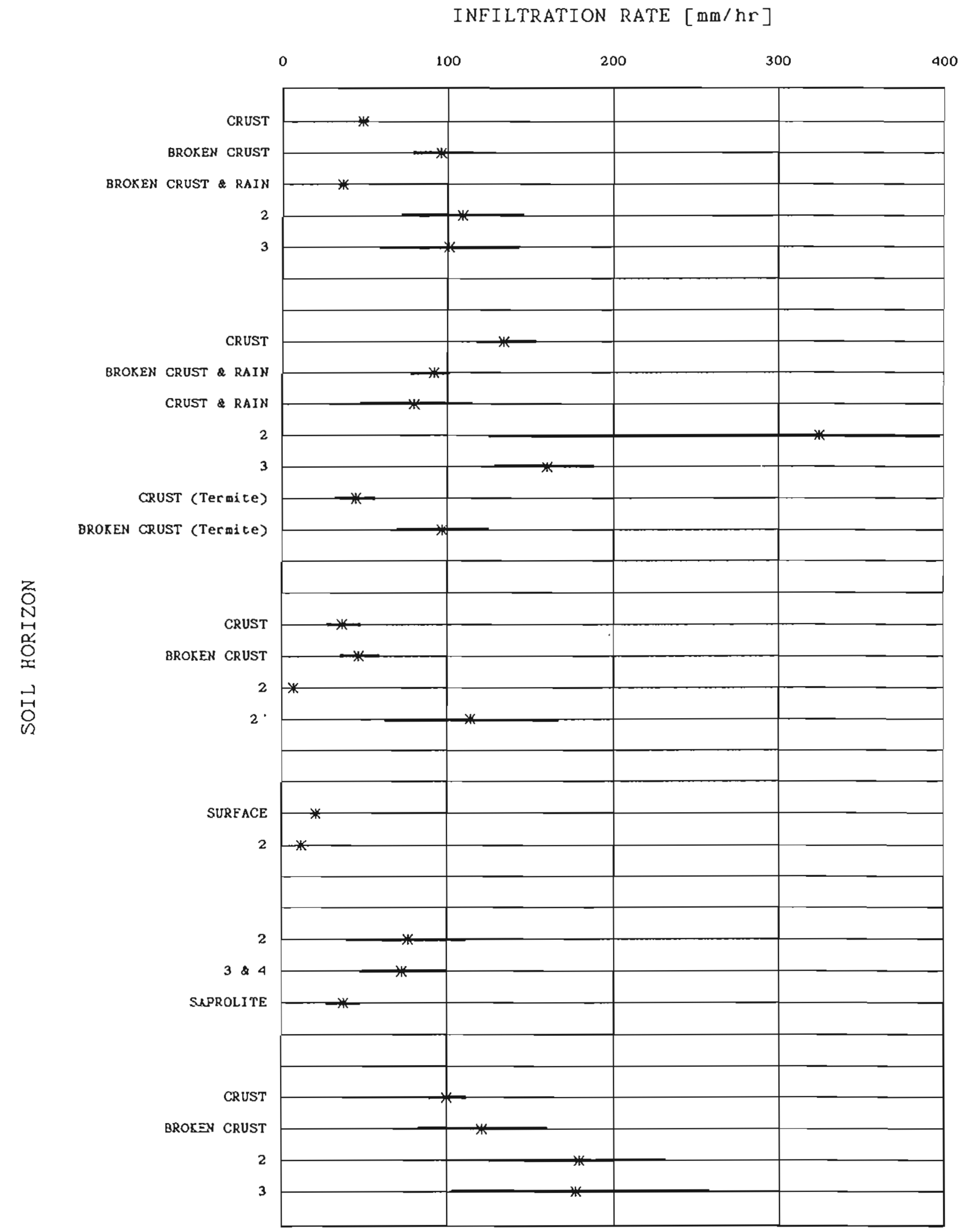


Figure 17 Summary of infiltration rates (with error bars).

The relatively high permeability of the soils means that the sorptivity dominated period is relatively short. Therefore a significant error may be produced if the zero time is not correctly measured. This may explain the nonconformity of the soils, though subsequent adjustment was unsuccessful.

As a consequence the sorptivity and hence the saturated hydraulic conductivity could not be calculated from the readings taken.

One value that can be estimated from the measurements is the steady state infiltration rate from the disk, (Figure 16 and Appendix 5). Note that horizons 3 and 4 of soil pit 5 have been grouped together. This was due to horizon 3 being too thin to be tested by itself.

All the soils tested, apart from the cracked clays, produced the characteristic bowl of wetness beneath the permeameter. For the cracked clays most of the initial water penetrated deep into the crack system until the clays swelled and sealed them.

It is suggested that those horizons in Figure 17 that have large standard deviations associated with their infiltration rates probably house macro-pores. This is to a certain extent confirmed by the soil pit descriptions.

4.1.6 Rainfall simulation

In the limited time it was only possible to investigate the effect of raindrop impaction upon the broken and unbroken grey crust (soil pit 2), and the broken red crust (soil pit 1). Visual disturbance of the soil surface was evident.

The average conditions for each crust type are described in Table 2.

Table 2 Summary of simulated rainfall conditions.

Type of crust	Shower height (m)	Av. Rainfall (mm/hr)	Av. Duration (sec)	Power per m^2 W/m^2
Unbroken grey	2	415 ± 60	70 ± 25	1.18
Broken grey	2	430 ± 51	93 ± 3	1.23
Broken red	2	408 ± 29	90 ± 1	1.16

The average drop diameter was calculated from 33 measurements to be 2.07 ± 0.22 mm. Lal's data gives a drop of this size a terminal velocity of 6.5 m/sec, (Lal, R., 1977: pp 51). Using this information the average drop impact velocity is calculated to be 4.5 m/sec, which equates to an impact energy of 4.3×10^{-5} J/drop. In Table 2 this has been converted to power per unit area.

4.2 LOCAL KNOWLEDGE

Eleven elders attended the meeting; further contributions were made outside of the meeting and have also been included when confirmation was available.

4.2.1 Initial conditions

The catchment was first settled in 1953. Before then man's impact upon the valley had been negligible. The hills and valley bottom were wooded apart from several wet areas that were located upon the brown and black clays and along sections of the main stream, (Photograph 11). In these areas there was an absence of trees, the dominant vegetation were long grasses. These areas were remembered as remaining wet for nearly the whole year. So wet that to walk upon them would cause water to be squeezed to the surface. Only after mid September to the first rains would the top soil dry.

All these wet areas over the last two decades have dried up.

Neither the major stream nor the three tributaries, (Photo 11), flowed all year round. Water in the form of pools would remain along the main stream bed until June. In some exceptional years pools would remain until September. One of the pools was permanently fringed by reeds. They remembered catching fish in these pools when they first entered the valley.

Tributary 1, (Photograph 11), was fed by a spring located half way up the side of the hill, (off the bottom of the image), which usually ran until the end of March. Domestic water was drawn from the spring during this period.

Tributary 2 was also fed by a spring that only supplied water during the rainy season.

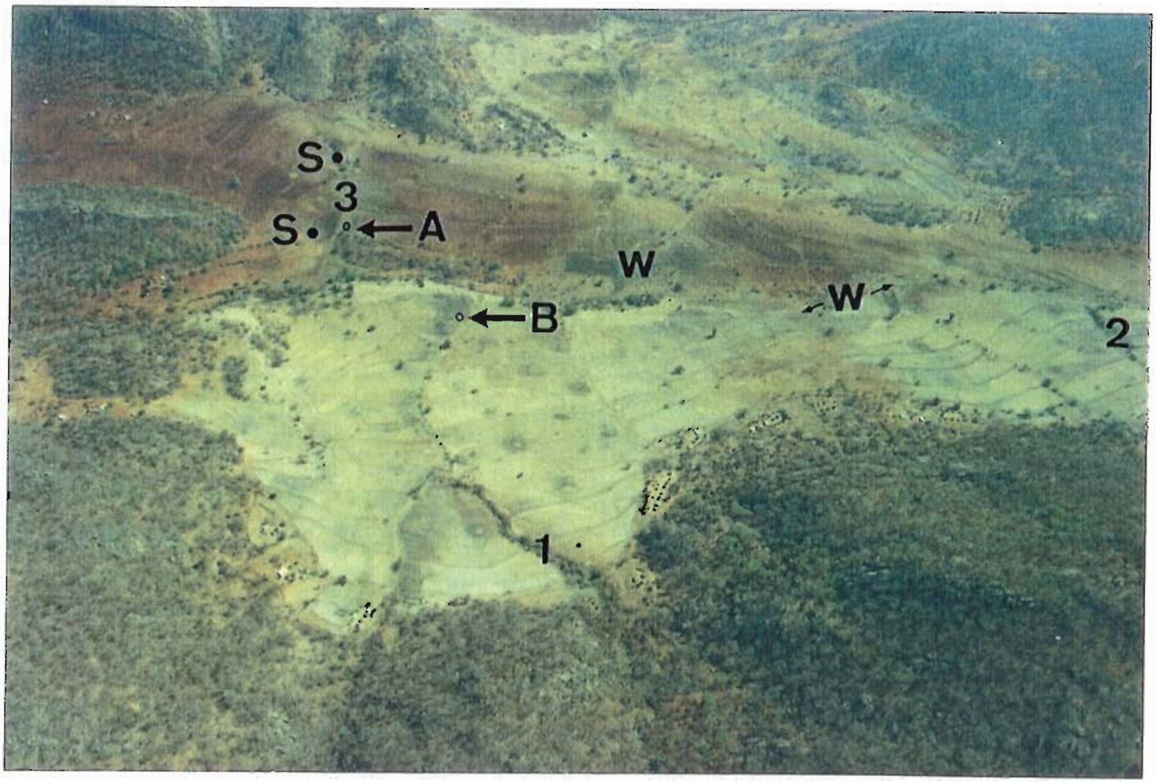
Tributary 3 was fed by two springs, (Photograph 11). One close to the inselberg and whalebacks that form the back of the small sub-catchment. The other near the bottom of the sub-catchment where an obvious band of rock crosses the sub-catchment exit. These springs again only flowed during and shortly after the wet season.

