The ecology of sodic sites in the Eastern Transvaal Lowveld

Clive Chappell

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Declaration

The contents of this dissertation are the result of the authors research, unless specifically stated to the contrary in the text.

C. Chappell

C. Chappell

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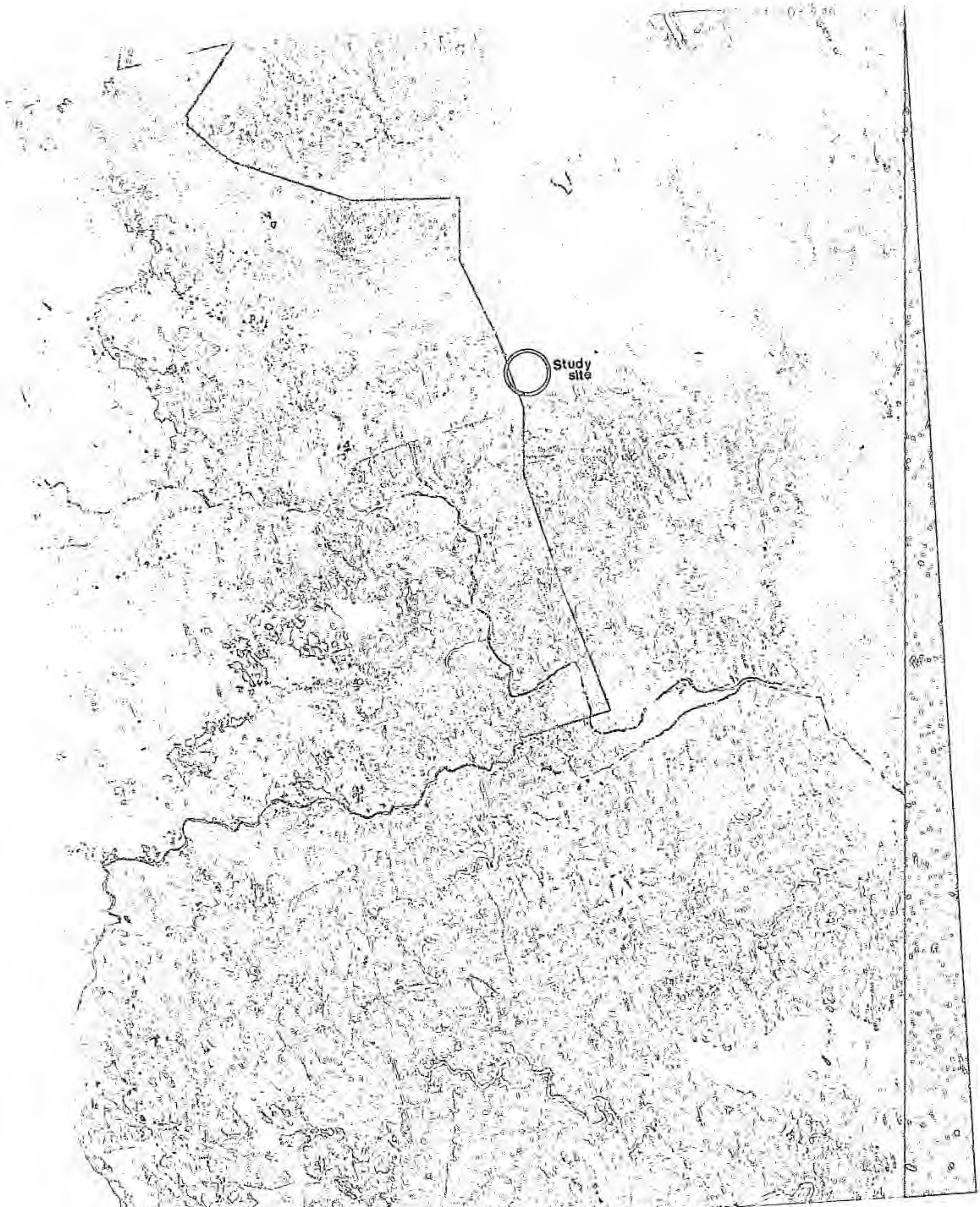
Study
site

Frontispiece

March 1987 Landsat image of the south-western Kruger National Park showing the location of the Ripape River study site. Areas within the park that are devoid of vegetative cover have been digitised and are shown in yellow.

Abstract

The effect of sodium on clays dominates the formation and ecology of granitic catenas in the Eastern Transvaal Lowveld. This study reviews the processes involved and explains the soil, vegetation and erosion patterns in this landscape.

Weathering parent rock gives rise to sodium in sufficient amounts to promote clay dispersion. Dispersed, mobile, clays respond to seasonal pulses of laterally moving soil water resulting in alternating zones of clay illuviation and clay deposition down the hillslopes. These clay-poor and clay-rich soil profiles generally parallel the slope contours and have a profound influence on vertical and lateral soil water movement. The soil profile development is reflected in the catenary distribution of the characteristic vegetation communities whilst the presence of impermeable sub-surface soil layers determines the nature and extent of the erosion processes. Details of these processes and their influence on catenary development are examined in this study.

For the purpose of this study four catenas in the Ripape River drainage system were selected. Their surface features and the distribution of the woody and herbaceous vegetation are presented here. Representative soil samples from the diagnostic horizons were analysed as regards texture, major cations and pH. Saturated hydraulic conductivity measurements, in the A and upper B horizons, were recorded and related to the within-profile sodium ion concentrations and accumulations of dispersed clays. A statistical analysis failed to demonstrate a significant relationship between sodium ion concentration and saturated hydraulic conductivity, clay percentage however was significantly negatively correlated in this regard.

Sodic site development is discussed in terms of the erodibility of sodic soils, aggregate stability, soil shear strength and hillslope hydrology. The importance of sub-surface lateral water movement in the development of the catena and of sodic sites is demonstrated. The hydraulic effects of laterally moving water, confined by

impermeable soil horizons, explains the phenomenon of piping erosion which was found to be an integral part of sodic site development. Evidence from the study shows that sodic sites and soil piping erosion are forms of accelerated erosion developing in naturally susceptible soils. The relationship between these forms of soil erosion and range management are discussed.

A pilot study in which gypsum was used in the rehabilitation of an established sodic site showed an increased saturated hydraulic conductivity in the upper soil horizons when treated plots and controls were compared there was however no statistically demonstrable difference between the treatment levels. The herbaceous response, assessed in terms of dry mass yield, was statistically significant at the highest level of gypsum application.

Arising out of the analytical data, and from observations on the study sites, a conceptual model of the Ripape catena is developed.

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Introduction

The thin sandy mantle developed by weathering of sodium-rich, acidic, granitoids under semi-arid conditions covers large tracts of land in the Eastern Transvaal Lowveld. In these areas a unique erosion process, attributable to elevated sodium levels in the soils, results in the formation of sodic sites.

The processes underlying the formation of sodic soils are well known at the molecular level but the mechanisms by which the movement of water, ions and clay interact to bring about the formation of sodic sites is not well understood at the landscape scale.

This is the area of interest of this project. It aims, by shedding light on current issues of pedogenesis, landscape ecology and dynamics, to contribute to the solution of rangeland management problems related to the erosion of sodic sites.

1.1 The sodic site environment

Lageat and Robb (1984) have identified three planation surfaces in the southern Lowveld. These benches correspond closely with the underlying geological units of the exposed Archean basement and reflect their relative susceptibility to weathering. The lower, most extensive and most weatherable of these surfaces is referred to as the Lowveld surface (Fig 1). This surface is underlain, for the most part, by gneissic and migmatitic granitoids, the weathering of which results in the formation of appreciable amounts of reactive clays and sodium ions.

It is the reaction between the clays and the sodium in these soils that accounts for their susceptibility to erosion and sodic site formation and explains the wide spread occurrence of sodic sites over the Lowveld surface.

The characteristic soil forms which occur on these slopes are disposed in a catenal association which provides evidence of soil forming processes driven by the subsurface movement of soil water. It is in the footslope segments of the hill slopes that sodic site formation occurs. It is a consequence of the accumulation of deflocculated clays in these areas. The distinctly two layered (duplex) profiles thus created have highly impermeable B horizons which promote the formation of seasonally perched water at the A/B horizon interface.

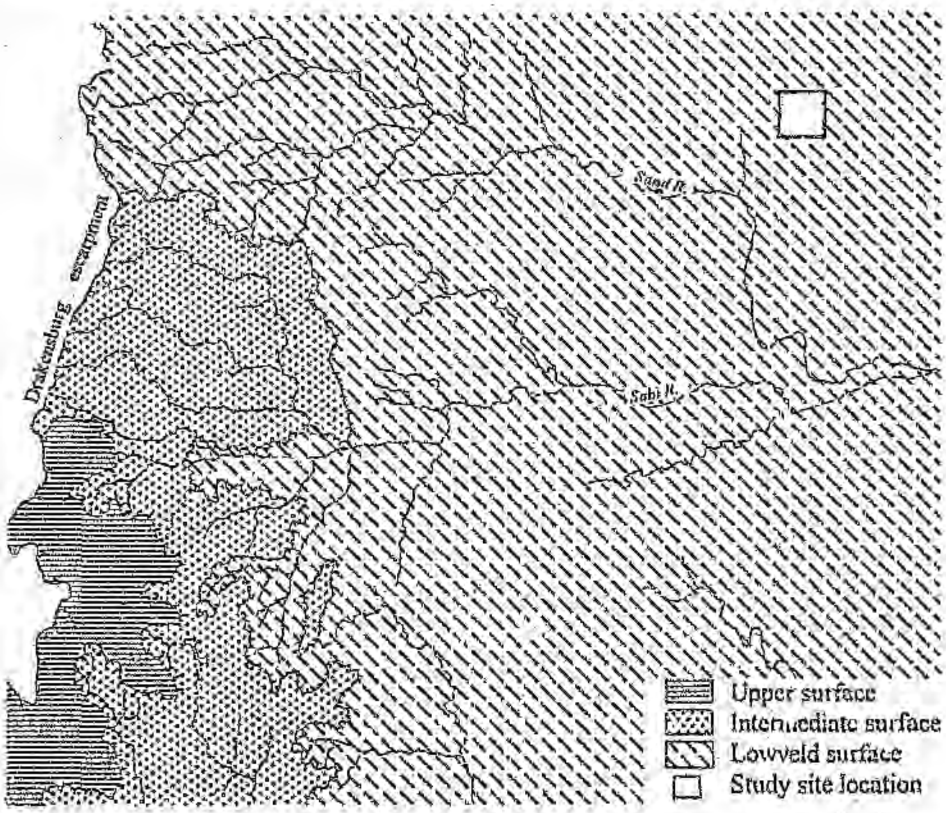

Fig 1. **Major plannation surfaces (south-central Lowveld)**
[modified from Lageat and Robb (1984)]

In situations where the protective grass cover has been heavily over-grazed, or otherwise destroyed, the A horizon soils, inherently low in organic matter, generally coarse textured and displaying low aggregate stability, respond to the rising pore water pressures by becoming virtually weightless. During the rainy season they literally 'float' away towards the drainage channel, leaving the underlying B horizon clays exposed.

1.2 Characteristics of sodic sites

Sodic sites are erosion features that involve the loss of the A horizon throughout its entire thickness and result in the exposure of the underlying dispersed clays of the B horizon soils. The affected areas appear as pinkish white patches in the landscape. The typically bleached

Plate 1. Sodic site erosion in the footslope
These characteristically whitish areas parallel the course of the drainage line. They support little vegetation but are frequented by many species of game.

appearance of these areas is due to a thin veneer of coarse quartz clasts overlying the dark clays. This sandy covering, seldom more than a few grains in thickness, represents the skeletal remnants of the topsoil following the loss of its finer, and more mobile, constituents.

Eroded sodic patches form most frequently in the footslopes of the hill slopes and they roughly parallel the course of the drainage channels, from which they are usually separated by a fringe of riverine vegetation (Plate 1).

In their progression the sodic areas tend to invade the footslopes in a direction parallel to the contour so that they have greater length than width. They may extend for varying, but usually short distances, in an upslope direction onto the base of the midslope and may range in size from a few square metres to tens of hectares.

Gertenbach (1983) describes the vegetation in the bottom lands of these granitic landscapes as open tree savannas and states that, in the absence of overgrazing, they support a dense grass cover which normally provides sufficient protection against erosion. Bailey (1990) has shown that the grasses growing on sodium affected soils accumulate high levels of sodium in their leaves and this may be the reason why certain grazing herbivores, particularly the short grass grazers, tend to favor these areas to the extent that they are frequently heavily over-grazed. Any management practice that favours high grazer concentrations on these sites has the potential for accelerating the destruction of the grass cover and promoting sodic site formation.

Bare sodic sites contribute nothing to herbage production but they are never the less frequented by many species of game. The occasional shallow surface depressions, on the impervious clays, accumulate water during the wet season and become mud wallows which are used by many animals. The water in these depressions is continually stirred up and maintains a high concentration of material in suspension and, in this condition, is thought to be particularly attractive to ruminants (Weir 1971). Wildebeest have been observed licking and ingesting the soil in the vicinity of these mud wallows, presumably as a source of sodium and other minerals. The role played by soil minerals in maintaining the electrolyte balance in ruminants has been investigated by Blair-West et al. (1963).

T e occasional scattered clumps of *Euclea divinorum*, which can survive on sodic sites, provide shade which attracts many species of ruminants. The lack of dense cover in these areas may also prove attractive in terms of predator avoidance.

1.3 Problems associated with sodic sites

The erosion associated with sodic sites is not always visually spectacular and its effects on range productivity manifest only slowly. In the more extensive areas this form of land degradation is often viewed as a natural process, of interest only in geomorphic terms. In the smaller, often privately owned blocks of land, where the ratio of affected land to the total area is greater, the visual impact is often more dramatic.

Many land owners view the problem with concern and see in it not only the loss of a non-renewable resource but also a process which impacts adversely on the productivity of their range. This latter view is supported by Roberts (1985), who points out that the dynamics of any system can only be sustained whilst the edaphic potential is maintained. Walker (1985) views productivity and sustainability as *the* most important issues in savanna management.

The need to distinguish between natural and accelerated rates of erosion is fundamental in the planning of land use and range management strategies (Cooke & Doornkamp 1990), and is especially maintains a high concentration of material in suspension and, in this condition, is thought to be particularly attractive to ruminants (Weir 1971). Wildebeest have been observed licking and ingesting the soil in the vicinity of these mud wallows, presumably as a source of sodium and other minerals. The role played by soil minerals in maintaining the electrolyte balance in ruminants has been investigated by Blair-West et al. (1963).

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The need to distinguish between natural and accelerated rates of erosion is fundamental in the planning of land use and range management strategies (Cooke & Doornkamp 1990), and is especially important in the case of sodic soils which have an inherently high erosion potential. Sediment yield data and erosion plot experiments have been used to quantify rates of natural erosion under a wide variety of environmental and experimental conditions (Schumm 1977, De Ploey & Gabriels 1980). Weathering boundary maps (Weinert 1965) and iso-erodent maps (Smithen 1980) have been compiled for the southern African region but, on a local scale, under rangeland conditions, the rate of natural erosion remains largely a matter of opinion.

In the absence of local weathering and erosion data, and to resolve the question as to whether sodic site erosion is a natural or accelerated process, the concept of an equilibrium between natural rates of soil loss and rates of formation is a useful starting point. On a time scale measured in centuries the active, year to year, forces of erosion are, in general, not of sufficient magnitude to disrupt the approximate balance that exists between the rate of weathering and soil formation on the one hand and the rate of natural denudation on the other (Selby 1990). The assumption is made that geologically 'normal' rates of soil erosion operate within ecosystems that are in a state of dynamic equilibrium and that where erosion is greatly accelerated ecological disequilibrium prevails (Beckedahl et al. 1988). Once a sodic site has formed it persists in the landscape as a bare eroded area in which the extremely hard, impervious, clays constitute an unsuitable medium for the re-establishment of a productive grass cover (Scholes 1986). A study of these areas shows that they are the sites of steadily progressive soil erosion.