All these springs have operated up until the recent droughts during the 1980s.

The clearance of the wooded valley bottom was completed by the early 1960s. It was by then that all the dwelling sites had been established. The wet areas adjacent to the stream remained wet until the 1970s. An explanation suggested for this was that it was at this time that their cattle grazing rights to another valley were taken from them. This resulted in these wet areas being intensively grazed and trampled changing the moisture status.

4.2.2 Rainfall

They were unsure concerning questions upon changes in rainfall pattern. Though several suggested that the frequency of long duration rain storms and the overall amount of rain had decreased.



__Photograph 11__ Aerial view of the catchment.

Numbers represent the tributaries.
A and B locate the sites of wells.
W indicates the location of what used to be grassywetlands.
S indicates spring sites.

Subsequent analysis of rainfall data, dating back to 1951, from two weather stations 10km north and 10km south of the valley suggests that the rainfall in the valley would be highly variable and that there is no discernable long term trend[10], (Figure 18).

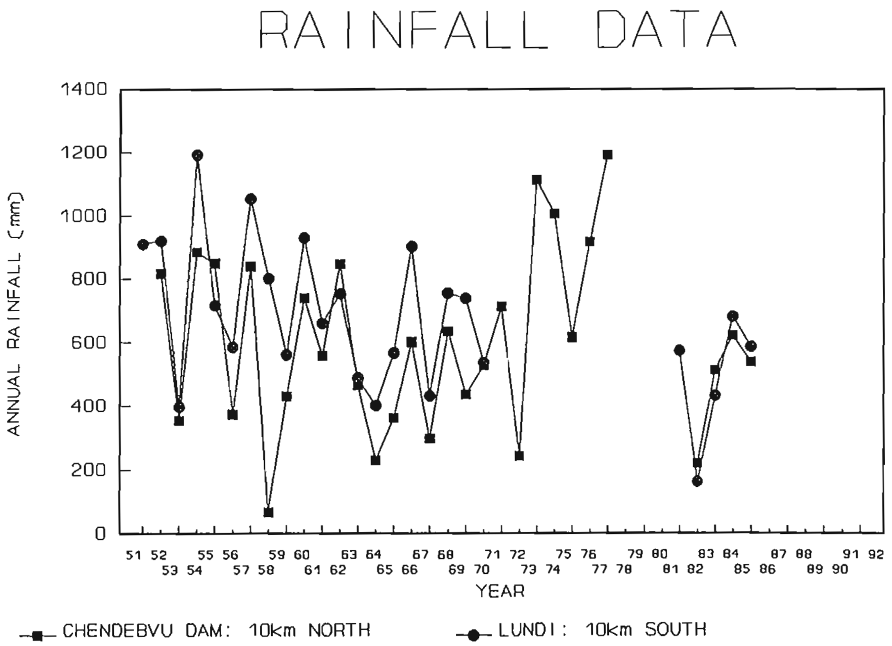


Figure 18 Rainfall data from stations close to Tamwa.

4.2.3 Crops Grown

Rain fed maize, groundnuts, rice and rapoko were initially favoured. The rice was grown upon all the clay soils, and also upon the grey soils to the south of the stream, where it used to be grown to almost half way up the slope. No rice was grown upon the red soil. The other crops would be grown either on the red or grey soils.

The crops now favoured almost anywhere in the valley are maize, sunflower and groundnut, and cotton on the red soils. The last rice was planted in what used to be the wettest areas in the early 1980s.

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[10] Data covering the last few years of drought was not available. Some data for the years preceding independence is also not available.

4.2.4 Catchment wells

Initially the domestic water supply was met by: the streams, the pools in the stream bed and from limited exploitation of the ground water. For the first two decades there were no more than two operational wells in the catchment. This may reflect either the abundance of surface water or just a small demand from a relatively small community. These two wells, A and B, are located upon photograph 11.

When well A was initially dug in the 1950s the rest water level was less than 2 metres. During the 1960s it collapsed and a replacement 5 metres deep was dug about 60m up slope. Though the water level fluctuated it was generally at 3 to 4 metres. During the drought at the beginning of the 1980s the well did not have to be deepened. In 1989 as a consequence of the present drought the well had to be deepened to 7 metres. In 1992 the well was further deepen to hard rock at a depth of 8 metres. Only a limited supply was available and worries were expressed that it would soon dry up.

Well B was dug during the 1960s. A plentiful supply of water was found at 2.5 to 3 metres. The well was slightly deepened just before it collapsed in the mid 1970s. A new well was dug to a depth of 5 to 6 metres adjacent to the old one. This was deepened in 1985 to 11 metres. The owner noted that the water level had not been a cause for concern until the 1980s, but since then the level seems to have consistently dropped, (Figure 19).

This seems to be confirmed in Figure 18. Only data from the newer well, at site A, is included because the old and the new wells were not constructed at exactly the same location. Since the two wells at site B are built adjacent to one another and they both have a depth measurement in 1975 both sets of data are included. A small adjustment is made due to the 1 metre difference in levels in 1975.

In the catchment there are over 20 hand dug wells, all with water levels greater than 6 metres. Subsequent to the meeting the age of each of the wells was ascertained, (Figure 20).

It should be noted that roughly half of these wells are running dry and that again roughly half have reached weathered though solid rock that prevents further excavation.

4.2.5 Observations during rainfall events

During the heavy rainfall events the water that falls upon the hill sides infiltrates either into the surface of the steep slope or into the area at the base of the hill. General surface runoff onto the soils of the valley bottom is not usually seen.

Their observation of the soils suggests that the rain infiltrates into the grey sandy soil significantly faster than on the red soil. They believe the red soil to quickly "seal" during the rainfall event, and they have observed sheet flow to be common. They also said that during a relatively dry year the rainfed crops upon the red soils were the poorest causing hardship upon those families dependent upon that soil. During normal rainfall years they did not make the distinction.

If surface runoff in the form of a channel was formed they said it eroded the grey soil to a much greater extent than the red which they described as having the ability to "stick together".

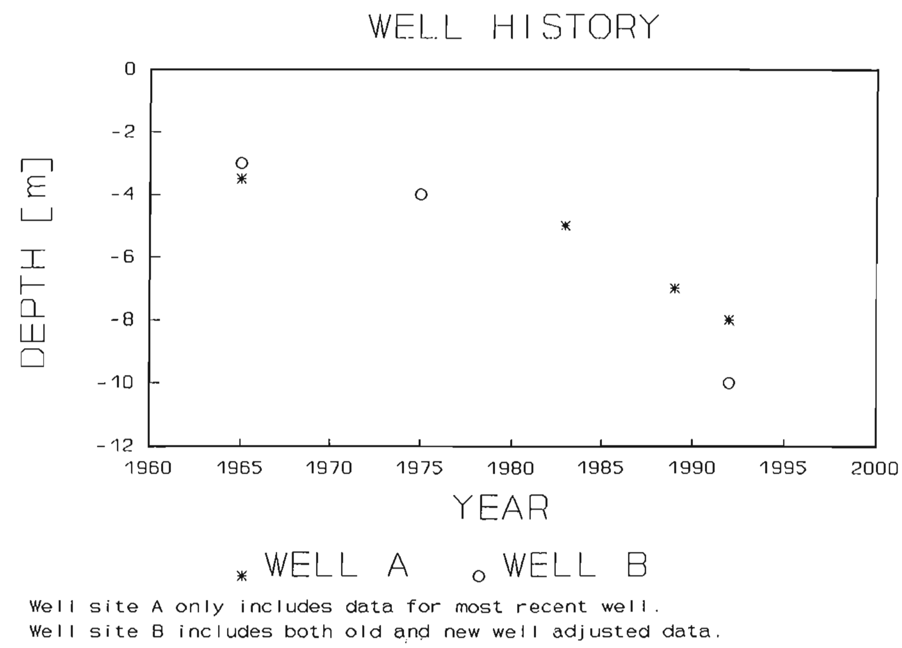


Figure 19 Water level history of wells A and B.

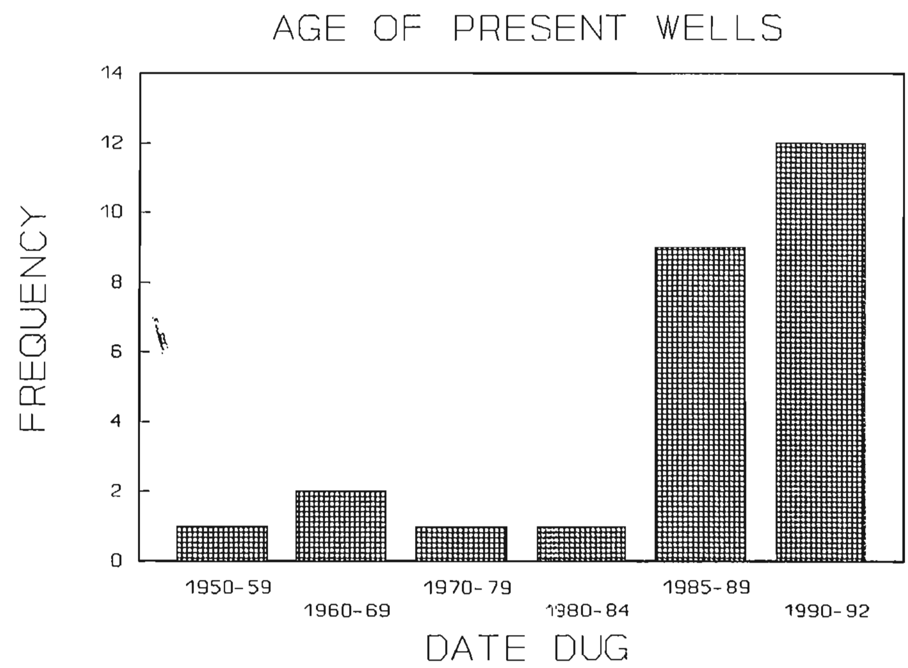


Figure 20 When the present wells were constructed.

4.3 WELL MONITORING

20 wells in total were monitored, of which all but one (number 8) were hand dug, (Figure 21). Number 8 is an unused borehole with no pump attached at the top. Its diameter is also too small to permit effective abstraction by using a vessel lowered on a rope. Therefore the water level is assumed to be unaffected by abstraction and to reflect the true water table of that particular area.

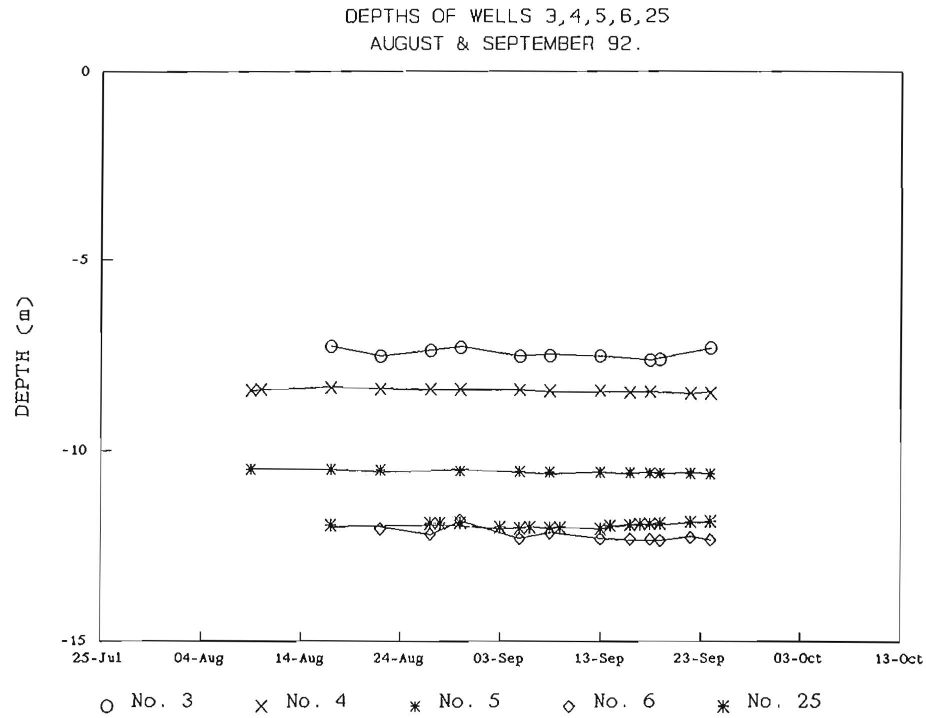
Figure 22 shows how each of these wells fared during August and September 92. Figure 23 indicates how the water level in number 8 has changed with time together with two wells, 4 and 5, which seem little affected by abstraction which suggests that they require only a short time to recharge and hence should also reflect the true water table. The rates at which the water level was falling are given in Table 3.

Figures 24 and 25 show the approximate position of the groundwater along the two surveyed lines X and Y.

Table 3 *The rate at which the ground water was lowering.*

WELL NUMBER	RATE OF DROP OF WATER
8	- 2.8 mm/day
4	- 3.2 mm/day
5	- 2.7 mm/day

Figure 21 Location within the catchment of each of the wells monitored.



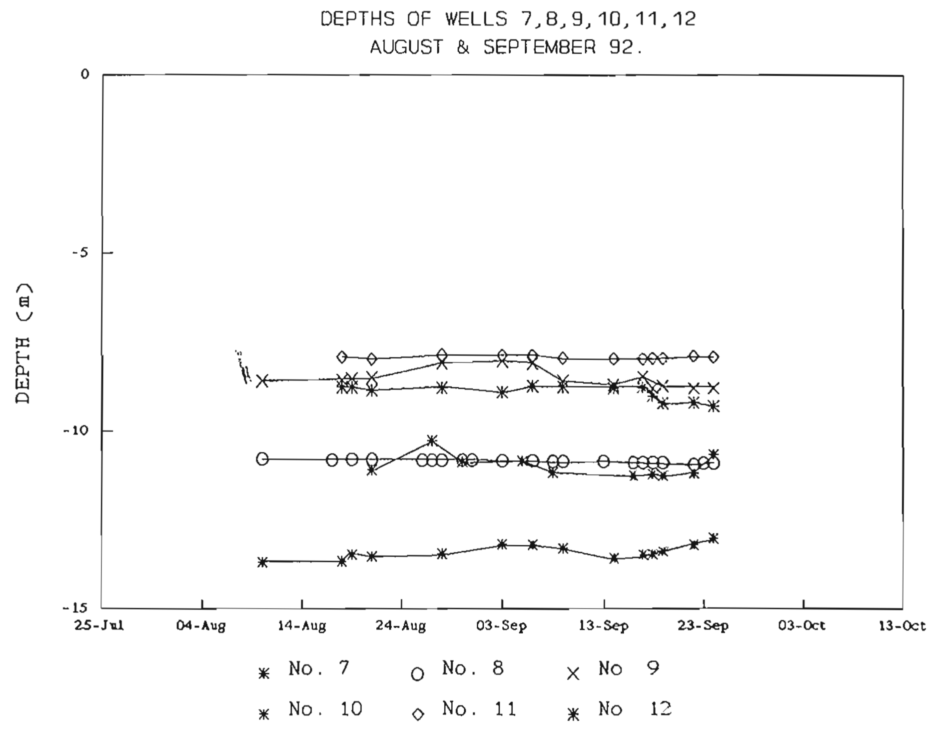
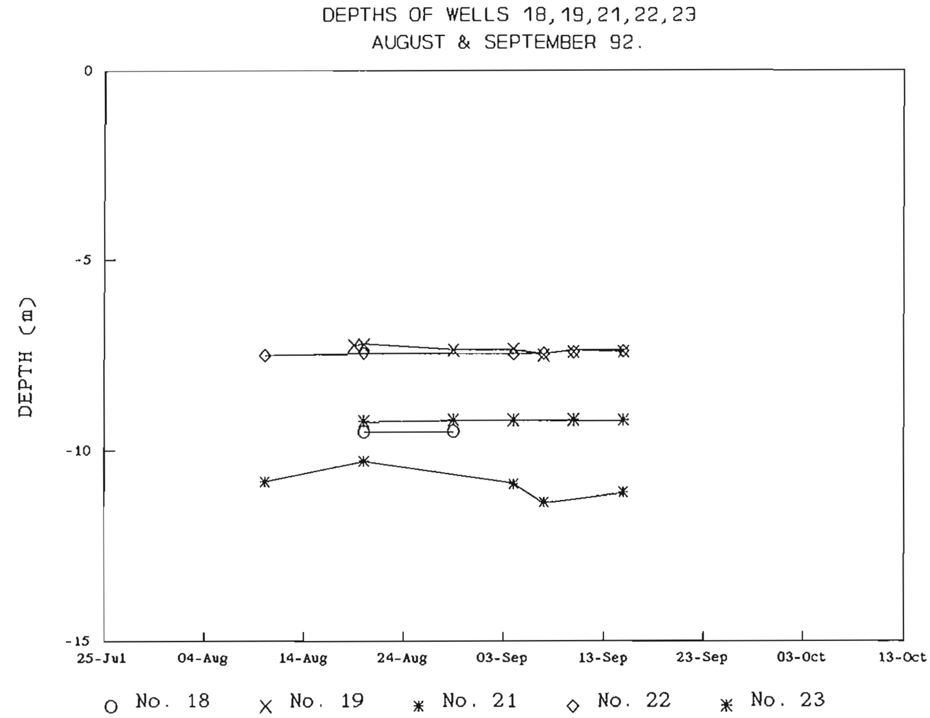


Figure 22 Well depths.