A feature of the majority of sodic sites is the presence of a distinct ledge or scarp which delineates the eroded area from the apparently unaffected, intact, top soils on the slope above (Plate 2). Following a period of rain water can be seen emerging from the face of the scarp at discrete points, at some of these points there are well defined soil pipe openings. The liquid discharged from these openings is a milky colloidal suspension of dispersed clay and solutes derived from the soils on the slope above. Apart from the obvious loss of soil from the site itself a more insidious process of subsurface erosion follows the altered hydraulic conditions created by the relatively unimpeded flow of water at the scarp face .

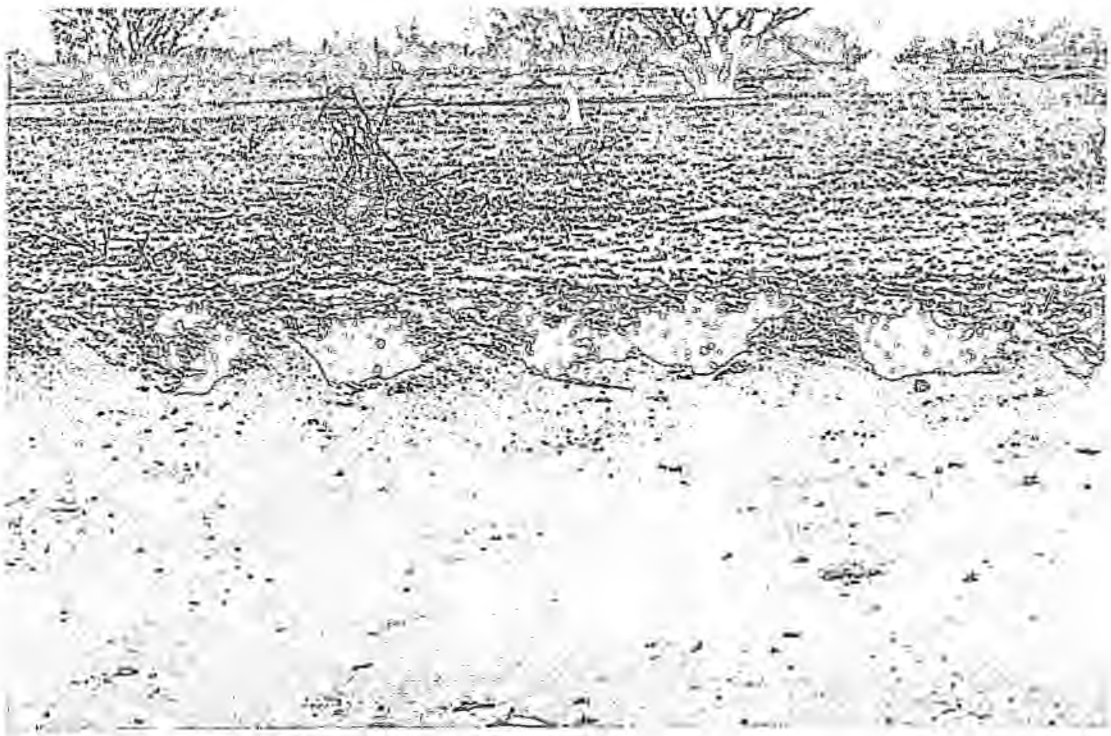


Plate 2. Features of sodic sites

The complete loss of the A horizon, the erosion scarp,the piping erosion openings and the intact soil and grass cover on the slope above - where there is no visible evidence of surface wash.

Jones (1981), in his extensive review of soil piping literature, points to the long standing association between soil piping and gully erosion. This relationship has been observed on sodic sites.

The gully and donga erosion, which frequently follows sodic site formation, is a complex process involving initial rill formation at the pipe outlets and in game tracks which are ubiquitous features on sodic sites. Rill enlargement progresses to gully formation and finally exposure of the unconsolidated and more permeable saprolite layer at the base of the B horizon. Much larger and more rapidly developing soil pipes are initiated at this lower level and, by head-ward extension, begin to invade the midslope. Eventual collapse of the soil above the enlarging pipes results in the formation of large dongas, cutting at right angles across the sodic area, and extending for increasing distances into the hill slope (Plate 3).

Apart from the progressive nature of sodic site erosion additional problems arise as a result of the large amounts of silt which are deposited in nearby drainage channels, natural water holes and water storage dams.

Responsible land owners wishing to address the erosion problems on sodic sites are, in view of the total absence of topsoil, faced with a difficult and sometimes costly task . Clearly the replacement of topsoil is an unrealistic option and the problem is best resolved by changing the physical structure of the exposed clays in order to make them more permeable to water and more favourable for plant growth. This is essentially a chemical problem which is discussed in the section dealing with sodic site rehabilitation. Once the erosion has progressed to the stage of extensive gully and donga formation rehabilitation is, in most cases, impossible.

1.4 Objectives of the study

1. To identify the factors associated with sodic site development.
2. To develop a conceptual model that relates the processes involved in sodic site development to the movement of water, ions and clay down the catena.
3. To determine the rate and direction of spread of sodic sites.
4. To address management options identified as being related to sodic site development and possible methods of sodic site amelioration.

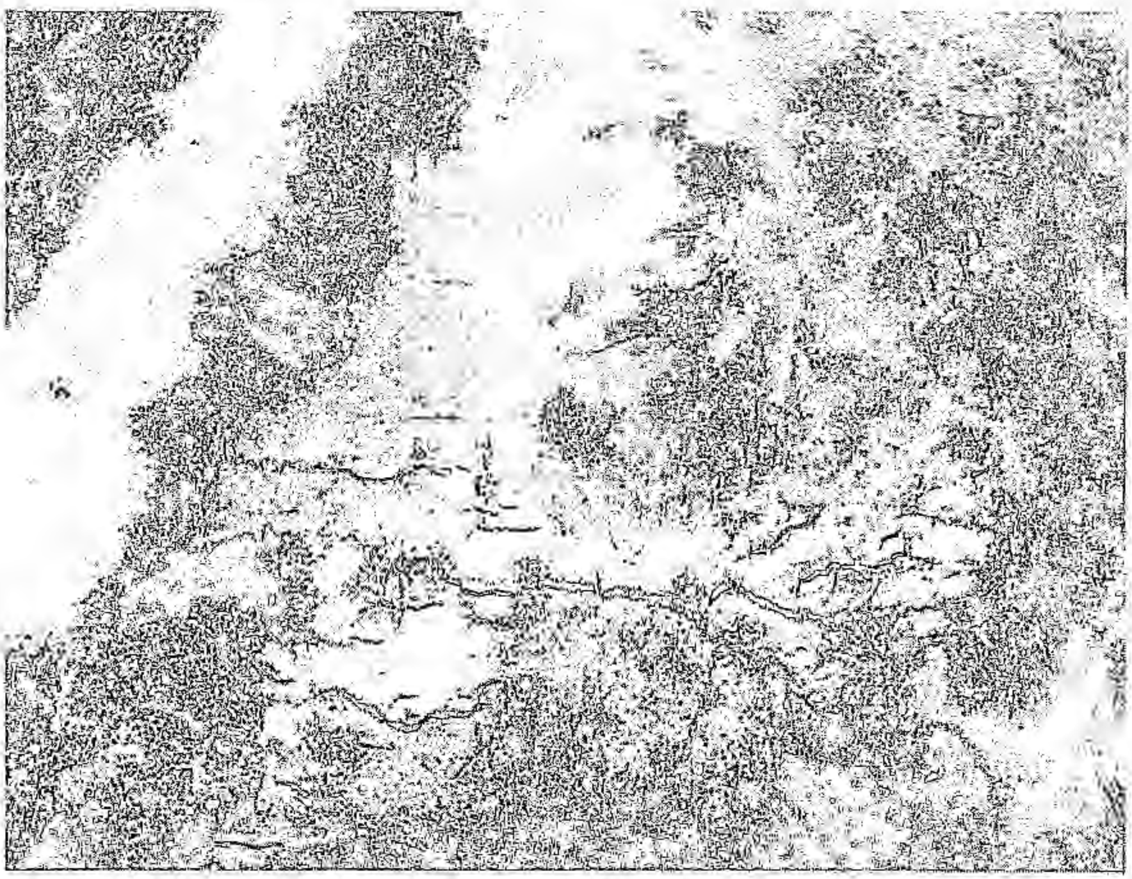


Plate 3 Advanced sodic site erosion
Sodic site erosion progressing to gully and donga formation. These features are frequently the result of collapse of sub-surface soil piping defects.

The Eastern Transvaal granitic landscape

General environmental characteristics

2.1 Climate

The climate of the Eastern Transvaal Lowveld can be described as subtropical and semi-arid. The rainfall is concentrated in the hot summer months. The dry winters are characterised by fine and mild conditions. Gertenbach (1980) describes a decreasing trend in annual rainfall from south to north and a less marked, but similar, trend from west to east. Low pressure cells, alternating with anticyclonic conditions over the interior, are responsible for summer thunder storms. At this time of year occasional widespread and prolonged rain occurs in response to low pressure troughs originating to the north. On rare occasions extremely high rainfall events have been recorded in the region. These events have been the result of late summer tropical cyclone systems moving inland off the Mocambique Channel (Schultze 1965). Anti-cyclonic conditions characterise the winter months and are, on occasions, punctuated by cooler cloudy conditions resulting from cold fronts moving into the region from the south. The climatic data for the study region are derived from weather stations at Tshokwane and Skukuza.

2.2 Temperature

During the mid summer months (November to February) the maximum daily temperature fluctuates between 31.8 and 32.3° C but may reach 40° C or more, on occasions (Venter & Gertenbach 1986). The coldest months are June, July and August, with average minimum daily temperatures being 6.1, 5.6 and 7.6° C respectively. Tinley (1979) reports occasional frosts in the region occurring from June to mid August with sufficient intensity to adversely affect the grazing in the valleys.

2.3 Rainfall

Tyson and Dyer (1978) have described a cyclical rainfall pattern in the summer rainfall areas of South Africa, Gertenbach (1980) and Venter and Gertenbach (1986), from long term Kruger National Park records, suggest a similar cyclical pattern for this region. The pattern has a periodicity of approximately ten years, during which cycles of above and below the long term average rainfall have been recorded.

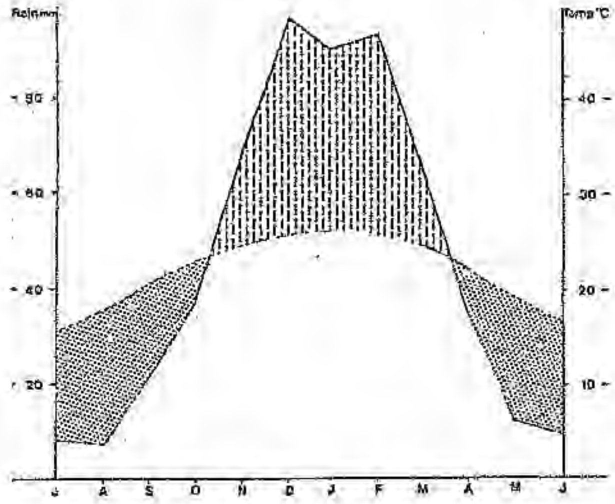


Fig 2. **Climate diagram for Tshokwane**

(rainfall records for 55 yrs and temperature for 12 yrs)

Data from the Tshokwane recording station show that the long term average for the area is 562 mm per annum. The rainfall is concentrated over the period extending from November to March, with peaks during December and February (Figs 2 & 3). The rainfall attributable to the low-pressure troughs occurs less frequently than the high energy thunder storm events, which herald the onset of the summer rains. The thunder storms are of short duration but of high intensity and, whilst these parameters are not recorded at the Tshokwane station, the isoerodent map of Smithen (1981) indicates that the region, in general, is subject to rainfall with a high erosivity potential. The isopleths for the 300 to 400 values of the EI_{30} parameter traverse this region and are amongst the highest values in South Africa.

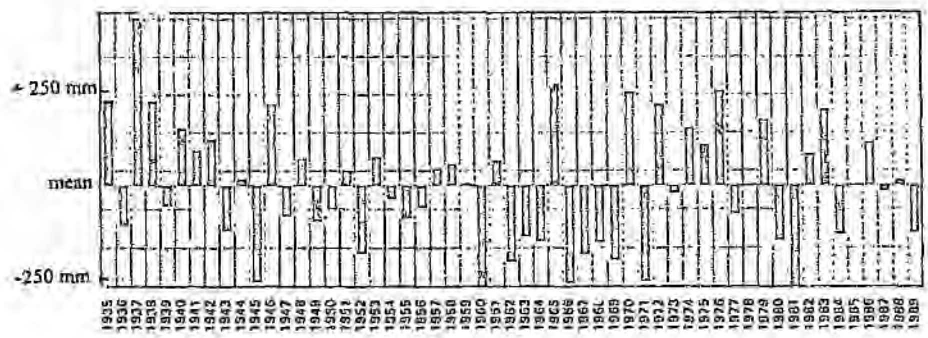


Fig 3. **Tshokwane long term average rainfall = 562 mm**

(years above and below the long term average)

2.4 Geology

A simplified map of the geology of the Eastern Transvaal Lowveld (Fig 4) shows that this region is, for the most part, underlain by the Archean basement granites.

Regional mapping of the area has been carried out (Geological Survey Map 1986) but not all areas have been studied at the same intensity. To the south the Nelspruit granite-migmatite terrain and the Cunning-Moore pluton, and to the north the Phalaborwa complex have received the greatest attention. Barton et al. (1986) have suggested that more detailed studies of the region as a whole are required.

The broad scale soil patterns map (Department of Agriculture and Water Supply 1986) eclipses the lithological subtleties and complexities of the underlying geology, at this scale however the indication is that these, largely granitoid, geologies have chemical and structural characteristics that are sufficiently similar to give rise to zonal soils that have many textural and chemical characteristics in common. The widespread occurrence of sodic soils in the region lend support to this assumption.

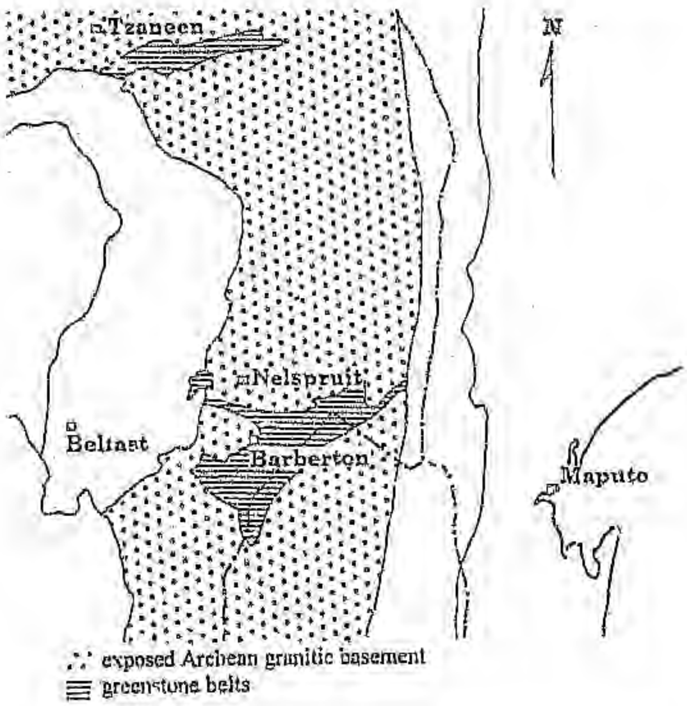


Fig 4. **Simplified geology of the Eastern Transvaal** showing the exposed Archean basement. [modified from Lageat and Robb(1984)]

Of pedological importance are the extensive areas of tonalitic and trondhjemitic gneissic and migmatitic formations in the north and central Lowveld and the Nelspruit granite-migmatite complex which dominates the southern Lowveld. The processes associated with migmatisation and the formation of gneissose forms are relevant both to the weathering of rock and to soil formation. In both these processes the metamorphic transformations initiated by the elevated temperatures and pressures culminate in the formation of appreciable amounts of new feldspar (Read and Watson 1987).