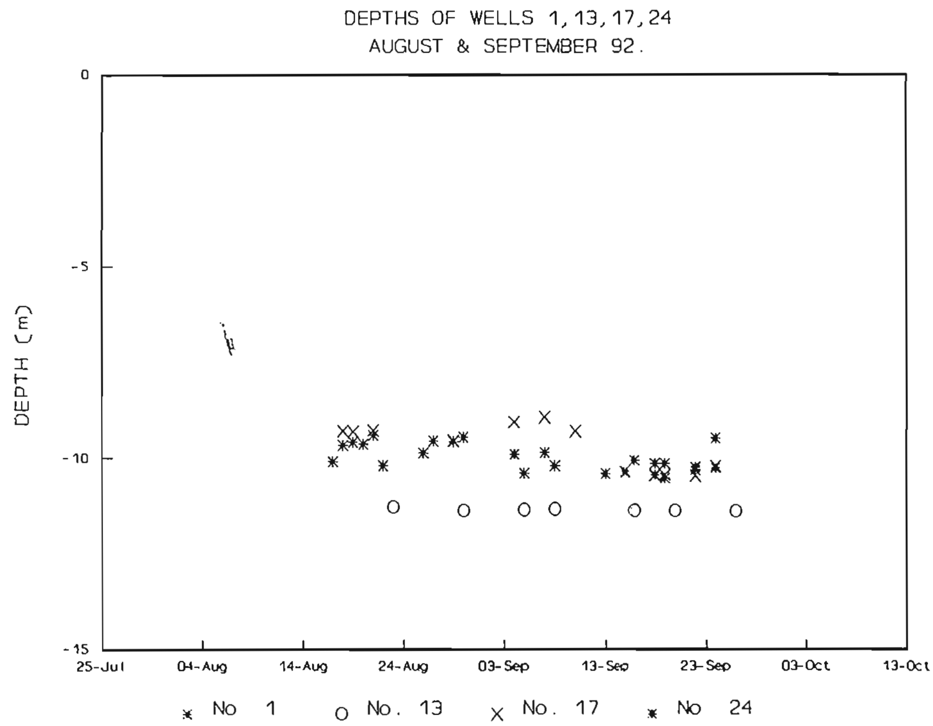


***Figure 22** (cont.): Well depths.*

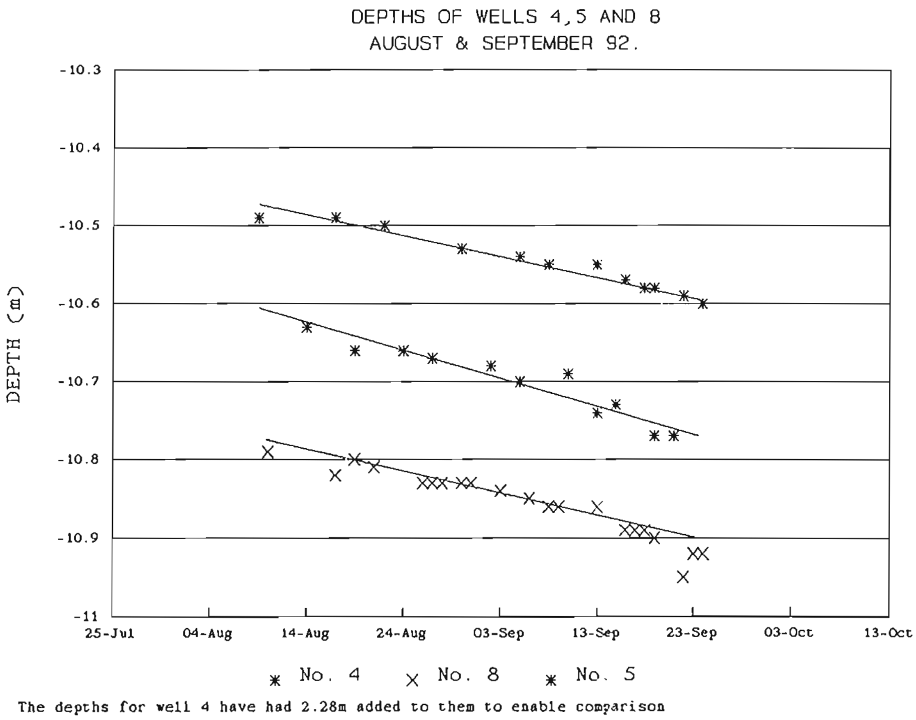


Figure 23 Rate of water level lowering in wells 4, 5 and 8.

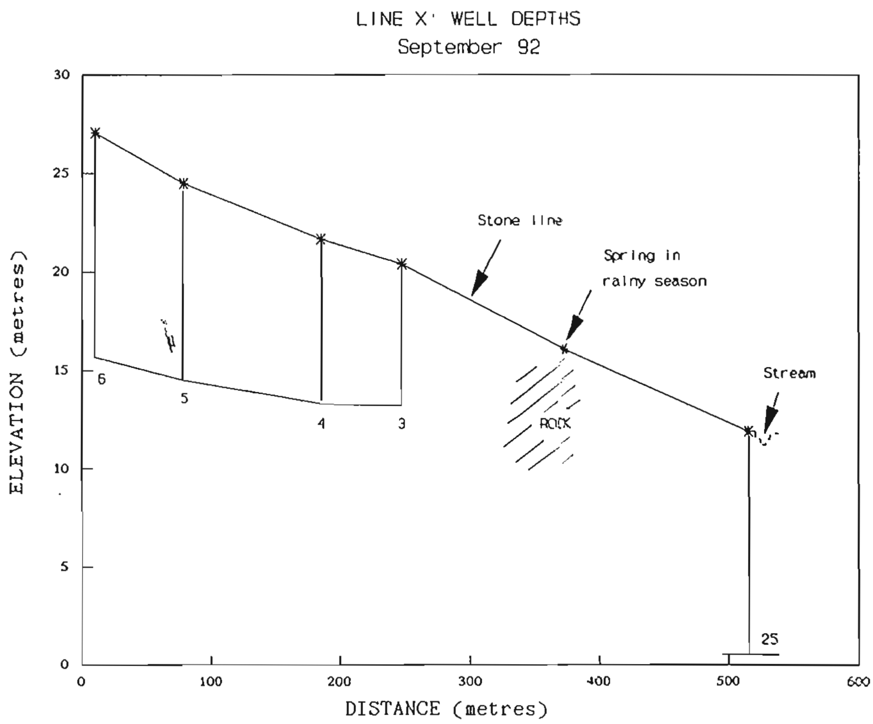


Figure 24 Water level along line X.

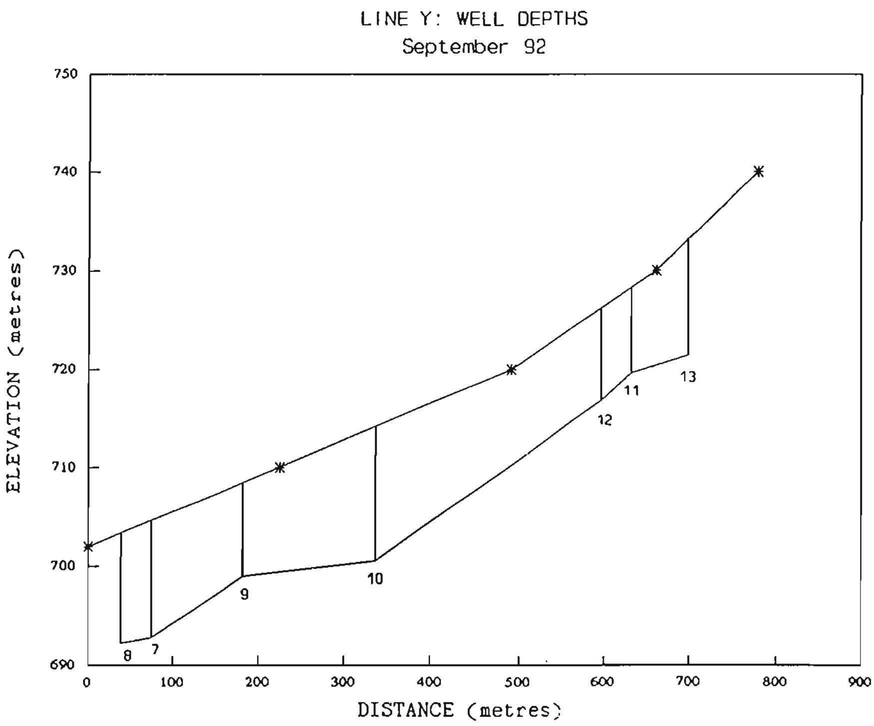


Figure 25 Water level along line Y.

5. Discussion

5.1 SOILS

Care must be exercised when consideration of the applicability of these results and conclusions to other catchments and areas is to be made. These results reflect the properties of soils specific to the locality and conditions experienced at Tamwa and may not reflect the properties of different soils that have had different parameters governing their genesis and recent condition.

The catenal assumption that the finer particles would be found to accumulate near the bottom of the slope was partially confirmed by the transect description. Along the red transect this was made obvious by clearly distinct areas of differing soils. Upon the grey transect is was visually less apparent, yet nevertheless almost certainly occurring. The extent to which this grading would effect the physical properties of the grey transect soils was not investigated. This should be remembered if seeking to apply these results elsewhere, since the physical properties of the soil may be sensitive not only to the general class of the soil but also to the location with respect to the slope within that class of soil.

5.2 DRILL SAMPLES

These together with the hand dug well observations provide evidence of substantial weathering down to at least 10 metres. The boreholes along the transect suggest a complicated aquifer with much spatial variability. This was later confirmed by further drilling in close proximity to the holes described here. Layers of perched water were observed, presumably reflecting the variability in the weathering of the rock.

The artesian nature of the aquifer supports observations made by J.Chilton in a similar landscape in Malawi, (Chilton, P.J and Smith-Carrington, A.K., 1984), and suggests that semi-confined aquifers may be generally common to such areas.

5.3 CRUSTAL STRENGTH

At the time of the field work the conditions found within the catchment were not typical. The region had been suffering a severe drought for several years which had culminated in the 1991/1992 rainy season almost completely failing. As a result the normal annual preparation of the land had not been applied. Therefore the bare surface had been exposed to a slightly different set of conditions compared to the usual year. Most the soils had therefore been left unploughed for a longer period of time than normal and this may influence the crustal properties. Though the resulting flatness of the soil did enable fairly random selection of sites for infiltration and strength testing. In the one place where ploughing had occurred at the start of the year it was impossible to test the surface infiltration rate using the disc permeameter and it would also have produced non random results for the crustal strengths if tested.

Comparison of the strength distributions for the red and grey soils can be made since they were last ploughed at roughly the same time. Despite nearly 200 tests to failure per crust the rather uneven appearance of the distributions suggests that even more tests should be made.