Migmatising emanations, rich in soda, result in the formation of oligoclase and albite and in the formation of granodioritic or trondhjemitic end products. These minerals and rock types are well represented in the Lowveld granitoids. In contrast to the process of migmatisation, in which there is a mixing within a single rock of two components from different sources, the development of gneissic forms is frequently the result of *in situ* feldspar production which segregates into typical lenticular or banded structures. Some gneisses are produced by the metasomatic introduction of sodium and potassium and in these cases they resemble, in origin, the migmatites.

A well defined order of mineral resistance to weathering is described by Purves (1975) in respect of Rhodesian granites and finds support in the work of Lageat and Robb (1984) on the Nelspruit granites. These workers point out that the plagioclase feldspars are the most easily weathered minerals, followed by biotite, potassic feldspar and muscovite, with quartz being relatively insoluble. Thompson (1965) and Dye (1977) have shown that extensive areas of sodic soils in Rhodesia (Zimbabwe) are to be found in areas where the underlying formations are rich in sodic plagioclase and that the granites, rich in albite, release sufficient sodium on weathering to initiate clay dispersion. A modal analysis of selected granites from Lowveld migmatites and gneiss terrains demonstrates the abundance of sodic feldspars, particularly albite (36.25%) in these rocks (Robb and Anhaeuser 1983). The foliate, or layered textures, resulting from preferred crystal growth along stress planes, are clearly seen in the migmatites and gneiss as well as in the tonalites and trondhjemites of the Lowveld surface (Robb and Anhaeuser 1983). The mineralogy and textural characteristics of these rocks, when subjected to the low to moderate intensity weathering of the semi-arid climate, explain the *in situ* formation and wide spread distribution of the moderately shallow, potentially sodic, sandy soils of the region.

Also on a regional scale, and throughout the crystalline basement, swarms of dolerite dykes, of Karoo age, have been intruded. Although numerous, at this scale they are not of an areal extent sufficient to disrupt the general granitic landscape. At the catenal scale however these dykes, where they occur, impact significantly on the hillslope soil sequences, on ground water distribution, on hillslope hydrology and on the vegetation. In the study area the location of a dike can frequently be detected by the presence of linear thickets of *Pterocarpus rotundifolius*.

In addition to the linear basic intrusions described above, large areas of medium to coarse grained gabbroic rocks form the extensive sills and prominent koppies of the north-south trending Timbavati gabbro. This formation occurs as arcuate outcrops along the entire length of the Lowveld - from south of Pretoriuskop to north of Shingwidzi. Walraven (1984) discusses the three types of gabbro, based on the olivine and quartz content, that comprise the Timbavati gabbro. The gabbros a rich in ferromagnesian minerals and give rise to very dark, base saturated, heavy, clay soils which are valuable for the grazing which they support, well into the dry season, and although heavily utilised are less susceptible to cover destruction and erosion than are the more felsic sodic granitic soils.

2.5 Topography and Geomorphology

The extensive central region of the Lowveld granitic terrain is sensibly planate and the topography is 'typical' on a regional scale. The eastwardly inclined Lowveld surface is, at this scale, a moderately undulating plane in which the low declivity hill slopes exhibit broad, rounded, convex crests, generally straight mid slopes and well defined footslopes.

The uniformity of the landscape is punctuated by isolated inselbergs, of which three types are described by Twidale (1988). The domed masses, referred to as bornhardts, occur more frequently in the southern region. Block strewn inselbergs, or nubbins, and angular castellated forms, or castle koppies, are more common to the north. The existence of these inselbergs is explained on the basis of the lithological contrasts in the country rock which define the differential rates of weathering. The forms which they take, bornhardts, nubbins or castle koppies, are to a large extent dependent on the sheet structure and fracture patterns inherent in the different granitoids.

The drainage pattern over most of the area is typically dendritic (Venter 1986) and the high stream bifurcation ratio points to the large drainage density over these granites as opposed, for example, to the basaltic planes further to the north-east. All the lower order streams are ephemeral and may only flow for one or two days following heavy thunder storms.

The precise origin of these granitic terrains is the subject of ongoing debate amongst geomorphologists. King (1963, 1978) holds that these are examples of pedeplains formed by coalescing mantled pediments which themselves result from scarp retreat. The processes involved in pedeplanation, for the most part, involve the transport of weathered material from its point of origin - the retreating scarp face - and implies that at least part of the soil mantle is derived from these remote sites.

Twidale (1988) maintains that field evidence argues against the scarp retreat hypothesis and suggests that these granite-gneiss terrains are in fact peneplains. Peneplains are formed, in contrast to scarp retreat, by the lowering of the land surface by a process of sub aerial denudation and conforms with the belief , based on soils data , that the soil mantle on these slopes is formed *in situ* and not from transported and reworked sediments. Granulometric evidence from the catenal soil studies in this project support the latter view of *in situ* soil formation.

Munnik et al. (1990), in their study of nine hill slopes in the southern Lowveld showed a bimodal distribution in respect of hill slopes displaying the presence or absence of a footslope unit. With respect to hill slope curvature the two groups differed in that those with no footslope segment had predominantly convex profiles throughout their extent. In the present study a smaller sample of four slopes which were surveyed, pointed to a possible correlation between stream order and hill slope morphology. Slopes associated with first and second order streams tend to have convex profiles whilst those associated with higher orders have well developed footslopes. In the latter, the profiles , from crest to drainage line, tend to be convex-straight-concave.

Scrutiny of the 1:50,000 contour map (Trigonometric Survey Office 1970) indicates that these observations are not at variance with some aspects of the Davinsian concept (Rice 1988) of landform evolution. This concept argues that the head waters of a drainage basin are the loci of stream incision by down-cutting, resulting in steep sided valleys. Lower order streams, according to this theory are closer to their base levels and the rate of down-cutting is replaced, in large measure, by lateral erosion and valley widening.

Whilst many of the aspects of the Davinsian model of landform evolution are considered to be no longer tenable, Rice (1988) points out that it is difficult to conceive that, in the longer term, changes in the rate of down-cutting will not be reflected in the form of the valley cross profiles.

There is no quantitative evidence to support the contention that sodic sites tend only to occur in those regions where well defined footslopes are present and the present survey was not extensive enough to be able to draw this conclusion. Based on theoretical considerations however the relationship between hillslope morphology and the subsurface movement of water on hill slopes (Dalrymple et al. 1968, Carson and Kirkby 1972, Chorley 1978 and Gerrard 1980) indicates that conditions most likely to favour sodic site processes would be found where the valley profiles are of this type. Scrutiny of satellite images of the region shows that sodic sites are seldom, if ever, found in the head water regions of the drainage basins.

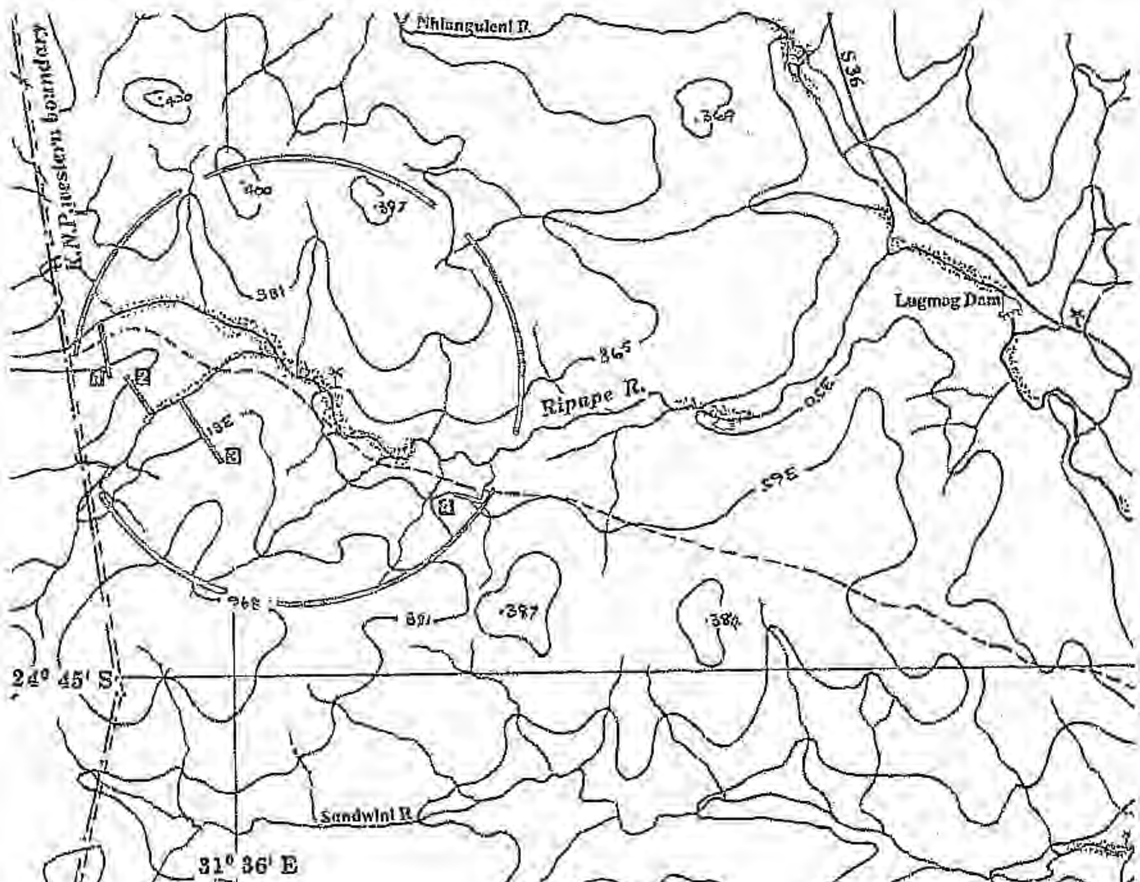


Fig 5. Ripape River - upper drainage basin

The catena concept

As originally defined, the term catena referred to recognisable soil associations differentiated by drainage and topography. The close relationship between soils on hill slopes and the gradients in plant community composition has lead to a broadening of the concept to include both soils and vegetation. In the following section the distinction between the soil catena and the soil-vegetation catena is made to facilitate the description of each and not as a denial of the relationship between the abiotic and biotic components of the landscape.

The catena concept is based on the observation that named taxonomic soil forms, with their inherent properties, vary in a systematic way with slope angle and position. The processes necessary for catenary differentiation are driven by gravity-induced soil water movement and are dependent on relief. In the absence of relief the soils are not exposed to these laterally displacing soil water movements and soil differentiation, in the catenary sense, is absent.

Studies that have concentrated on the taxonomic classification of hillslope soils are of use for mapping purposes but have revealed little about the important hill slope processes that are involved in soil development. The real power of the catena concept centers around those hillslope processes that are responsible for the development of the distinctive soil forms and, as noted by Gerrard (1980), not in the formal appearance of the end product.

The role played by relief in soil development has not always been acknowledged and it is only during the past few decades that subsurface water movement on hill slopes, and its effects on pedogenesis, has become recognised. Early models of pedogenesis paid little attention to topography and Gerrard (1980) notes that in the soil forming equation, developed by Dockuchaev (1898), relief was not included. Norton and Smith (1930) in their investigation into the influence of topography on soil profile character concluded that definite quantitative relationships existed between the slope of the land and certain profile characteristics and that relief was of great importance in differentiating soil types in the field.

Jenny (1941) developed a five factor soil-forming equation and included 'topofunction' as one of the factors. In this model, topography was treated primarily as a determinant of the amount of rainfall that would infiltrate, as opposed to the amount that would run off at the surface. On this basis soils on sloping land, where runoff exceeded infiltration, were recognised as 'locally arid', on level terrain as 'normal' soils and in depressions as 'locally humid'. Lateral movement of subsurface soil ater was observed to occur on hill slopes but was referred to by Jenny (1941) as ..." internal drainage, a function of permeability, not to be regarded as a soil forming factor ".

Milne (1935) recognised that oil forms could be linked in their occurrence by conditions of topography and suggested that, other factors remaining equal, predictable soil sequences would be repeated where-ever similar topography,climate and parent material prevailed. He saw, in this lateral concatenation of soil types, a physical linkage brought about by the movement of soil water and the re-assortment of mobile soil constituents. To this phenomenon he attached the term catena.

The catena was viewed by Morrison (1948) as analogous with an individual soil profile in that it could be regarded as having eluvial, colluvial and illuvial components. Implicit in this idea is the selective mobilisation, translocation and deposition of soil constituents, both vertically and laterally, and is in general agreement with Milne's (1935) theory of catenal development.

The catena concept is now widely recognised and catenas in a wide variety of areas have been described. Gerrard (1980) notes however that the idea is still associated with a measure of controversy. The debate appears to be centered mainly around the restriction, imposed by the definition, which demands uniformity of parent material Watson 1964).

It has been noted that if the term is used to include all the soils, from interfluve to drainage channel, a problem arises with the soils in the footslopes since, in many instances, these arise from distant sites and from disparate parent materials. Winters (1949) suggests that these footslope soils should not be included in the hill slope catenary sequence. Bushnell (1942) reports that Milne agreed that the term catena should be restricted to soils on similar parent materials but so defined as to include both residual and colluvial deposits within one catena.

A further criticism of the catena concept is related to hillslope process studies and is directed at the fact that the catena is a two dimensional representation of what, in reality, is a three dimensional system. Huggett (1974) notes that as a basis for modeling soil genesis this is analogous to the approach of many geomorphologists who view the two dimensional hillslope as the basic landform equilibrium unit.

This author proposes, as the basic organisational unit of the soil/landscape system, the three dimensional drainage basin.

Hillel and Hornberger (1979) state that in view of the mathematically intractable nature of three dimensional drainage basin models, and at the present level of understanding of these systems, a more pragmatic stance is advisable. He favours the extension of knowledge of localised processes to a scale intermediate between a point and the entire watershed. This approach lends support to the view that the catena is a suitable unit on which to base soil studies.

The Lowveld granitic catena

4.1 Soils

The influence of parent material and the weathering processes that predominate in the semi-arid climate have produced, in the Lowveld granitic terrain, hillslopes and soil mantles in which outstanding examples of the soil catena are to be found. These catenas demonstrate the close relationship between soils and landforms and the role played by subsurface water movement in hillslope processes in general.

Hillslope soil associations in the region have been described by a number of workers (Tinley 1979, Olbrich 1984, Scholes 1986, Venter 1986 and Munnik et al. 1990) and studies on similar sodium rich granites in Zimbawe (Purves 1975 and Dye 1977) have lead to a general picture of the structure of the granitic catena. Venter (1986) has described, in broad terms, the soil sequence sandy, hydromorphic, duplex and alluvial, arranged in order from interfluve to drainage channel. These distinctive soils correspond with the hill slope units arbitrarily defined as crests, mid slopes footslopes and valley bottoms.

The lack of uniformity in defining the exact extent and location of each hill slope unit has been recognised by Munnik et al. (1990) and as these authors point out this has led to discrepancies arising between the various descriptions of the 'typical' catena, particularly [illegible] respect to the relationship between the soil form and slope position.

Hillslope morphological units are regarded by Wright (1973) as useful taxonomic 'individuals' in land classification but he draws attention to the problems encountered in defining boundaries, particularly in stable, low amplitude, landscapes. The distinction between 'crests', 'mid slopes' and 'footslopes', used in the following description, is based on hill slope processes and associated soil forms rather than on rigidly defined morphological units and follows Venter's (1986) recognition of sandy, hydromorphic, duplex and alluvial sequences.