Despite this the average values and the general shapes suggest that the surface of the red soil does produce a substantially tougher crust. There is the suggestion that the proximity of the termite mound increases the crust's strength. The latter is not altogether unexpected since the termites are known to be selective in choosing particles for building, (Lee, K.E. and Wood, T.G., 1971). Therefore the material washed off the mound will probably have a different texture and hence different physical properties as perhaps witnessed in both the strength and infiltration rate results.

The results for the crust developed upon the brown clay are not as useful since the crust had already naturally cracked in places and hence the parameters governing the mechanics of the test will be slightly different.

The orange loamy-sand also seems to produce a strong crust.

There is no evident correlation between crustal strength and infiltration rate. These results therefore serve as a means of labelling the condition of the crust examined.

5.4 INFILTRATION RESULTS

As described above the conditions after a prolonged drought are possibly not representative of the normal conditions. Though a certain importance should be given to such conditions since after such a long drought it is all the more important to ensure good infiltration so that the depleted groundwater can recover.

The inability of both the Disc and Guelph permeameters to measure either the sorptivity or the conductivity indicates that the soils investigated do not form homogeneous layers; or that the theory, that is based upon several simplifying assumptions, does not hold for these particular soils.

In fact the infiltration rates measured can not even be regarded as the true infiltration rates because the geometry of the permeameter unavoidably introduces large edge effects. These edge effects will be dominated by capillarity processes, which are accounted for in the permeameter theory, but for standard infiltration tests are normally minimised by the use of a second concentric ring to supply the edge effect water. By doing this the water infiltrating from the central ring will approximate to 1 dimensional flow. 3 dimensional flow is established in the case of the disc permeameter; therefore the steady state infiltration rates shown in Figure 15 will be significantly higher than standard values. Nevertheless they do give an indication as to what the relative infiltration rate properties of the horizons are. From this it should be possible to identify the flow determining horizons.

The results for soil pit 1 indicate that the crust is the "throttle" layer, having hydraulic properties that are about twice as restrictive to the flow of water as that of the lower layers. Also a clear difference in the infiltration rates of the broken crust depending on whether or not the surface has been subjected to raindrop impaction confirms the necessity of simulated rainfall tests. It also highlights one of the roles vegetative cover plays in enhancing infiltration. The result suggests that it may not be beneficial to break the crust in the hope that this will greatly increase the infiltration rate. This is confirmed by what the locals have observed when they say that this surface "quickly seals" in a heavy rainfall event.

The predominantly fine to medium grained grey sand located at the base of the hill has a much higher crustal infiltration rate. For ponded water no layer can obviously be identified as being the rate determining horizon. But after simulated rain the crust seems to represent the throttle layer regardless of whether the crust was initially broken or not. Though the rate of infiltration is still almost twice that of the red crust. The locals' observations again substantiate this result, as does the lack of stream channels radiating from the hill bottoms.

The high apparent permeability of horizons 2 and 3 is not surprising considering their highly porous nature.

The simulated rainfall data suggests that the surface is better sealed immediately after the rain rather than after a long desiccating period. Further work would be required to substantiate this.

The underlying horizons of clay once wetted very effectively prevent the downwards passage of water in pits 3 and 4, though, initial penetration along the cracks is very rapid.

In the absence of infiltration data for the surface, the resulting throttle layer in soil pit 5 seems to be the saprolite. The apparent permeability of this is relatively low, almost half of that of the above horizons that could be tested (the crust unfortunately could not be tested because it had been recently ploughed). The rate recorded for the saprolite was substantially less than the slowest horizon from soil pit 2. If the saprolite in soil pit 2 is similar then this may determine the rate of recharge to the groundwater from around the base of the hill. Though since the saprolite tends to occur over a metre down it is very unlikely to cause a backlogging of water that might stimulate surface runoff and hence erosion. If the soil above the saprolite was 35% porous and 2 metres in depth it could hold 700mm of water. This is roughly the expected annual rainfall, it is therefore unlikely to completely saturate, though it should not be discounted since the runon from inselbergs could substantially increase the volumetric input of water.

The crust again seems to be the important layer at soil pit 6; though no simulated rain data is available. All the layers seem to be highly permeable.

5.5 SIMULATED RAINFALL

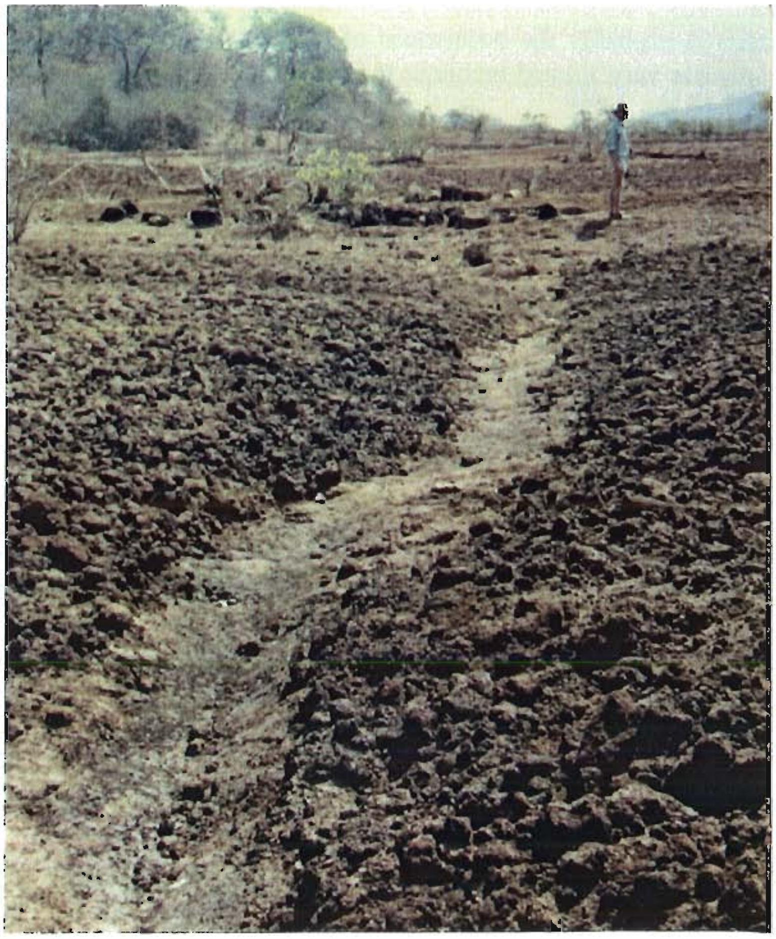
The simulated rainfall results have an important bearing upon the infiltration rates. Does the experimental rainfall represent a good simulation, and are the results likely to be experienced in real life?

To answer this comparisons are made to independent data. Lal suggests that a 2mm raindrop equates to a drop likely to be the average size in what he terms as a "heavy rain", which is about the heaviest that would be expected in the temperate zone, (Lal, R., 1977). Lal lists possible drop size diameters of up to 6mm, which are associated with tropical cloudbursts. The maximum intensities he lists are up to 100mm/hr, which is only a fourth of the simulated intensity. But the maximum quoted overall energy per second per metre squared is 1.2 W/m^2 which is the same as that calculated for the experimental rain. Therefore although the intensity was several times larger than could be realistically expected the drop size and power were acceptable and it is suggested that the experimental results are suitable as a guide to what may really happen. Though a more controlled experiment would be desirable.

The implications of the infiltration results are interesting. As noted in the introduction, the particúlar geomorphology of the region will tend to concentrate large quantities of water in relatively short time scales across the base of the hills.t is along this fringe that the most permeable soils are fortuitously located, assuming that the soils from pits 2 and 6 are representative. The type of soil, though maybe not its management, seems to be optimum for recharge, which also helps reduce the threat of erosion. Confirmation of this comes from the locals' observations, the lack of established channels radiating from the hills and even the positioning of the dwellings which are sometimes located at the bottom of large expanses of bare rock that must shed a tremendous amount of water during heavy storms.

Though the type of soil may well be suited to rapid infiltration it does not necessarily mean that the soil can cope with all the runoff. The established runoff channels may not be common, but recent top soil erosion channels are evident, (Photograph 12). These are particularly evident where the contour bunds have fallen into disrepair and causes the double problem of erosion and reduced infiltration. The amount lost to the soil and deeper recharge could be significant, particularly in such a place where rain fed cropping is presently so marginal.

To help combat recharge problems two major factors have to be addressed: i) maximising the hydraulic properties that pertain to infiltration, and, ii) holding the water upon the soil for as long as possible to give it a chance to infiltrate.



Photograph 12 *Evidence of channelled surface runoff in a ploughed field at Tamwa.*

Many techniques to achieve these aims have been devised, yet the problems still exist due to their inseparability from other environmental parameters and problems. No one hydrological technique on its own will be capable of solving the water management problem. Instead a whole suite of management practises is required that not only tackle the environmental science problems but also address the economic and socio-cultural aspects of such places. Integrated catchment sized management is desirable.

5.6 WELLS

The information regarding the wells within the catchment must be treated carefully. The graph of the levels within wells A and B (Figure 19) is based upon locally recalled dates and depths and will be subject to some understandable error. The graph has only a few points and is only based upon two sites which may not be representative of the whole catchment. But nevertheless it does imply an accelerated water level drop during the 1980s and early 1990s. The loss of available water is also suggested by the evidence of many more wells being dug particularly between 1985 and 1992, (Figure 20). Though the numbers will be biased towards the recently dug since those that had collapsed have not been included. Though the inclusion of the collapsed wells is very unlikely to alter the conclusion of a rapid proliferation of wells.

Did the water level drop due to increased exploitation due to the greater number of wells, or was it related to a decrease in recharge?