4.1.1 Crestal soils

These are uniformly sandy red/yellow apedal soils of moderate depth, characteristically the coarse and medium sand fractions are well represented and there is an abundance of partially weathered material in the lower profile. This material, according to Thompson and Purves (1978), is typical of these upland sites and continued slow weathering contributes to a steady supply of bases and colloids, which are redistributed down into the profile and laterally down the slope.

The crest is the most uniform of the slope segments, in terms of soil form. Munnik et al. (1990) recorded only Hutton soils on the crests. Venter(1986) describes Hutton, Clovelly, Glenrosa and Cartref forms on these sites.

A unifying feature of the crestal soils is that they have macroscopically structureless B horizons which are highly porous and well drained. The overlying A horizons are generally thin sandy loams with similar rapid infiltration characteristics and there is seldom evidence of surface runoff from this hill slope unit. The iron oxides, arising as a result of oxidation of the mafic minerals such as biotite, impart the typical reddish hues to these soils.

4.1.2 Midslope soils

There is no perceptible change in slope gradient that marks the crest/midslope junction at the surface, but changes in soil form are clearly indicated by changes in the vegetation. The change from crest to upper midslope is generally accepted as the beginning of the hydromorphic zone. Venter (1986) describes these soils as hydromorphic sands and clays with the dominant soil forms being Cartref and Fernwood.

A characteristic of the soils on this hill slope unit is the presence of a pale leached E horizon above a dark B horizon, as in the Cartref form, or coarse textured, structureless, regic sands extending from below a thin A horizon down to decomposing rock, typical of the Fernwood form.

The pale, bleached appearance of the E horizon, or of the deep sands, stands in contrast to the reddish colours of the crest soils The transition is a gradual one with increasing distance down the slope. The seasonal build-up of water and its subsequent lateral flow through these sandy horizons is, according to Macvicar et al. (1977), responsible for reducing conditions and accounts for the loss of ferric colouring materials. The occasional ocherous mottling and flecks of bluish colours encountered at depth is indicative of the temporary presence of perched water.

Textural analysis of these horizons shows that the silt and clay fractions are depleted. Thompson (1967) has noted that in those soils which show a marked disparity in particle size distribution, and where the colloidal fraction lacks the stabilising influence of strong flocculation, the finer fractions are easily mobilised and translocated, moving with relative ease through the coarse grained matrix. The point is made that, under these conditions, even minor degrees of dispersion would result in appreciable lateral clay movement.

Whilst it was noted that no noticeable change in gradient occurs to mark the beginning of the hydromorphic zone, observations on the study catenas recorded occasional shallow surface depressions towards the lower end of this zone. These are thought to arise due to localised subsidence following lateral loss of bulk material (White and Agnew 1968).

At variable distances into the midslope unit clay begins to accumulate. Initially the clay layer is in the form of a thin stratum overlying the decomposing rock. This layer rapidly thickens, over a short distance, and rises to occupy the entire thickness of the B horizon, forming a typically duplex profile. The overlying A horizon soils are, at this point, darker than those in the hydromorphic zone and have a higher clay content.

The clays are highly structured and, when moist, are highly impermeable and are responsible for the seasonal retention of water in the hydromorphic soils on the hillslope above. Purves (1975) likens this phenomenon to the formation of a 'sub-surface dam wall'. In terms of hill slope hydrology it behaves as such and results, in times of above-average rainfall, in the formation of contour seeplines which are one of the most characteristic features of the granitic catena.

The soils in which these structured clays accumulate are typically Estcourt forms and they tend to grade, with increasing down-slope distance, into Sterkspruit forms.

4.1.3 Footslopes

According to most descriptions of typical granitic catenas of the region, duplex profiles cover the entire midslope and extend from the seepline onto the footslope below. A variety of soil forms have been described in the lower midslope and these include Sterkspruit, Kroonstad and Valsrivier forms. Approaching the drainage channel these give way to stratified alluvium of the Dundee and, occasionally, to Inhoek forms.

On the study catenas a restructuring of soils in the lower midslope region was found to occur on all slopes. Following this zone of more permeable soils, a second region of structured clays was found to occur. Whether or not this sequence occurs, the footslope soils are uniformly dominated by structured, dispersed clays which eventually grade into the stratified alluvium along the stream banks.

4.2 Vegetation

The Lowveld granitic catenas display characteristic vegetation gradients in which community structure and composition is closely related to soil type and soil water relations. Venter and Gertenbach (1986) claim that these communities can be regarded as edaphic climaxes in which fire and zootic subclimaxes exist at a local scale. Dye (1977) has demonstrated the relationship that exists between the vegetation and edaphic conditions in the granitic soils of Zimbabwe.

In the southern region, where the annual rainfall is in excess of 600 mm, the vegetation is classified as sour bushveld. To the north, where the annual rainfall drops to below 500 mm, the granitic terrain supports a mixed *Combretum apiculatum / Colophospermum mopane* tree savanna. Located between the moist and arid extremes is a central region, on similar substrates, that is classified as mixed *Combretum spp. / Terminalia sericea* woodland. These communities are classified and described in detail by Gertenbach (1983). It is within this central region that the typical granitic soil-vegetation catena reaches maximum expression and the gradients in community composition are particularly well displayed.

The typical vegetation pattern on these slopes has emerged from a number of studies in the area (Tinley 1979, Gertenbach 1983, Olbrich 1984, Venter & Gertenbach 1986, Venter 1986, and Scholes 1986) and recognises broad-leafed savanna woodlands on the crests, dominated by *Combretum spp.* and a field layer of low quality, low productivity grasses. The duplex soils which occur on the mid slopes support a dense grass cover but few trees. Towards the base of the midslope and extending onto the footslope the density of woody species increases. Here the thorny small-leafed species are the most conspicuous and the grass layer is described as dense and productive.

On the crests *Combretum zeyheri* and *Combretum apiculatum* are numerically dominant but the scattered *Sclerocarya birrea* are conspicuous by virtue of their greater height and canopy size. Within the field layer two distinct groups are identifiable - the tall sub-canopy communities composed largely of *Digitaria eriantha* and *Panicum maximum* and a short, sparse, between-tree community in which *Pogonarthria squarrosa* and *Aristida congesta* are commonly present.

The most characteristic feature in the vegetation, which is repeated regularly at the landscape scale, is the distinct ecotone which coincides with the occurrence of hydromorphic sands in the soil profiles. Beginning at the point where the leached sandy profiles become identifiable, scattered *Terminalia sericea* individuals become established within the predominantly *Combretum* woodland. These trees increase in number, with increasing depth of the leached horizon, to the extent that they form almost monospecific stands along the upper margin of the seepline contour.

Although other woody species occur at these sites, for example *Dalbergia melanoxylon* and *Peltophorum africanum*, their occurrence is sporadic and the dominant marker of the ecotone is, in all cases, *Terminalia sericea*. Within the grass layer, at this point on the slopes, the most notable change that occurs is the presence of several sedge species including *Fimbristylis hispudila*, *Fimbristylis complanata*, and *Cyperus rupestris*. *Eragrostis gummiflua* is widely recognised as a reliable marker of the hydromorphic zone.

The relationship between *T.sericea* and seasonally wet hydromorphic soils has been mentioned in several studies. Fraser et al. (1987) have suggested that, unlike the woody species growing on the crests, *T.sericea* has higher water requirements. Van Wyk (1974) notes that seasonally wet conditions favour this species to the extent that they form dense stands at these sites.

Olbrich et al. (in press) indicate that the shallow rooting behaviour combined with the presence of large conducting vessels in the roots enables *T. sericea* to exploit this niche. Soil pits excavated on all the study catenas in the Terminalia fringe during the mid-winter months demonstrated the dryness of the entire profile at this time of year. This observation together with the fact that this species is deciduous is not consistent with the observation of Tinley (1982) that bodily removal of these trees, ..."at the height of the dry season"... resulted in accumulation of free water in the hole to the extent that it was seen to flow onto the grassland areas below.

From the point on the slope at which the duplex profiles force the laterally moving soil water to the surface, woody species are generally absent or are represented only by a few, scattered, young or stunted individuals. The field layer is dense and apparently highly productive but the grasses have a low forage value. This region, which extends for variable distances through the midslope is commonly referred to as the hydromorphic grassland and it has been suggested (Olbrich et al. in print) that the seasonal water-logging of the rooting zone is of sufficient duration to kill woody plants. The extremely hard nature of the dispersed clays, compromised for only one or two months of the year during the wet season, may constitute a barrier to the deeper root penetration required for the successful establishment of trees.

Further down the midslope, and concurrent with the observed restructuring of the B horizon clays, there is a gradual transition back to an open woodland community. Changes in the field layer are due to the appearance of *Themeda triandra, Dactyloctenium aegyptium*, and *Urochloa mossambicensis* in increasing numbers in the open sward and, as the trees increase in number and in canopy size typical sub-canopy species become apparent.

Excluding the broad-leafed species that favour the alluvial soils close to the drainage channels, the woody species growing at the lower end of the mid slopes and on the adjacent foot slopes are predominantly thorny small leafed species such as the Acacias.

Able to become established on the heavy soils of the bottom lands, and generally confined to these areas, are individuals and occasional thickets of *Euclea divinorum*. Notable amongst the grasses are *Sporobolus nitens, Eragrostis trichophora*, and occasionally, *Cynodon dactylon.*

Salt affected soils and the halomorphic sequence

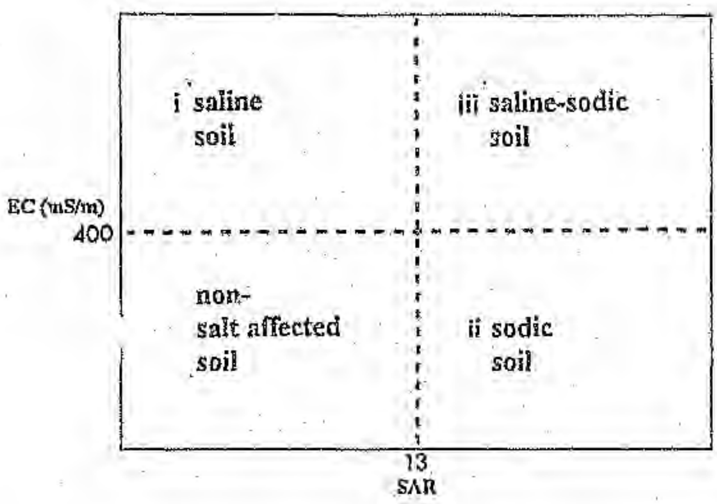
Soils which contain appreciable amounts of soluble salts occur frequently in those areas experiencing arid or semi-arid climates (Bresler et al. 1982). An annual rainfall insufficient to effectively leach accumulated salts from the soil, low humidity and the resultant high evaporative demands are considered to be the major factors contributing to elevated soluble salt levels in soils of arid and semi-arid zones. The widespread occurrence of salt affected soils can be appreciated from the observation that 33% of the Australian continent is, according to Peck (1977), affected by excessive sodicity or salinity. Similar data for southern Africa are not available but reports from Zimbabwe (Thompson 1957, Purves & Blythe 1969, Purves 1975, Dye 1977, Thompson & Purves 1978, and Dye & Walker 1980), South Africa (Cass 1970 and Scholes 1986) and Namibia (Loxton & Gardiner 1967) indicate that salt affected soils are a common phenomenon in the subcontinent.

In pedological terms, soluble salts are defined (Macvicar et al. 1977) as those with a water solubility greater than calcium carbonate. Miller and Donahue (1990) list, as the most frequently occurring and usually the most abundant soluble salts in soils, those containing the cations sodium, calcium and magnesium and the anions chloride, sulphate and bicarbonate.

The origin of these salts differs according to locality. The major sources that have been identified (Bressler et al.1982) are: cyclic salts, redistributed in rainfall; fossil salts, from former lacustrine sediments; salts redistributed in surface and ground waters; and salts arising as second-order minerals as weathering products of primary minerals.

A distinction based on electrical conductivity (EC) and sodium adsorption ratio, (SAR) has been made between the various classes of salt affected soils. Three groups are recognised (Soil Science Society of South Africa 1990) and are referred to respectively as Saline, Sodic and Saline-Sodic.

The three groups can be defined as follows:



i **Saline soil** = saturation extract with an EC of > 400 mS/m
SAR of < 13

ii **Sodic soil** = saturation extract with an EC of < 400 mS/m
SAR > 13. A low soluble salt content but sufficient sodium to cause significant clay deflocculation

iii **Saline-sodic soil** = saturation extract with an EC > 400 mS/m
SAR > 13 Both the salt content and the SAR to qualify as saline and sodic

The use of SAR values has replaced the previously used exchangeable sodium percentage (ESP) as a measure of sodium ion concentration in the exchange complex. On theoretical grounds certain objections have been raised with regard to the use of SAR as the appropriate index in this regard.

The SAR is defined by the relation -

$$SAR = [Na^+]/[(Ca^{++}+Mg^{++})/2]^{1/2}$$

Bressler et al (1982) have pointed out that SAR is expressed in terms of ion concentrations rather than ion activities. Furthermore they note that this ratio fails to account for reductions in the free ion concentrations due to ion pair or complex formation, which they claim are important in the case of Ca^{++} and Mg^{++}. Another aspect of the SAR which is discussed is the combining of Ca^{++} and Mg^{++} in the expression for which, it is noted, there is no theoretical basis except for the fact that valence is a more sensitive parameter in predicting exchange relations than is ion size. In spite of these theoretical considerations it has been recognised that there are fortuitous opposing trends with regard to activity coefficients for monovalent and divalent ions, and this, together with the fact that most clays show a preference for Ca^{++} over Mg^{++} in exchange reactions negates the effect of differences in the hydrated ionic radius (Ca^{++} = 0.96 nm, Mg^{++} = 1.08 nm). These considerations are seen as sufficient justification for accepting SAR as an appropriate index for making ion exchange predictions.

The classification of salt affected soils is founded on salinity hazard assessments for agricultural soils that are brought into production under irrigation and the values adopted for EC and SAR are arbitrary ones based on crop response.

The Soil Science Society of America have suggested that there is sufficient justification for lowering the criteria used in these definitions since several instances have been recorded where crop damage has occurred at the currently defined 'safe' levels.

In respect of non-cropping soils, under range conditions, the findings in the present study suggest that clay dispersion and swelling occur at SAR values well below those mentioned in the formal definitions. With regard to the behaviour of clays, reliance on the defined SAR or ESP values can be misleading. Emerson and Bakker (1973) have shown that in a Ca - Na system an ESP of 5 initiated dispersion whereas in a Ca - Mg system significant dispersion occurred at an ESP of only 3. It is relevant to point out that, whilst sodic soils are defined as having an ESP of > 15 (equivalent to an SAR > 13), there are many situations where these soils could be similarly affected at much lower exchangeable sodium concentrations.

Another factor which impacts on the response of the soils colloidal fraction to a given level of exchangeable sodium is the ionic composition and concentration of the ambient soil solution. The work of Quirk and Schofield (1955) has demonstrated the low SAR values that will initiate dispersion in the presence of soil solutions of low electrolyte concentrations, such as rainwater.

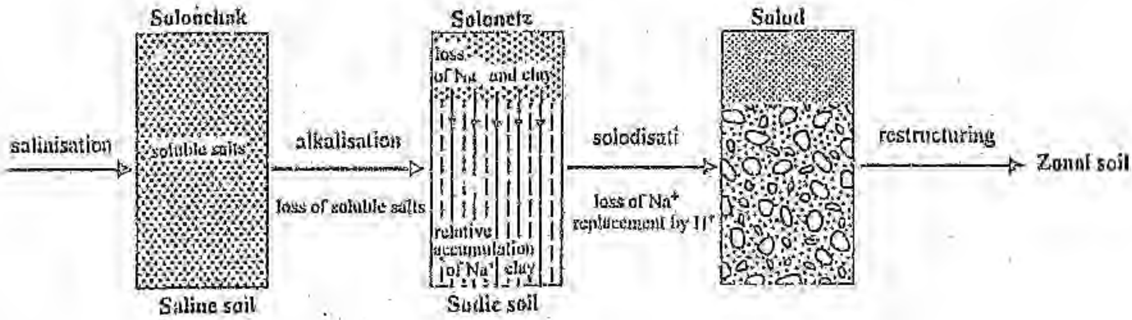
A useful approach to the problem of distinguishing between salt affected soils, that avoids recourse to the arbitrarily defined EC and SAR values, is based on the recognition of a genetic link in their evolution. Roberts (vide Cass 1970) describes a halomorphic sequence which links solonchaks, solonetzic and solodized soils on the basis of qualitative chemical changes and morphological characteristics.