The dominant reason is probably the occurrence of droughts in 1983 and during 1988 to 1992. During these years very limited recharge if any could have occurred.

Though work by Meigh, (Meigh, J., undated), in the Lowveld suggests that significant recharge may only occur when a rainfall event of the right intensity and duration occurs and that this may not happen every wet season. In his analysis only 3 out of 8 years seemed to have the right set of conditions for recharge. This implies that a lack of the required heavy rain is more important than whether it is a drought season or not, and hence the occurrence of droughts may be slightly less significant than at first thought. Though this argument is tempered by the fact that his work was not done in a landscape that concentrates large quantities of water in certain areas, viz the base of the hills and inselbergs.

Another factor could be an increased exploitation of the groundwater related to a recent trend towards irrigated gardens in the catchment.

The possibility of a change in the rates of infiltration within the catchment sounds unlikely since the same type of rainfed agriculture across the same area of land was practised before and during the 1980s. Though this is not to say that a more gradual reduction in infiltration has not occurred since the people settled and altered the land use of the valley. Many of the local people suggested that the contour bund system had deteriorated in recent years. Breaching of the ridges has occurred allowing high energy water to reach the main stream bed. There is common evidence of such erosion channels around the whole of the catchment, (Photograph 12).

Perhaps the best way of discovering the reason would be to wait until the present drought breaks and monitor the groundwater's response. If adequate recharge occurs this may suggest that the principal problem lay with the drought, if not, serious thought should be given to how man has affected the hydrological system.

Ground water was found between 7.5 and 14 metres within the catchment via the well monitoring programme, though it is possible that some of this water could be perched. These levels several metres lower than normal non-drought years. The levels also constitute a reasonable guide to the depth of unconsolidated material, since the majority of the wells have been deepened until hard rock has prevented any further progress.

Several of the wells exhibit relatively erratic water levels. The reasons for this could be due to slow recovery rates, movement of the datum and possibly legitimate ground water level changes. Well 1 was particularly prone to fluctuating levels with a range of almost 1 metre. It is possible that ground water exploitation at a similar depth from the collector well, 90 metres away, could be the cause of this. Such influences render as difficult the interpretation of level trends in these wells.

The requirement of an undisturbed well is met in the case of well 8. The water level shows a constant drop of almost 3mm a day. The nearly constant level in wells 4 and 5 suggests that these also are little effected by external influences. Their lowering rates are consistent with that of well 8 even though they are located in a different part of the catchment. If it were assumed that such a rate was ubiquitous within the catchment and the porosity of the saprolite known, then the volumetric loss of water during the drought period could be calculated.

For example if the loss were assumed to be constant throughout the year and a storage capacity of 10% taken, the annual loss from the water budget would be of the order of 100mm. This is roughly equivalent to a tenth of the rainfall. For these circumstances it would also be the average recharge required to ensure sustainability of the aquifer. Obviously this is only a rough estimate that does not take into account variability of porosity, seasonality nor plant transpiration rate at differing depths to saturated groundwater.

Figure 24, illustrating the groundwater levels in comparison to the soil surface along line X, highlights the importance of a continuous exposure of bed rock across the direction of slope. Water is retained within the upper section of the subcatchment in the form of a subterranean reservoir, whilst down slope the ground water is significantly lower. Well 25 is in fact located where the stream bed exits the catchment study area through a narrow gap between two hills. This should be one of the most likely sites for water loss via leakage from the overall catchment. Yet well 25, which was dug down to the bedrock, is one of the deepest in the catchment and had been abandoned due to poor water yields. This suggests that the water loss, suggested by the lowering of the groundwater, is due to it either finding a different route out of the catchment or that the loss is via a different mechanism: evapotranspiration or water abstraction.

Figure 25 shows the groundwater status along the slope to the south of the stream bed. Wells 9 and 10 suggest an obstruction to the passage of water between wells 7 and 9 though no surface evidence validating this suggestion is observed.

The rest water levels in two of the boreholes drilled within the clay regions along the red transect indicate that the aquifer has artesian properties. This is consistent with findings in Malawi in similar terrain where surface layers of clay produce semi-confined aquifer conditions, (Chilton, P.J. and Smith-Carrington, A.K., 1984). It is interesting to note that these rest levels represent the shallowest water in the whole catchment.

6. Future work

To gain a fuller understanding of the hydrological situation it would be useful to model: the general water budget of the whole catchment, the moisture content of specific soils, and to further investigate the hydrological processes of the soils in an attempt to clarify their relative properties. Groundwater monitoring would also be desirable. These results would be instrumental in decisions relating to similar regions concerning:

a) Improved land management practices of agriculture areas.

b) Techniques for enhancing aquifer recharge.

c) The siting of collector wells, or any other high yielding abstraction method, to try to ensure a sustainable location.

d) Environmental management of the area where the high abstraction well/pump is located.

e) General water resource management and environmental management purposes within similar catchments.

f) Development planning of region.

6.1 GENERAL CATCHMENT WATER BUDGET

The topography of the catchment is advantageously shaped to form a reasonably self confined catchment. The periphery is predominantly comprised of distinct steep sided hills and the surface drainage exit is concentrated through a narrow valley less than 100 metres wide. Though there are three topographic saddles connecting to other catchments the largest is topped for much of its length by an exposure of smooth domed rock that probably forms an effective watershed and the other two are relatively small features.

The stream would need to be gauged to measure the outflow and the rainfall accurately recorded along with the other climatic parameters effecting the hydrological cycle. From these and using generalised analytical methods, (Meigh J., undated), surface runoff, evapotranspiration, possible magnitudes of recharge and baseflow can be estimated.

This method is likely to only produce a generalised estimate of the fluxes involved and may suffer from errors due to unrecorded, subterranean leakage that can easily lead to over estimation of evapotranspiration.

6.2 MOISTURE CONTENT MODEL

To try to understand the relative recharge contributions made by each soil type a soil moisture model could be constructed, (Houston, J., 1988).

A basic model requiring: daily rainfall data, the infiltration capacity, actual evapotranspiration and the variation in the soil moisture deficit would provide a good understanding, (Meigh J., undated), though accounting for such factors as: depression storage, interception and through-flow would produce more accurate estimates.

Note that a reasonably accurate infiltration value would be required. To measure this a different approach than that taken in this work would be necessary because of the inapplicability of small scale physics to real soils that have considerable spatial and also temporal variability.

The applicability of a larger scale approach such as that proposed by Bonell would be investigated, (Bonell, M., 1991), where a cascade system comprised of many troughs of the order of 10 metres long and offset at about 25 metres down the slope are used, (Figure 26). This design is based upon the assumption that the overland flow observed in the upslope trough is an estimate of the runon on to a 250m^2 plot and that the runoff is monitored in the downslope trough.

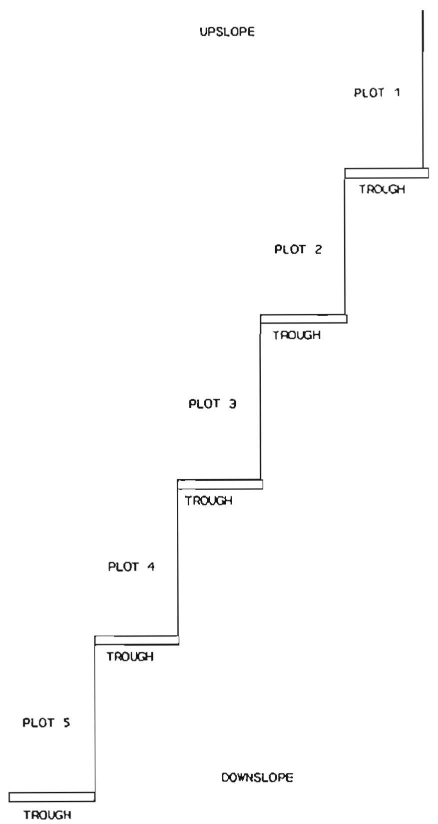


Figure 26 Proposed cascade system.

The infiltration for a given period would be calculated as follows

$$I = R + U - D - dS - Dv \qquad (1)$$

Where I is the infiltration, R is the rainfall, U is the upslope runon, D is the downslope runoff, Ds is the change in surface storage and Dv is the change in interception storage. For short time intervals Ds and Dv will be small and could be taken as zero, consequently the plots will approximate to a constant head infiltration device from which the infiltration can be determined, (Williams, J. and Bonell, M., 1987).

The advantage of measurement over a large semi unbounded plot would be that these dimensions refer to a scale that appears to be representative of the landscape element.

Site selection for such a project must include the basal fringe of the steep hillslopes. If the work were to be conducted at Tamwa it is suggested that one cascade be constructed along the length of the grey soil catena to the south of the stream bed, and another that focuses upon the basal fringe of the hills and the red soil to the north of the stream bed. Such work should be conducted over a period of several years.

6.3 OTHER WORK

Other work should include the comparison of rainfall to the water levels in the wells and boreholes. This would give valuable information concerning the rate of recharge and may even shed light upon the intensity of rainfall required for infiltration to occur. Though its usefulness would be significantly enhanced if the porosity of the saprolite could be experimentally established.

Hydrochemical analysis of the aquifers water around the collector well at Tamwa would help elucidate the age and flows of the water in the aquifer. This would provide valuable information towards the understanding of the processes and the aquifer's rate of recharge.

Controlled variable rainfall simulation to increase the understanding of the role played by impaction by raindrops. Such an experiment should be designed so that the intensity, duration, drop size and energy are all capable of being controlled.