This approach avoids the problem of relying on quantitative criteria that have been shown to be closely linked to environmental circumstance. The halomorphic sequence begins with the formation of a saline soil (solonchak) which arises as a result of the accumulation of soluble salts, either introduced or derived from the weathering of parent material. Initially these are friable soils exhibiting favourable permeability and structural characteristics. When exposed to appropriate leaching conditions the salts undergo differential segregation, carbonates and bicarbonates of calcium and magnesium are precipitated and there is a *relative* increase in the sodium ion concentration.

The following stage depends on the leaching process which promotes the movement of soluble salts, and some of the clay, from the upper horizons to greater depths. At depth the concentration of sodium eventually reaches a critical level and clay dispersion is initiated, (this 'critical level' is not a fixed value but depends on the prevailing electrolyte status) leading in time to the formation of the highly structured duplex profiles which characterise the sodic (solonetzic) soils. Further development in the sequence results when sodium ions are replaced by hydrogen ions and the solonetzic profile undergoes restructuring, becomes more permeable and develops the structural and textural characteristics of a solod or zonal soil.

Deviations from this idealised sequence have been described and sodic soils have been shown to develop *de novo*, without having been through the solonchak stage (Hallsworth & Waring 1964). De Villiers (vide Cass 1970) has pointed out that where solonetzic development has reached full expression the permeability is so low that the removal of sodium by leaching is almost impossible and the solonetz remains stable, at least in the medium term, without undergoing solodization.

The following diagramatic summary of the halomorphic sequence (modified from Roberts 1964, vide Cass 1970) indicates that the typically heavy, compact, columnar, sodic profile is degraded to produce the medium to coarse textures of a typical solod.



The changes which occur are accounted for in terms of cation exchange equilibria and the valency dilution effect (Reeve & Bower 1960). Reeve and Doering (1966) have shown that as the leaching solution rises in concentration there is a corresponding reduction in the exchangeable sodium fraction. These observations form the basis for the removal of excess sodium from the soil profile by percolating waters of high electrolyte content.

The model of the Ripape catena (Chapter 13) is based on this concept and on the fact that cation exchange reactions are rapid and reversable (Hillel 1980 a), and that they respond dynamically to changes in the composition and concentration of the soil solution.

Clay minerals in the catena

Within a given climatic zone the differences between catenas can usually be traced to differences in parent materials. Assuming uniformity of parent material however, within catenal variations are generally attributable to those factors which affect the movement of soil water.

Several models have been developed that address the post-infiltration redistribution of soil water and many of these have been reviewed by Hillel (1980 a,b). From these studies it appears that the textural and structural attributes ... re of fundamental importance.

The most notable of the ... hanges that occur within granitic catenas is due to the rel ... of clay, particularly in the B horizons. The majority of mod ... lopment on hillslopes are based on the assumption that the upland ... sites of eluviation and that the footslopes are sites of illuviation. The granitic catenas of the study region deviate from this general pattern in that there is no simple pattern of mobilisation of soil material and its transport down a gradient to the footslope area. Rather there is a complex pattern of accumulation, deposition and transport occurring alternately along the toposequence and which appears to be determined largely by the presence of reactive clays and their response to changes in the electrolyte status of the soil solution. These unique characteristics are not accounted for in the simple model previously referred to.

6.1 The origin of clay minerals

The soil mantle covering the Archean granitoids of the Lowveld surface owes several of its important characteristics to the susceptibility of the first order minerals to chemical alteration under the prevailing climate.

Within the parent rock the plagioclase feldspars and ferromagnesian minerals rank low in terms of resistance to weathering. The 'feldspathic index', which is the ratio of alkaline feldspar to alkaline feldspar plus plagioclase, has been used by Lageat and Robb (1984) to classify the tonalites and trondhjemites of the region as holo- and sub-plagioclastic rocks, in which the plagioclase fraction is dominant. These authors claim that, with few exceptions, most of the remaining granitic rocks are monozonitic types in which both the alkali and plagioclase feldspars are represented.

The most commonly occurring ferromagnesian silicate mineral in these rocks is biotite and, according to Purves (1975), is the first to undergo chemical alteration. Under even the most benign weathering environment biotite undergoes substantial structural change and, by a process of ionic substitution, results in the formation of smectites (Read and Watson 1987). Grim (1964) notes that owing to the presence of magnesium and iron, the clays that result from the breakdown of biotite belong mainly to the montmorillonite and illite 2:1 lattice groups. During the process of clay synthesis, silica and the soluble carbonates of magnesium, iron and calcium are also released. The acid ferrous carbonates, $Fe(HCO_3)_2$, or the basic carbonates, $Fe(OH)(HCO_3)$, are readily oxidised to reddish haematite, Fe_2O_3, which under appropriate conditions undergoes hydration with the formation of hydrated iron oxides and ochres. The reddish staining frequently seen along the margins of fractures in exposed granite boulders is, according to Purves (1975), due to the rapid breakdown of biotite, the release of ferrous iron, and its precipitation as ferric iron. The presence of reddish hues in the upland soils is also taken as evidence of oxidising conditions and the formation of ferric iron, and is well demonstrated in the well drained, apedal, B horizon of the Hutton soils of the crestal slope unit.

Concurrent with, but progressing at a slower rate than the breakdown of biotite, the plagioclase feldspar lattices undergo decomposition. The processes involved include ionic solution, hydration and hydrolysis. In all cases the free bases K^+, Na^+, Ca^{++} and Mg^{++} are released and the aluminium and silica react with hydroxyl ions to form the phylosilicate clay minerals. Under conditions of adequate drainage the bases are removed in solution as free ions or carbonates, many are adsorbed and retained by the newly formed clay minerals (Read and Watson 1987).

According to Thompson and Purves (1978), it is the susceptibility of the parent material to weathering that determines the clay content of the soil and the proportion of the individual bases that are released. It is generally agreed that under intense weathering conditions (high temperature and rainfall) the composition of the parent rock is less influential in terms of soil properties than is the case where arid and semi-arid conditions prevail. Under the latter conditions parent rock composition, it is claimed (Thompson 1967), exerts its influence on the soils almost indefinitely. Where there are large reserves of unweathered material in the soil, as is the case in the soils of the semi-arid granitic catenas of the Lowveld, it can be assumed that the production of clays and the supply of bases is not constrained by a lack of first order minerals.

Factors which govern the accumulation and distribution of soil water, and therefore the soil climate, will have a profound influence on the extent and rate of weathering and on the type of clay that is formed. Grim (1964) has remarked on the labile nature of clay minerals and on the rapidity with which they are able to undergo transformation from one type to another.

It appears, therefore, that the clay species present in the soil, at any one time, are not determined by the parent material so much as by changes that have taken place in the soil environment since their initial crystallisation. In this regard the soil wetness, pH and base saturation are of greatest importance.

There is an established relationship between the weathering intensity and the type of clay formed. Munnik et al. (1990) found high percentages of kaolinite in the soils of the southern Lowveld, under high rainfall conditions. Scholes (1986) notes that kaolinite dominates the clay fraction in the upland soils whilst smectites are found in lower catenal positions in the Lowveld granitic catenas. Buhmann and Kirsten (1991) claim that kaolinite is the most common alteration product of granites under most climatic conditions, from arid to humid.

Lageat and Robb (1984) found kaolinite to occur in much smaller quantities on the Lowveld surface as compared with the higher erosion surfaces to the south and west, where more resistant potassic gneisses dominate the substrate. This low kaolinite content is explained in terms of the relatively shorter duration (geomorphologically) and reduced intensity of weathering under the drier Lowveld climate.

Thompson and Purves (1978) have associated high intensity weathering with soils displaying low reserves of weatherable materials, the presence of 1:1 clays, appreciable amounts of sesquioxides and a low silica / sesquioxide ratio. Low intensity weathering, these authors note, is associated with soils containing large reserves of weatherable minerals, high base saturation, predominantly 2:1 lattice clays and a high silica / sesquioxide ratio Between these two extremes, referred to respectively as ferralitic and sialitic soils, these authors recognise an intermediate group which they refer to as fersialitic.

Grim (1964) has found that weathering of igneous rocks with a high magnesium content, under arid conditions, results in the accumulation of this element in the weathering zone and leads to the formation of smectites. This is particularly so in the face of low potassium levels. The presence of calcium in these soils is said to block kaolinite and favour smectite formation.

6.2 Clay swelling and dispersion

The stacking of the unit layers of montmorillonite clays to form the clay crystal is in the nature of a loose assemblage of lamellae with a variable basal spacing between the lamellae. The bonding between lamellae, responsible for the variable spacing, is through cations which can exchange with those in the surrounding outer solution. This 'flexible' structure, in contrast to the rigid H^+ or OH^- bonding of the kaolinites, or the non-exchangeable K^+ ion bonding of the illites, gives to the smectites the ability to expand and by so doing increase their reactive surface several fold.

The initial stage of smectite expansion has been shown to correspond closely with the degree of hydration of the exchangeable cations. The accumulation of water in the hydration shells of these cations results in an increase in the basal spacing from 0.96 to 2.0 nm. At this point the increase stabilises owing to the electrostatic attraction between the cations and the negatively charged lamellar surfaces.

Swelling beyond this point can only occur if the hydration energy of the cations is sufficient to overcome the forces due to electrostatic attraction. Where the cations are predominantly polyvalent, e.g. Ca^{++}, no further expansion occurs unless an external shearing force is applied. In the case of monovalent Na^+ the hydration pressure is sufficient to overcome the electrostatic attractive forces and the basal spacing continues to expand. The expansive effect of sodium, due to its hydration energy, is augmented by osmotic forces generated by the relatively larger number of monovalent ions required to balance the negative surface charges on the lattice, and increasingly so as the electrolyte concentration in the external solution falls.

Hillel (1980 a) notes that attempts to calculate the swelling pressures generated by expanding clays are generally based on the diffuse double layer theory and the van't Hoff equation (which relates the osmotic pressure differential and ionic difference between the double layer and the intermicellar solution). This author claims that the theoretical approach bears little relation to actual conditions in the field. Warkentin and Scholfield (1962) have found however that Na-montmorillonite behaves, in this respect, in accordance with theory and that the forces generated can be considerable - of the order of several bars. The practical implications of these observations are related to the effect that swelling clays have on soil structure and permeability. Marshall and Holmes (1979) note that the swelling of soils containin montmorillonite clay can result in a 20-fold increase in bulk volume but this is accompanied by an overall reduction in porosity and directly impacts on the soils hydraulic conductivity.

The swelling of clays and their tendency to deflocculate are complimentary phenomena which are closely related to the composition of the exchange complex and the physical extent of the diffuse double layer.

The Guoy-Chapman equation (Appendix A 1.) shows that the extent of the double layer is inversely related to the valence and the concentration of the ions in the ambient solution. The Gapon equation (Appendix A 2.) relates the composition of the exchange complex to the concentration and composition of the surrounding solution and shows that the adsorption mechanism favours the higher valence ions, increasingly as the surrounding solution becomes more dilute. Hillel (1980 a) points to Shainbergs selectivity coefficient (Appendix A 2.) for the calcium-sodium exchange system and shows that in a mixed system of this type most of the Ca^{++} ions are adsorbed in the Stern layer whilst the Na^{+} ions are relegated to the outer regions of the diffuse layer.

The tendency of colloids to disperse is a function of the inter-particle distance and, in the case of clay colloids, the potential extent of the diffuse double layer determines this relationship - the proximal determinant of which is the valence and the concentration of the adsorbed cations. As previously noted a sodium-dominated clay will expand due to ion hydration and the osmotic attraction of external water, and as shown by the Gouy-Chapman relationship , monovalent ions in a dilute solution result in maximum swelling.

The like charges in the outer diffuse layer (Na^{+}) encroach on one another as the double layer extends fully, inter particle repulsion occurs, followed by dispersion. The increasing inter particle distance, beyond 150 nm negates the "London-van der Waal" forces of attraction as well as those reputed to be responsible for plate condensation (Hillel 1980 a) and facilitates the process of dispersion.

The reversibility of the dispersion process depends on readjusting the ionic balance and forms the basis for the ameliorative procedures that were carried out as part of this project and are described in the relevant chapter.

Giesking (1949) has noted that suspensions containing as little as 2% montmorillonite form thixotrophic gels which render soils practically impervious to water and, in this condition, when subjected to a lateral stress, these clays show a strong tendency to flow.

Jones (1981), reporting on piping erosion in sodic soils, refers to the change in yield strength that accompanies changes in the equilibrium particle spacing. This characteristic will be dealt with in the discussion on soil erosion and soil piping.

6.3 Analysis of study site clays

A technique, currently u... development (Geophysical Research Department - Anglo American Corporation of SA. Ltd.) was employed to identify the clay species present in soil samples from all slope positions on catena 1. The sample is scanned to obtain a pattern of reflectance, which is then compared with a computerised library of patterns from samples of known composition.

The wavelengths of im... ce with regard to the layer lattice minerals are in the range 2120 to 2400 nm. The inflections of the trace are determined by the ionic composition of the mineral under examination. Once the general spectral pattern is taken into account the minor 'bumps' in the trace are considered to be of diagnostic importance. An example of the output generated by the technique is given in Fig 6.

Using this technique the clays that were identified indicated that the crestal soils were dominated by beidellite - a member of the 2:1 smectite group of reactive clays. Where the seepline clays begin to accumulate, at depth in the hydromorphic sands, halloysite was identified as the dominant clay present.

These results might be interpreted as indicative of slower rates of weathering in the sandy, well drained soils of the crests, a result which is supported by the abundance of unweathered material in these soils; and a more aggressive process of weathering in those areas where the duplex profiles occur and where prolonged moisture retention can be expected -hence the occurrence of kaolinitic clays at these sites. These assumptions are not consistent with the macroscopic appearance of the columnar seepline clays which are generally considered as being more typical of the 2:1 forms. In addition the pH of these regions was found to be in the alkaline range which, theoretically, should not favour the 1:1 kaolinitic forms.

- - - - Kaolinite standard 1.
-·-·-·- Montmorillonite standard 8.
-·-·-·- Sample Catena 1 crest/B1 horizon

Fig 6. **Spec.ral analysis of clay sample**

In view of these unexpected results a prediction of the clay type was attempted using the recorded clay percentages from the same sites. The prediction is based on figures given by Miller and Donahue (1990) which indicate that each clay percentage contributes 0.6 cmol(+)/kg, in the case of montmorillonite , and 0.1 cmol(+)/kg in the case of kaolinite, tc the cation exchange capacity. Fig 7 shows that the predicted clay type, at the beginning of the seepline clay accumulation agrees with the findings of the spectral analysis. The high magnesium levels in these soils may explain the dominance of montmorillonitic clays on these slopes in general.