Finally it is suggested that this work should be carried out within the Tamwa catchment for the following reasons:

a) The catchment has been the site for several hydrological investigations, hence there is already a considerable amount of information that can be referred to.

b) The topography should prove adequate for catchment sized experiments aimed at providing data for water budget calculations.

c) The catchment includes a range of soils, hence the results should be widely applicable outside of the valley.

d) An extensive well and borehole system exists in the catchment together with an almost daily dipping record for August and September 1992.

e) The success of the collector well project has fostered a good relationship with the local community, which would probably lead to a willingness to accept such a project and help in its success.

7. Conclusions

a) The normal catenal progression of soils derived from siliceous gneisses in the valley is complicated by the occurrence of a mafic band of rock running parallel and to the north of the stream bed.

b) For all but the clay soils the surface crust represents the infiltration rate determining layer. This means that once the water has passed through the surface there will be no other soil layer that will impede its progress to such an extent that either subterranean waterlogging or the stimulation of saturated lateral flow will occur.

c) The top surface of the saprolite seems to be less permeable than the soil horizons above it. Possibly this or even deeper material will determine the rate of recharge to the aquifer. The saprolite is generally deep enough not to cause surface waterlogging problems, though near the hillslopes where large volumes of rain water are believed to be concentrated this may not be true. It is postulated that throughflow may occur at the soil saprolite interface.

d) The clay soils react differently. The infiltration controlling clay horizon is located beneath the top horizon When desiccated it will permit rapid transport of water via a crack system. This occurs until the clay swells and seals the cracks. It then represents an impermeable layer. These soils are not considered important in the context of aquifer recharge.

e) The soils occurring at the base of the hills seem to possess the highest infiltration properties which is fortuitous since it is estimated that these areas receive large volumes of runoff in short periods of time. Evidence of recently forged surface flow channels suggests that at present the surface is incapable of absorbing all this water.

f) The effect of raindrop impaction was shown to be important when considering surface infiltration. The kinetic energy of the drops seems capable of re-aligning the soil particles into a significantly less permeable layer. Though this conclusion is reached from post rainfall infiltration tests it is believed that this phenomenon of reducing the surface's permeability will occur during rainfall events. Therefore ploughing crusted land to enhance infiltration may work more for the reason that the rough surface can store more water and prevent runoff, rather than allowing a faster rate of infiltration.

g) Of the two dominant soils in the valley the red soil, derived from the mafic band, tends to be less permeable than that of the grey soil developed from the siliceous gneiss. Though further research is suggested to discover the importance of the catenal characteristics upon this statement.

h) The plough pan, although mechanically harder than the soil above it, does not represent the infiltration rate determining layer.

i) The determination of saturated conductivity and sorptivity by point tests based upon the theory of homogeneous soils is labour intensive, may not be representative unless a large number of tests are performed and is likely to be impossible if the soils are heterogeneous. The soils in the valley were not homogeneous and values for saturated conductivity and sorptivity could not be calculated.

A soil water balance approach on a large enough scale to help reduce spatial variability is advocated to calculate the hydrological properties of the soils.

j) The present alarming decrease in groundwater level is probably due to the drought. Though man's influence upon infiltration and recharge rates and his increased extraction rate of water for irrigated gardens should not be dismissed without further study.

k) An implication of the work is that the present crops would prosper and attain a greater reliability if soil surfaces could be prevented from being left totally bare, as presently occurs. Another improvement would be to utilise techniques that hold the water upon the soil's surface without allowing runoff to occur. Both of these measures would also reduce erosion and help increase aquifer recharge.

l) The water level lowering rate of roughly 3mm a day in the wells is of limited use unless the porosity of the substrate is known. If it were known then water losses and recharge rates could be estimated.

m) Within the valley several different types of aquifers are thought to exist: semi-confined aquifers with artesian properties; subterranean reservoirs where a band of rock prevents down slope drainage; variable weathering permitting the existence of regionally localised aquifers and the probable occurrence of perched water.

n) The valley has been significantly changed over the last 40 years by man. This will have an effect upon the local hydrology and is perhaps reflected in: the loss of the wetland areas, the gradual change in the appropriateness of different rain fed crops and the lowering of the groundwater level.

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9. Bibliography

Bonell, M. 1991. Applications of Hillslope Process Hydrology in Forest Land Management Issues: The Tropical North-East Australian Experience, in "Water Management of the Amazon Basin", Ed.s Bragar & Fernandez-Jáuregui, UNESCO, pp 45-82.

Brady, N.C. 1990. The Nature and Properties of Soils, 10th Ed., MacMillan Pub. Company, pp 99.

Chilton, P.J. & Smith-Carington, A.K. 1984. Characteristics of the Weathered Basement Aquifer in Malawi in the Relation to Rural Water Supplies, In "Challenges in African Hydrology and Water Resources" (Proceedings of the Harare Symposium, July 1984). IAHS Publ. no. 144.

Elwell, H.A. 1972. The Influence of Agricultural Systems on Rainfall Runoff, R.A.J. Tech. Bull., no. 15, pp 13-26.

Elwell, H.A. 1984. Sheet Erosion from Arable Lands in Zimbabwe: Prediction and Control, In "Challenges in African Hydrology and Water Resources" (Proceedings of the Harare Symposium, July 1984). IAHS Publ. no. 144.

Grainger, A. 1990. The Threatening Desert: Controlling Desertification, Earthscan Pub. Ltd.

Houston, J. 1988. Rainfall - Runoff - Recharge Relationships in the Basements Rock of Zimbabwe, in I.Simmers (ed), "Estimation of Natural Groundwater Recharge", D.Reidel, pp 349 - 365.

Jackson, I. 1990. Climate, Water and Agriculture in the Tropics, Longman, 2nd Ed..

Lal, R. 1977. Analysis of factors Affecting Rainfall, Erosivity And Soil Erodibility, in "Soil Conservation and Management in the Humid Tropics", Ed.s: Greenland D.J. & Lal R. Wiley, pp 49-56.

Lee, K.E. & Wood T.G. 1971. Termites and Soils, Academic Press Inc. (London) Ltd., pp 100-106.

Lister, L.A. 1987. The Erosion Surfaces of Zimbabwe, Zimbabwe Geological Survey Bulletin No. 90.

Lovell, C. *et al.* 1992. Development of Small-scale Irrigation using limited Groundwater Resources: Third Interim Report, Institute of Hydrology Publication, ODA 92/4.

Matarira, C.H. 1990. Drought over Zimbabwe in a Regional and Global Context, Intern. Journal of Climatology, vol.10, pp 609-625.

Meigh, J. Undated. A Preliminary Estimate of Groundwater Recharge in the Chiredzi Area, Unpublished report for the ODA,Institute of Hydrology.

Muchenga, F. 1975. Geological Map of the Country: South of Chibi, Geological Survey

Office, Harare.

Philip, J.R. 1969. Theory of Infiltration, Adv. Hydrosci. 5: 215-296.

Ref.1 1988. CSIRO Disc Permeameter: Instruction Manual, CSIRO Centre for Env. Mech., Canberra, Aus.

Shuttleworthm, W.J. 1988. Evaporation from Amazonian Rainforest, Proceedings of the Royal Society of London, Series B, 233,321-346.

Williams, J. & Bonell, M. 1987. Computation of Soil Infiltration Properties from the Surface Hydrology of Large Field Plots, International Conference on Infiltration, Development and Application (Ed. Yu-Si Fok), University Of Hawaii, Water Resources Centre, pp 272 - 281.

10. Appendices

APPENDIX 1: NOTES UPON PENETROMETER USE

It is very important not to drop, or in any other way exceed the uniform pressure exerted by the permeameter. This means that a flat piece of crust is required to ensure that the weight is evenly distributed. This is obviously never realistically possible unless the very top surface of the crust crumbles in response to high pressures exerted upon those bits that stand above the rest of the surface. This was observed to occur on a number of occasions without breaking the bulk of the crust. Searching for the flattest portion near the centre of the square introduces a bias. But since each soil crust was treated in the same way it is thought that these problems represent a uniform standard error.

For the majority of the tests the crust punctured, alleviating worries that one square may adversely effect those adjacent to it by cracks that propagate into neighbouring squares. Occasionally the crust did not collapse in the characteristic manner. These results were omitted since there was no clear indication as to when the crust failed.

Often upon positioning the grid some of the squares would contain fresh disturbances that were judged to be as a result of the work program. These were omitted from the test. This actually represents a very real logistical problem that should be considered at the commencement of the work, especially as the field worker should expect to be an attraction to the local population which can result in a trampling of the surface.

APPENDIX 2: THE DISC PERMEAMETER THEORY

The principles of operation are as follows. When a source of water, such as a circular disk of water, is placed upon the surface, the initial stages of flow into the soil are dominated by the soil's capillary properties in a one dimensional fashion irrespective of the size of the disc. This initial cumulative infiltration is expressed by

$$Q/\pi r^2 = St1/2 \qquad \text{(a)}$$

(Philip, 1969), where Q is the cumulative volume of water infiltrated, r is the radius of the disc of water, S is the sorptivity and t is the time from commencement of infiltration.

As time progresses, both the size or geometry of the water source and effects due to gravity influence the flow. For homogeneous soils the infiltration will tend towards a steady-state flow rate which is governed by the capillarity, gravity, size of disc and the pressure at which the water is supplied to the soil. The

steady state flow is expressed by

$$K = q/\pi r^2 - (4bS^2)/(\pi r[\delta_o - \delta_n]) \qquad \text{(b)}$$

(Ref.1, 1988), where q is the steady-state volumetric flow, K the saturated hydraulic conductivity, b is a dimensionless constant whose value for field soils is approximately 0.55, δ_o is the volumetric moisture content at supply potential and δ_n is the initial volumetric moisture content of the soil.