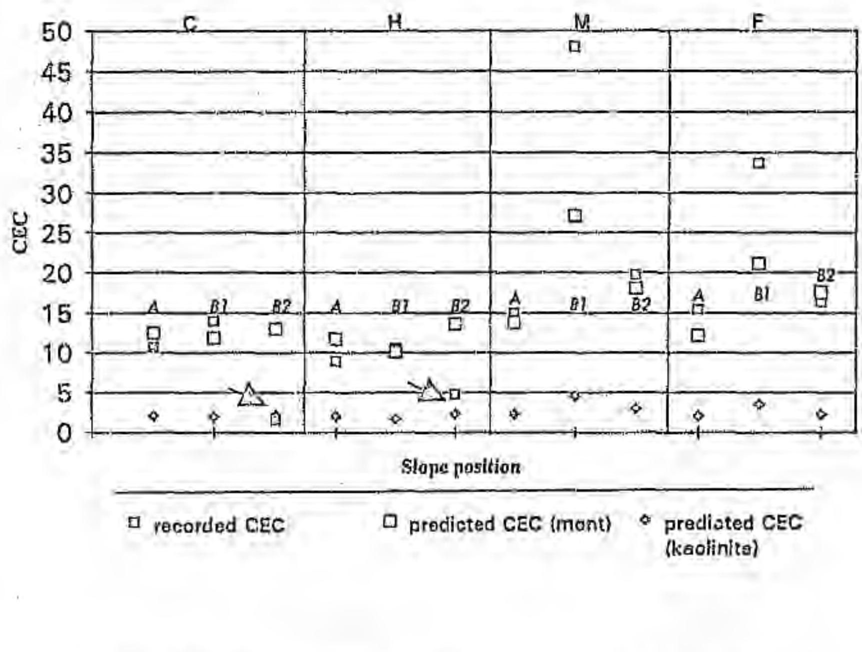


Fig 7. Clay species predicted from recorded CEC values

A,B1,B2 = horizons
C = crest
H = hydromorphic zone
M = midslope
F = footslope
△ identified as halloysite (spectral analysis)

The study catenas

7.1 Location

Selection of the area for study was made from standard vertical aerial photographs (Department of Survey and Mapping) and was based on identifying areas showing sodic site involvement. Sodic sites appear as high reflectance areas on these panchromatic images and are readily identifiable owing to their characteristic location in the valley bottoms.

A suitable area was identified in the upper Ripape River drainage basin (24° 40' S : 31° 36'E), within the Kruger National Park, close to the western boundary fence. Ground inspection confirmed the suitability of the area and a selection of four hill slopes was made, excluding from the selection those slopes that showed granite outcrops and dolerite dikes. The topographic map, (Fig 5) shows the location of the study area and the altitude (~365 m).

The geomorphology of the region is the archetype of the Lowveld granitic terrain as previously described. According to the Geological Survey (1986) the region falls within the Nelspruit Granite Suite and is classified as migmatite and gneiss.

The lithology of the region is described as grey to pale brown, medium to coarse grained quartz-feldspar biotite gneiss. The essential minerals are listed as quartz, plagioclase and biotite with lesser amounts of microcline. Accessory minerals are epidote and sphene.

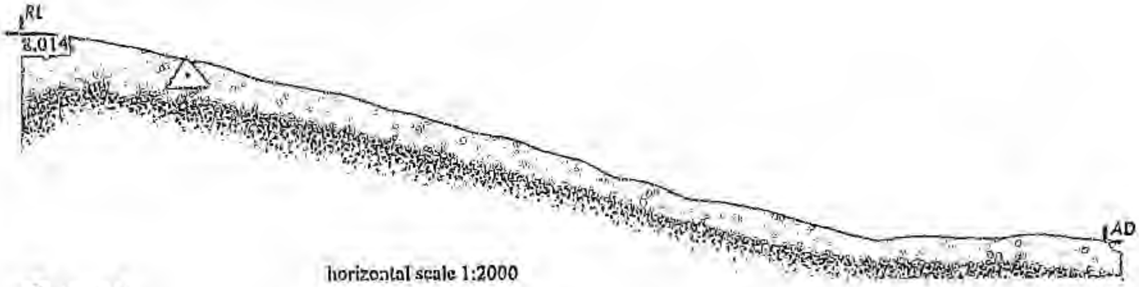
7.2 Slope morphology

Hillslope morphology was mapped at 10 metre intervals using a Wild T16 theodolite and the details of slope length, fall and average gradient for each catena were recorded.

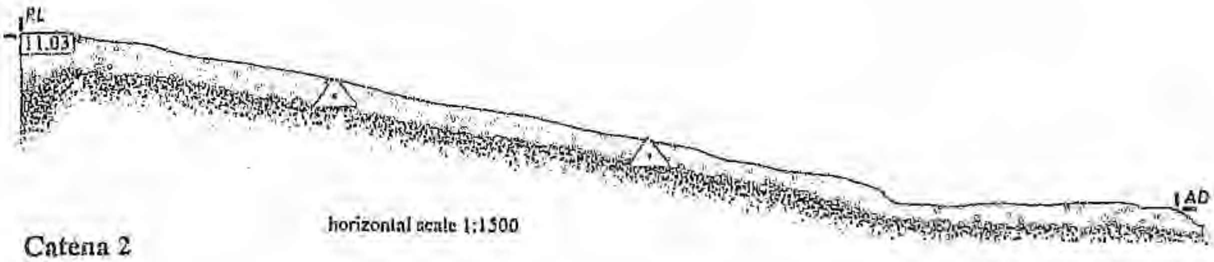
Details of the slope morphology, profile characteristics and the location of the seeplines of the four catenas are summarised and graphically depicted in Fig 8. With the exception of catena 4, which was convex throughout, the remaining slopes were convex-straight-concave in profile with distinct footslopes. Established sodic sites were present in the footslopes of catenas 1 and 2. Catena 4 was associated with a first order tributary whilst the remaining slopes were associated with lower order streams. The profiles conform to the previously stated observation that higher order streams and convex profiles are related.

7.3 Soils

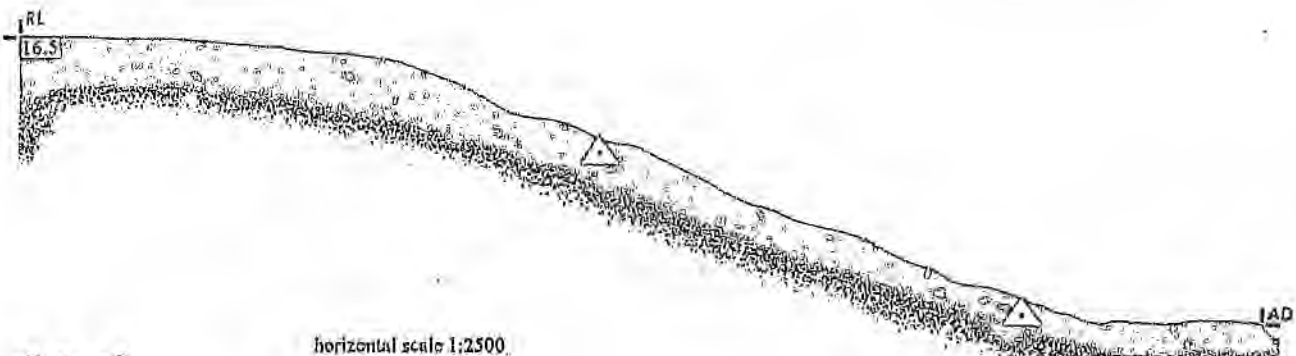
To obtain soil samples for analysis, and to study the profile configuration, pits were excavated at selected sites along each slope. The selection of sites for pit excavation was determined following an initial exploratory auger sampling and by taking note of the characteristic vegetation distribution along each slope.



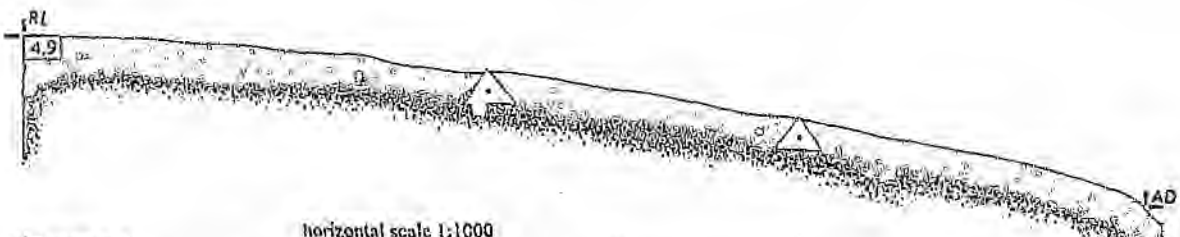
Catena 1



Catena 2



Catena 3



Catena 4

location	Catena 1	Catena 2	Catena 3	Catena4
slope length	410 m	340 m	625 m	200 m
fall	8.014 m	11.03 m	16.5 m	4.9 m
gradient	1.95 %	3.24 %	2.64 %	2.45 %
aspect	north	south-east	north	east
seepline location △	60 m	90 and 180 m	250 and 480 m	90 and 150 m
arbitrary datum AD = 0 m				
reduced level RL = ht in m above AD				

Fig 8. Slope morphology -study catenas

Dominant soil forms for each hill slope unit (averaged over all catenas), the thickness of the diagnostic horizons and their characteristic colours are summarised in Table 1.

Table 1. Summary of major soil forms/characteristics (Ripape catenas).

Slope unit	Horizon	Depth (m)	Soil characteristics	Munsel colours	Form (Macvicar et al. 1977)	Series
Crest	A	0.15	Dark brown - to - Dark yellowish brown Sandy loam	10YR 5/2 - to - 7.5YR 4/2 5YR 5/4	Hutton and Clovelly	Mesinga Portsmouh Southwold Clovelly
	B	0.75 to 1.0	Dark yellow/brown - to - Yellow/red Structureless sandy	10YR 5/2 5YR 5/8		
Hydro-morphic	A	0.15	Dark grey - to - Yellowish red	10YR 5/ 5YR [illegible]/8	Cartref .. Fernwood Kroonstad	Cranbrook Grovedale Saldana Avoca
	E	0.75 to 1.0	Light grey sand	10YR 8/1		
	below E		Very dark grey clay with mottling	N3/0 2.5YR 5/6 in N3/0 matrix		
Midslope	A	0.1 to 0.15	Dark brown - to - Very dark grey Sandy loam	7YR 4/4 N3/0	Estcourt .. Sterkspruit	Balfour Estcourt Grootfontein Sterkspruit
	B	0.6 to 0.15	Very dark grey - to - Black structured clay	N3/0 N2/0		
Lower midslope	A	0.1 to 0.15	Similar to mid	Similar to mid	Shortlands Valsrivier	Glendale Arniston
	B	0.6 to 0.75	Similar to mid plus Brown	Similar to mid 7.5YR 4/4		
Footslope	A	0.15 to 0.3	Very dark grey	N3/0	Dundee Inhoek	Dundee Coniston
	B	>1.5	Brownish yellow sand between layers of very dark grey black clay	10YR 5/6 N3/0 to N2/0		

Undisturbed soil samples from each diagnostic horizon from each soil pit, were obtained for laboratory analysis. Soil textures were determined after initial sieving to remove gravel (>2 mm). The coarse sand (0.5 to 2 mm) and medium sand (0.2 to 0.5 mm) fractions were separated by sieving and the fine sand (0.02 to 0.2 mm), silt (0.002 to 0.02 mm) and clay (<0.002mm) were determined by the hydrometer method, after initial dispersion in a soda buffered 4% sodium hexametaphosphate solution.

Major cations were determined in a 1 M ammonium acetate extract using an atomic absorption spectrophotometer. The pH's were read in a soil water solution and in a 1 M KCl solution. The dry bulk densities were obtained by weighing the oven dried, undisturbed samples of known volume.

7.4 Soil analysis results*

The major soil forms and series that were common to all catenas are listed in Table 1. The identification of the series and forms follow the binomial system according to Macvicar et al. (1977). The soil mantle on these slopes is approximately one metre thick. The table indicates that the A horizons increase in thickness in a downslope direction and that shallower B horizons occur in the upper midslopes The deepest soils are those associated with the stratified alluvium adjacent to the drainage channel.

*Laboratory soil analysis results, in tabular form, are presented in Appendix B.

7.4.1 Soil textures

The soils, throughout the slopes, are poorly graded with the fine sand and silt fractions being poorly represented. There is an abundance of weatherable material at depth as reflected by the relatively high coarse and medium sand fraction, particularly in the crests and upper mid slopes, and conforms with the belief that the rates of weathering are low.

Thompson and Purves (1978) report that soils with a high clay content show a tendency for both the clay percentage and the coarse sand fraction to increase with depth. Whilst this was observed to occur on the crests and hydromorphic areas at all lower slope positions, although the clay percentage increased with depth the coarse and medium sand fraction followed a reverse trend. The significance of this observation, in terms of the overall hillslope dynamics, is not clear. A higher average grain size in the more superficial layers would promote higher rates of lateral subsurface water movement, as compared with vertical movement, and lend support to the contention that the subsurface lateral flow of water is the dominant slope process.

Fig 9. shows the increasing clay fraction in the B horizon of the mid and lower slope segments. Fig 17a. and b. show that this is accompanied by an decrease in mean grain size and an increase in the sorting value. Both mean grain size and sorting value change little throughout the slope in the A horizon soils, a condition which further indicates that overland flow is not a significant factor on these slopes.

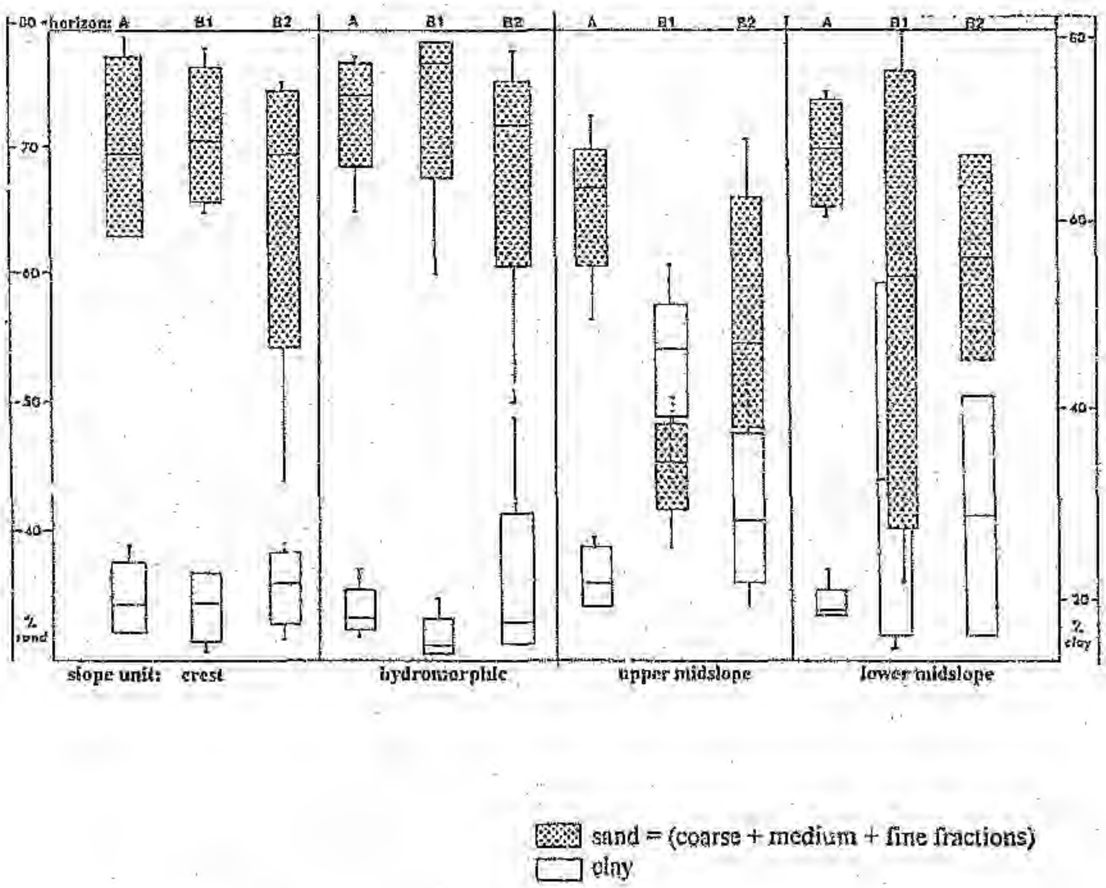


Fig 9. **Box plots of sand and clay percentages (horizons / slope units).**

An analysis of the clay and sand fractions shows that the clay percentage was more constant throughout the catenas than was the percentage sand, but that with respect to horizons and slope units there were significant differences. Significant differences for both textural fractions occurred between the A and B1 horizons, between crests and midslopes and between the hydromorphic areas and the midslopes (Table 2).

Table 2. Analysis of variance and multiple range tests (clay and sand fractions).

ANOVA				
Clay	Main effects	df	F ratio	95% Sig level
	Catenas	3	3.731	P = 0.0189
	Horizons	2	3.350	P = 0.0454
	Units	3	5.547	P = 0.0029
	Residual	39		

Multiple range test (95% Tukey HSD)				
Contrasts	Catenas	Horizons	Units	Sig dif
	1 and 4	A and B1	Crest --Mid	*
			Hydro--Mid	*

ANOVA				
Sand	Main effects	df	F ratio	95% Sig level
	Catenas	3	8.502	P = 0.0002
	Horizons	2	3.782	P = 0.0315
	Units	3	7.737	P = 0.0004
	Residual	39		

Multiple range test (95% Tukey HSD)				
Contrasts	Catenas	Horizons	Units	Sig dif
	1 and 3	A and B1	Crest -- Mid	*
	1 and 4		Hydro -- Mid	*
	2 and 4			

The mean grain size for all slope positions was calculated according to the method described by Campbell (1985) (see Appendix A 4) and plotted against distance along the slope (Fig 17a). This plot shows that the mean grain size is remarkably constant for the A horizon soils over the whole slope. The standard deviation of mean grain size, as an index of the sorting value (Munnik et al.1990) follows a similar consistent pattern for this horizon. These observations are indicative of minimal surface water movement on these slopes.

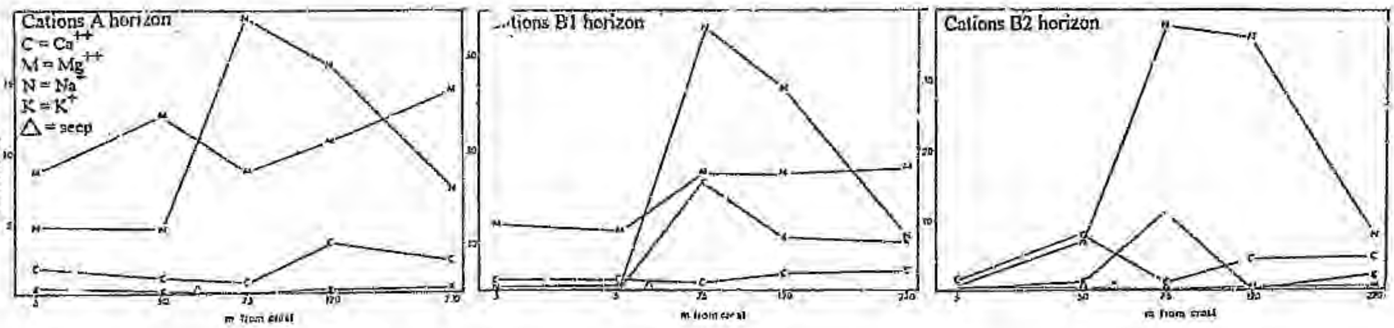
7.4.2 Major cations and pH

The analysis of the major cations (Ca^{++}, Na^{+}, Mg^{++}, and K^{+}), for the four catenas, underscores the site-specific differences that exist between the hill slopes and probably reflect the mineralogical differences that occur in the parent rock. Because of the differences, generalisations are not easily made. The most conspicuous features to emerge were the high sodium and magnesium, and the generally low calcium and potassium concentrations in these soils (Appendix B and Fig 10). According to the 1986 regional soil map (Department of Soil and Irrigation Research institute 1986) the soils are generally low in calcium in the upland sites but that this element shows its presence in the low-lying positions. The study slopes tended to confirm this pattern and support the concept that calcium, displaced by sodium from the exchange complexes, is transported to lower slope positions where it accumulates as insoluble calcium carbonate.

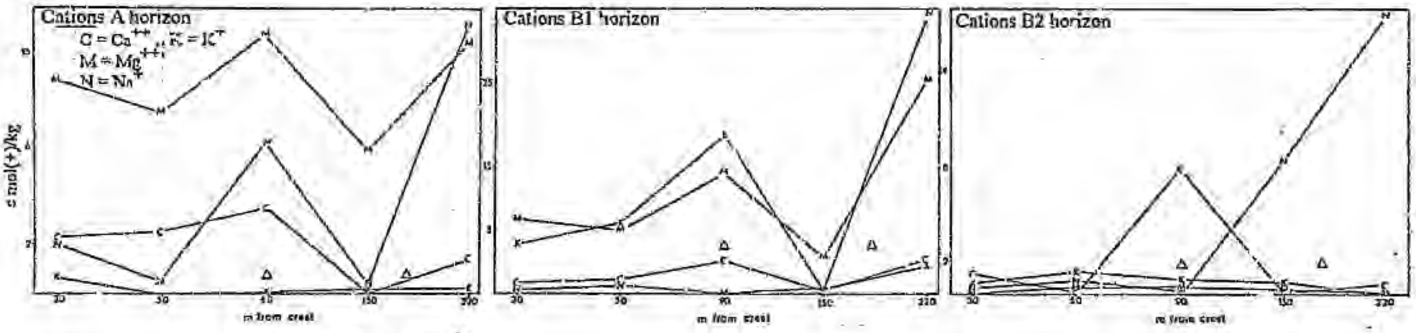
At the catenal scale all the major cations follow similar trends in relation to slope position and correspond, as might be expected, to the seepline clay accumulations (Fig 10 a,b,c and d). This trend is most marked in the case of magnesium and sodium, which suggests that these cations dominate the clay lattices. Low overall cation concentrations characterise those slope positions where the saturated hydraulic conductivity readings were highest (Fig 13) and where infiltration and percolation can be expected to promote leaching.

At many localities within the study area gullies have eroded the footslope soils exposing the depths of " B horizon. The surfaces of these gully walls and bases were found to be covered with large whitish nodules. These were not subjected to laboratory analysis but treatment, in the field, with 10% HCl produced strong effervescence suggesting that they are carbonates, probably of calcium and magnesium. The high magnesium levels in the study slope soils may account for the dominance of montmorillonitic clays.

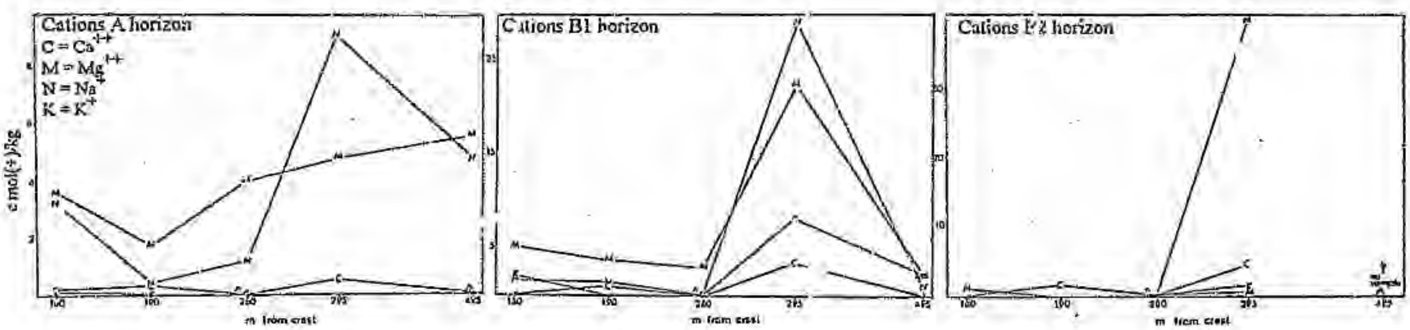
The terms 'alkali' and 'calc-brack' are frequently applied to sodic sites and suggest that these are areas of high soil pH. Dye (1977) has recorded pH values as high as 10.3 in sodic site soils. The pH values recorded on the study sites shows that the footslope soils of catena 1 had a value of 7.9 but that the remaining catenas never exceeded 7.3 and were generally mildly acidic, dropping as low as 4.9 in one case. Sodic sites are apparently not uniformly alkaline.



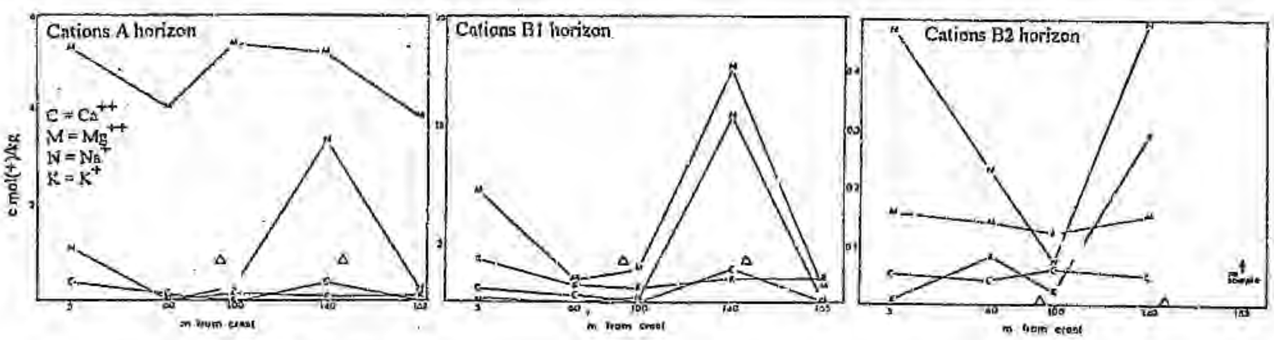
a. catena 1



b. catena 2



c. catena 3



d. catena 4

Fig 10. Major cations (cmol(+)/kg) plotted against distance (m) down the catena

7.5 Seepline development

The coarsest textured soils occur in the crests and hydromorphic zones and conform with the higher hydraulic conductivities recorded on these slope segments. These data indicate that these upslope sites are the areas of maximum water entry into the hillslope and owing to their elevation are optimally situated to act as the principal mechanism responsible for soil differentiation along the toposequence. An indication of the extent of leaching that occurs in these sites is found in the well developed E horizons of the hydromorphic zones.

Where the profiles have been exposed beyond the hydromorphic zone, the point at which clay begins to accumulate is clearly evident . There is an sharp transition from the pale, sandy soil of the E horizon above to the dark compact clay layer beneath. Within a short distance - between 15 and 30 metres on the study slopes - the clay layer increases in thickness, to dominate the entire B horizon. The clay accumulation develops from the depths and advances progressively upwards. The upper boundary, where it abuts against the sands above, is so abrupt that it suggests that the clay wedge is the result of clay translocation and deposition by water rather than a diffuse process resulting from the progressive elevation of the SAR and resultant clay dispersion, which might be expected to give a more gradual and less distinct change in the profile. On the upslope side of the impermeable clay barrier the deeper parts of the sandy profile shows evidence of waterlogging in the form of mottling indicating that water is held in these regions for extended periods during the year.

An opportunity to observe seepline formation, from the first trace of clay, at depth, to the point where it had reached full development was provided where a trench had been excavated throughout the length of the slope (for laying of a water pipeline) in the Sabi Sand Reserve. Measurements taken from this site together with soil pit and auger core data from the study catenas confirmed the relatively short distance over which the clay wedge develops (Plates 4.1, 4.2, 4.3) and the fact that the upper surface of the clay is inclined at an angle to the horizontal (Fig 11).

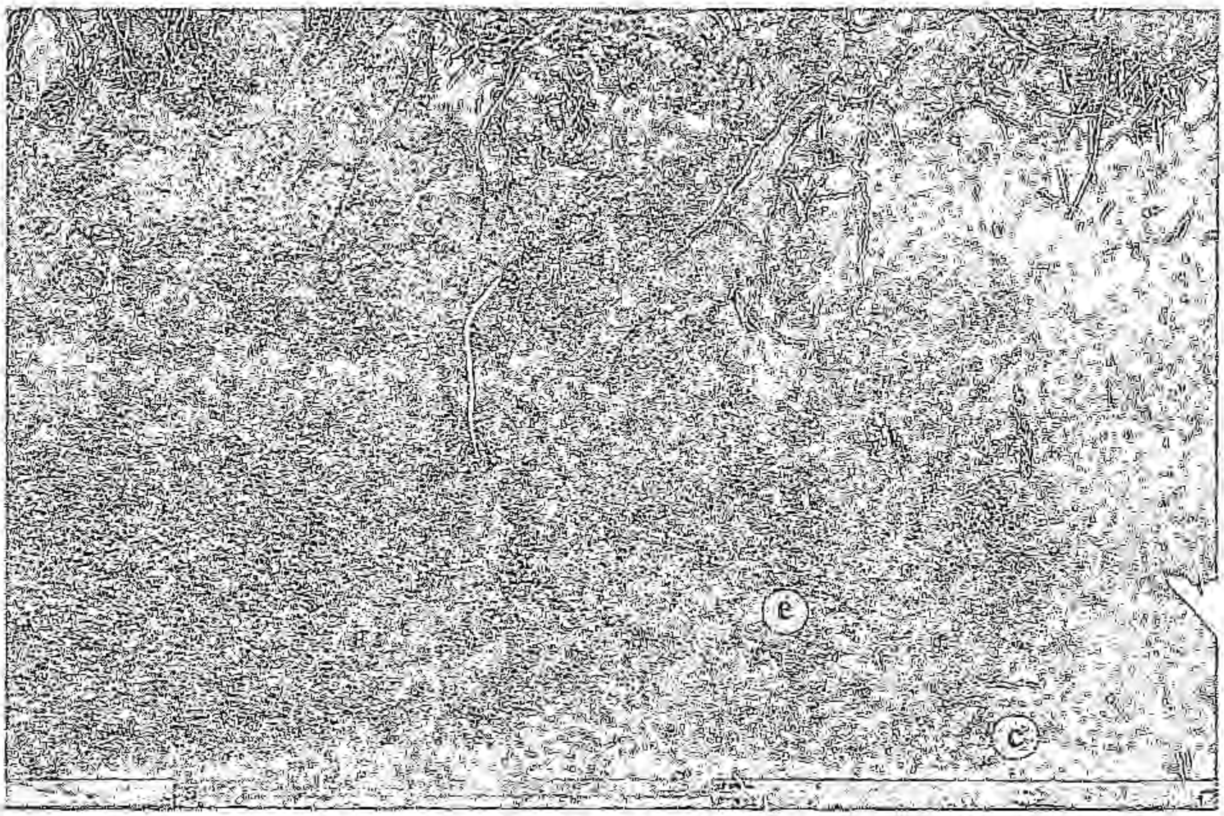


Plate 4.1. Seepline clay deposition i.