Therefore S is calculated from a graph of the initial infiltration data by plotting $Q/\pi r^2$ versus $\sqrt{t}$ and finding the gradient. K can then be calculated from a knowledge of the steady-state flow rate, the initial moisture content and the moisture content at the supply potential, together with the calculated value of S.

APPENDIX 3: CALCULATION OF DROP ENERGY

To estimate the raindrop energy the size and the velocity of the drops are required. Slide photographs were taken of the water jet and later projected so the drop size could be measured. To calculate the velocity the following equation needs to be solved

$$m(Dv/Dt) = mg - AV \qquad \text{(c)}$$

Where m is the mass of the drop, V the velocity, T the time, g the gravitational acceleration and A is a constant. The first term on the right represents the gravitational force; the second represents the drag force. Separating the variables, integrating and including the boundary conditions gives,

$$V = mg(1 - \exp[(-A/m)T])/A \qquad \text{(d)}$$

Differentiation then gives,

$$X = g.\exp[(-A/m)T] \qquad \text{(e)}$$

where x is distance. The constant A is calculated using established terminal velocity data, (Lal, R., 1977: pp 51). Once A is known the impact velocity from a stipulated height can be determined from equations 4 and 5. Then the average energy associated with each impact can be determined using,

$$\text{Kinetic Energy} = 1/2.m.v^2 \qquad \text{(f)}$$

Given the resources available it is realised that the experimental procedure is somewhat crude, and the results should be considered with this in mind. But it does provide a valuable indication of what might actually occur.

APPENDIX 4: SOIL ANALYSIS

SOIL PIT 1:

Zimbabwe classification - Fersiallitic (5 P).

HORIZON	1	2	3	4
DEPTH (cm)	0-12	12-47	47-95	95-140
DM %	99.6	98.2	98.5	98.8
TEXTURE	mSaL	mSaCL	cSaC	cSaCL
CLAY %	12	32	40	26
SILT %	6	9	9	14
FINE SAND %	41	29	23	29
MEDIUM SAND %	30	19	12	14
COARSE SAND %	11	10	17	17
GRAVEL %				
pH ($CaCl_2$)	5.2	4.8	5.4	5.7
CARBONATES %				
EX Ca (me %)	2.4	3.4	4.3	1.7
EX Mg (me %)	0.7	1.2	2.1	0.8
EX Na (me %)	0.06	0.00	0.07	0.03
EX K (me %)	0.53	0.31	0.21	0.13
TEB (me %)	3.7	5.0	6.6	2.4
CEC (me %)	5.2	8.2	8.1	2.4
BASE SAT %	72	61	82	100
E/C	44.6	25.7	20.3	9.1
S/C	32.1	15.6	16.7	9.1
ESP	1.1	0.0	0.9	1.3
EKP	10.0	3.8	2.6	5.2

SOIL PIT 2:

Zimbabwe classification: Fersiallitic

HORIZON	1	2	3	4
DEPTH (cm)	0-12	12-65	65-105	105-140
DM %	100.0 100.0	99.1	99.3	
TEXTURE	mS	mLS	mSaL	cSaL
CLAY %	4	8	19	14
SILT %	3	6	9	11
FINE SAND %	33	38	30	34
MEDIUM SAND %	48	40	27	22
COARSE SAND %	12	8	14	19
GRAVEL %				
pH ($CaCl_2$)	4.9	4.0	5.1	5.3
CARBONATES %				
EX Ca (me %)	0.8	0.3	6.0	6.4
EX Mg (me %)	0.3	1.9	1.5	1.7
EX Na (me %)	0.00	0.00	0.14	0.19
EX K (me %)	0.10	0.06	0.41	0.47
TEB (me %)	1.2	2.3	6.5	8.7
CEC (me %)	2.2	2.6	6.5	9.2
BASE SAT %	55	87	100	95
E/C	56.2	31.4	33.2	66.6
S/C	30.8	27.3	33.2	63.2
ESP	0.0	0.0	2.1	2.0
EKP	4.8	2.4	6.3	5.1

SOIL PIT 3:

Zimbabwe classification - Sodic (no parent material)

HORIZON	1	2	2′
DEPTH (cm)	0-10	10-140	30-52
DM %	98.1	96.1	96.1
TEXTURE	mSaC	C	mSaCL
CLAY %	38	57	22
SILT %	13	9	18
FINE SAND %	29	16	32
MEDIUM SAND %	13	10	19
COARSE SAND %	7	8	9
GRAVEL %			
pH ($CaCl_2$)	4.7	7.0	5.2
CARBONATES %		0.0	
EX Ca (me %)	5.5	9.5	2.9
EX Mg (me %)	5.9	13.7	2.6
EX Na (me %)	0.24	4.14	0.26
EX K (me %)	0.07	0.08	0.09
TEB (me %)	11.7	24.6	5.8
CEC (me %)	16.3	24.6	6.2
BASE SAT %	72	100	94
E/C	42.8	42.8	28.2
S/C	30.8	42.8	26.5
ESP	1.5	16.8	4.2
EKP	0.4	0.8	1.4

SOIL PIT 4:

Zimbabwe classification - Siallitic (4)

HORIZON	1	2	3	4
DEPTH (cm)	0-10	10-70	70-132	132-145
DM %	94.2	94.4	100	100
TEXTURE	C	C	C	C
CLAY %	46	52	52	48
SILT %	15	10	10	14
FINE SAND %	24	19	25	27
MEDIUM SAND %	10	10	7	7
COARSE SAND %	5	9	6	4
GRAVEL %				
pH ($CaCl_2$)	6.3	7.9	7.8	7.5
CARBONATES %				
EX Ca (me %)	13.5	30.4	32.4	24.0
EX Mg (me %)	13.2	20.1	16.6	16.0
EX Na (me %)	0.28	1.32	0.89	0.75
EX K (me %)	0.44	0.07	0.07	0.09
TEB (me %)	27.4	36.5	42.6	40.9
CEC (me %)	32.3	36.5	42.6	45.2
BASE SAT %	85	100	100	91
E/C	70.8	70.1	82.1	94.8
S/C	60.1	70.1	82.1	85.8
ESP	0.9	3.6	2.1	1.7
EKP	1.4	0.2	0.2	0.2

SOIL PIT 5:

Zimbabwe classification - Fersiallitic

HORIZON	1	2	3	4	5
DEPTH (cm)	0-11	11-35	35-45	45-102	102-145
DM %	96.9	98.9	100.0	98.2	99.3
TEXTURE	mS	mLS	mSaL	cSaC	cSaL
CLAY %	4	7	11	46	12
SILT %	4	5	5	9	12
FINE SAND %	36	40	25	18	30
MEDIUM SAND %	37	37	38	12	26
COARSE SAND %	19	12	21	15	20
GRAVEL %					
pH ($CaCl_2$)	5.2	4.7	5.3	5.6	5.6
CARBONATES %					
EX Ca (me %)	3.1	2.9	1.1	4.2	12.2
EX Mg (me %)	3.1	2.0	0.0	3.0	8.9
EX Na (me %)	0.12	0.26	0.06	0.08	0.22
EX K (me %)	0.17	0.03	0.18	0.08	0.31
TEB (me %)	6.5	5.2	2.2	7.3	21.6
CEC (me %)	8.4	6.1	2.6	9.4	25.2
BASE SAT %	77	85	87	78	86
E/C	236.5	89.3	23.2	20.4	207.3
S/C	182.7	75.9	20.2	16.0	177.6
ESP	1.5	4.3	2.4	0.8	0.9
EKP	2.0	0.4	7.1	0.8	1.2

SOIL PIT 6:

Zimbabwe classification - Fersiallitic.

HORIZON	1	2	3
DEPTH (cm)	0-10	10-17	17-85
DM %	99.7	100.0	100.0
TEXTURE	mLS	mLS	mSaL
CLAY %	6	6	1
SILT %	6	5	9
FINE SAND %	43	45	44
MEDIUM SAND %	28	30	25
COARSE SAND %	16	14	11
GRAVEL %			
pH ($CaCl_2$)	5.8	5.1	4.7
CARBONATES %			
EX Ca (me %)	3.3	2.1	2.0
EX Mg (me %)	1.3	1.2	1.2
EX Na (me %)	0.13	0.04	0.06
EX K (me %)	0.05	0.14	0.08
TEB (me %)	4.8	3.5	2.6
CEC (me %)	6.4	4.0	2.6
BASE SAT %	75	88	100
E/C	108.5	63.5	23.9
S/C	81.3	55.6	23.9
ESP	2.0	0.9	2.2
EKP	0.8	3.7	3.2

APPENDIX 5: INFILTRATION DATA

Infiltration rates and their errors (errors recorded as standard deviations).

PIT	HORIZON	INFIL.RATE [mm/hr]	S.D. [mm/hr]
1	CRUST	49	4
1	BROKEN CRUST	96	15
1	BROKEN CRUST & RAIN	37	4
1	2	109	33
1	3	101	36
2	CRUST	134	16
2	BROKEN CRUST & RAIN	92	12
2	CRUST & RAIN	80	31
2	2	325	205
2	3	160	23
2	CRUST (Termite)	45	11
2	BROKEN CRUST (Termite)	97	24
3	CRUST	37	9
3	BROKEN CRUST	47	10
3	2	7.2	
3	2'	114	47
4	SURFACE	21	0.2
4	2	12	
5	2	77	35
5	3 & 4	73	26
5	SAPROLITE	38	10
6	CRUST	100	10
6	BROKEN CRUST	121	33
6	2	179	57
6	3	177	74

Soil pit 2 crust is divided into two categories, viz: the area in close proximity to a termite mound and that crust distant from it.

Horizons 3 and 4 in soil pit 5 were tested at the same time due to the thin nature of horizon 3.