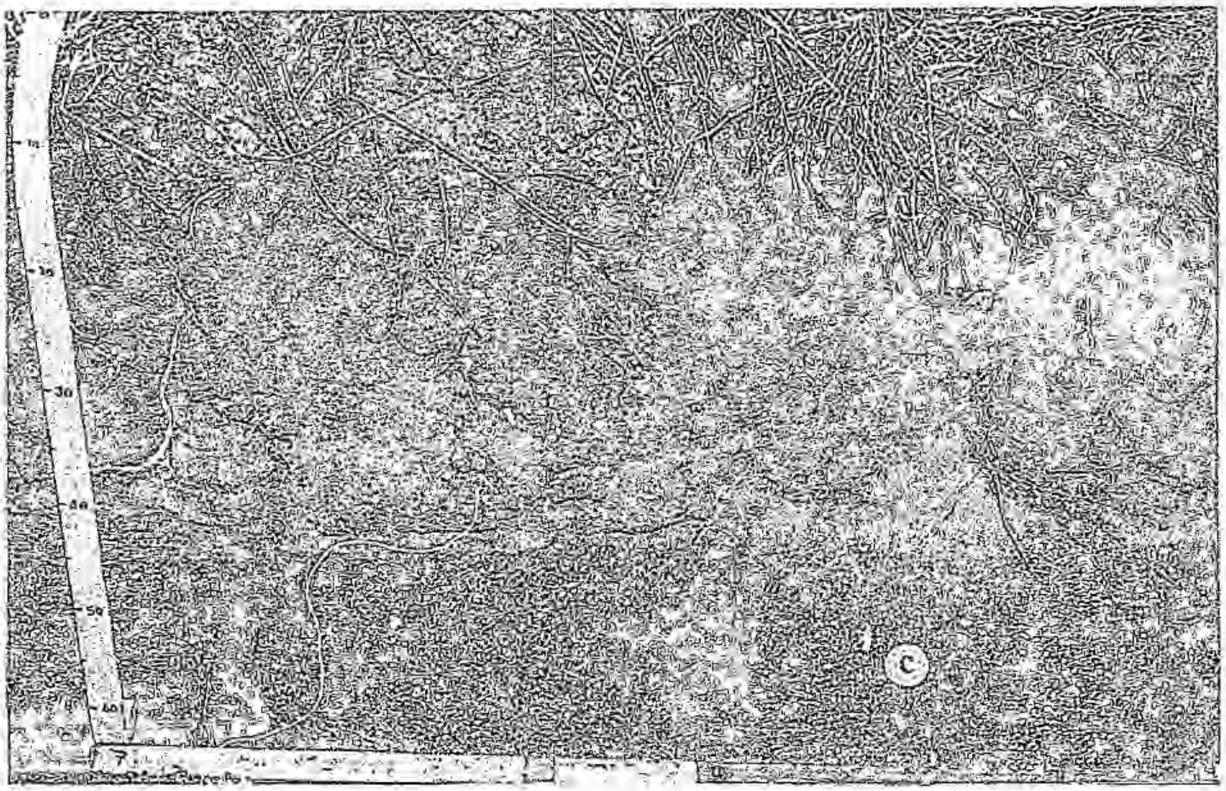


Plate 4.2. Seepline clay deposition ii.

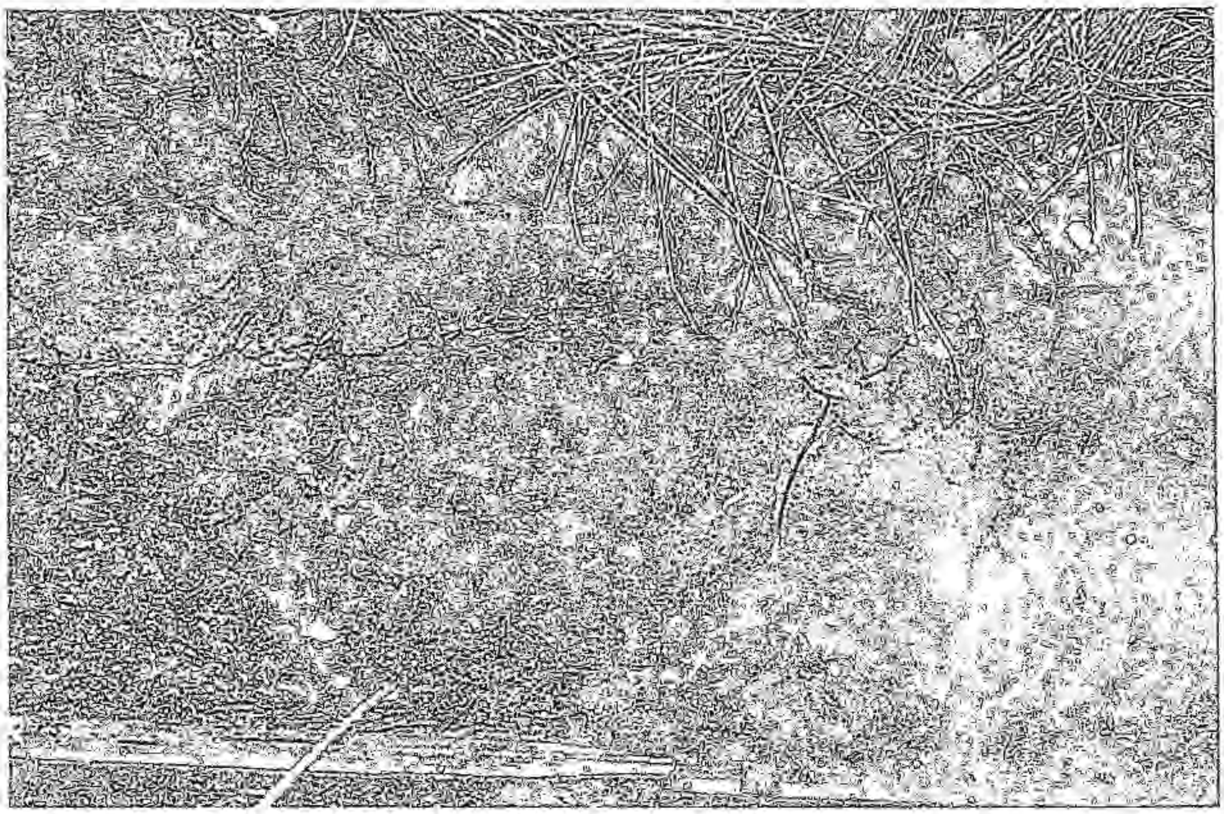


Plate 4.3. Seepline clay deposition iii.
The sequence i, ii and iii shows the deposition of clay (c), beginning at depth, below the leached E horizon (e) and becoming columnar as it advances towards the surface

The fact that the clay barrier is inclined at an angle would support the concept that a 'pocket' of water is trapped in this region following the cessation of the rainy season. It is in this region of prolonged near-saturation that the concentration of the soil solution would increase to above those levels found where drainage and throughflow is rapid. The model of the catena which is offered rests on the assumption that this reservoir of concentrated soil solution becomes displaced onto the slope below with the first rains of the succeeding wet season.

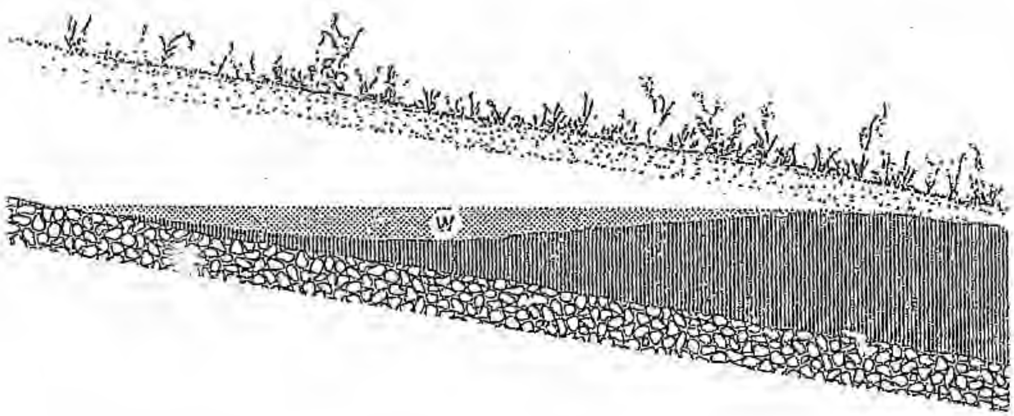


Fig 11. Seepline structure

Seepline clays, rising at an angle to the horizontal, trap a residual body of water (w) on the upslope side of the clay barrier, at the end of the rainy season.

This initial influx of 'concentrated' water is seen as the reason for the improved structural characteristics that are the general rule in the regions of the midslopes below the seepline.

Towards the base of the midslope or at its junction with the footslope a second cycle of clay accumulation occurs which in many respects resembles the clays of the upper midslope seepline. They are columnar in structure and highly impermeable. The position at which this second contour band of clay develops indicates that they are products of processes originating higher on the slope and that they are not related to the alluvial clays that are found in the stratified alluvium flanking the drainage lines. In theory, there could be more than two seeplines on a long catena, but two was the maximum observed.

The contour seeplines on these granitic catenas result in alternating bands of wet and dry soils along the slopes and in this respect these slopes differ from the general expectation that gradients of increasing wetness occur in a downslope direction.

The clay accumulation near the base of the midslope appears to impose hydraulic conditions that can be linked to the processes responsible for the formation of sodic sites. Evidence suggests that where these clay accumulations have reached maximum expression they set the upslope limit to sodic site progression.

7.6 Vegetation

The area falls within the 'type 5' Landscape of Gertenbach and is classified as mixed *Combretum spp. / Terminalia sericea* woodland (Gertenbach 1983). The distribution and species composition of the woody and herbaceous vegetation, which were recorded on the study catenas, corresponds with this landscape type.

7.6.1 Woody species

On the study slopes the woody vegetation was recorded within a 5 metre belt transect extending from the interfluves to the drainage lines and are represented graphically in Fig 12. Since individual heights and canopy size were also recorded, these characteristics were approximated in constructing the diagrams. Table 3 summarises species presence and distribution.

7.6.2 Herbaceous species

Plots were subjectively located on each catena according to the characteristic soil forms which correspond to the crest, hydromorphic, midslope and footslope areas (no footslope was present on catena 4). Each plot measured 25 by 50 metres and was oriented with its short axis paralleling the slope contour.Within each plot fifty 0.5 x 0.5 m quadrats were located on a symmetrical grid pattern and species present, relative abundance and cover rating were recorded. The species recorded and their percentage contribution in each hill slope area, for each catena, are presented in Table 4.

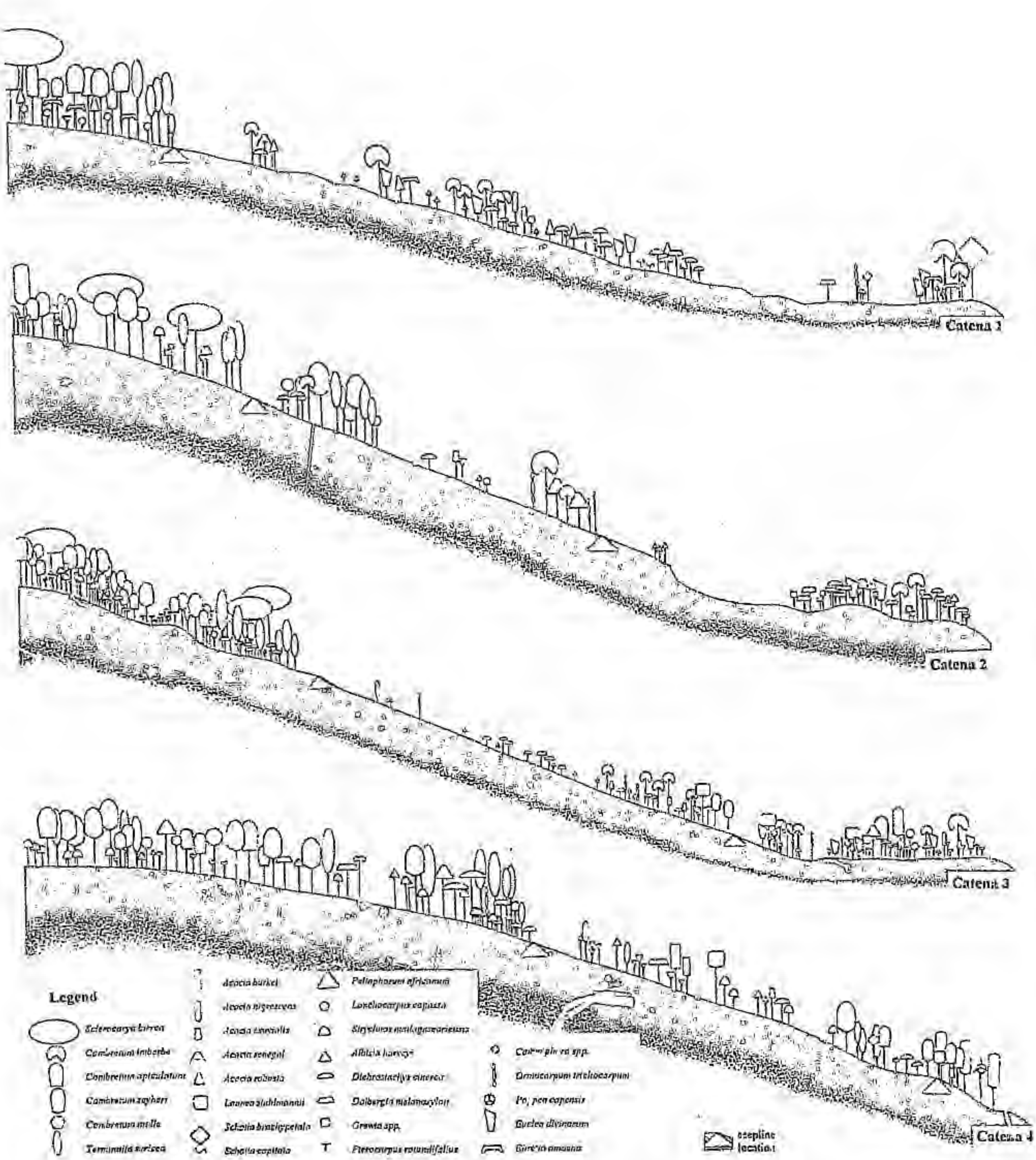


Fig 12. Woody vegetation on the study catenas

Table 3. Woody vegetation on the study catenas

Slope unit	Crest				Hydro				Mid				Lower mid				Foot		
CATENA	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3
SPECIES [1]																			
Sclerocarya birrea	x	x	x	x															
Combretum imberbe		x							x	x			x				x	x	x
C. apiculatum	x	x	x	x		x													
C. zeyhere	x	x	x	x										x					
C. molle	x			x															
Terminalia sericea	x	x	x	x	x	x	x	x								x			
Strychnos madagascariensis	x	x	x	x			x	x			x					x			
Lannea stuhlmanni		x		x												x			x
Peltophorum africanum				x						x								x	
Dalbergia melanoxylon			x	x				x						x		x			
Pterocarpus rotundifolius			x											x					
Lonchocarpus capassa		x			x			x										x	x
Commiphora spp.			x	x															
Acacia burkei								x								x	x	x	
A. nigrescens	x																		
A. exuvialis	x	x		x		x	x	x	x							x			
A. gerrardii													x	x			x		
A. robusta	x												x						
Albizia harveyi				x		x	x				x	x	x	x	x	x		x	x
Dichrostachys cinerea		x		x		x		x			x	x	x	x	x	x	x	x	
Ormocarpum trichocarpum				x			x			x	x				x	x			
Schotia capitata											x				x				
S. brachypetala																	x		x
Grewia spp.		x																x	
Maytenus heterophylla		x		x										x			x		
Euclea divinorum													x			x	x	x	x

[1] x Denotes Species present

Table 4. Herbaceous vegetation on the study catenas
(percentage bulk contribution)

Slope Unit	Crest				Hydromorphic zone				Midslope				Footslope		
CATENA	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3
SPECIES															
Digitaria eriantha	23	6	2	2	28	11	13	18	19	15	24	26	32	6	21
Panicum maximum	12	48	37	54	4	6	8	13	15	6	6	19	9	25	10
Schmidtia pappophoroides	16	2	5							2		2	4	2	
Aristida congesta	14	9	3		12	15	10	9	5	12	21	9	8	21	13
Pogonarthria squarrosa	10	11	29	10	1	19	20	4	9	3	2	12	5	2	9
Perotis patens	10	4	12			6		2							
Tricholaena monachne	5	7		3								3	2	2	
Urochloa mosambicensis	4	10	7		24	35	16	8	1	12	7	5		9	9
Enneapogon cenchroides	1														
Trichoneura grandiglumis	1					3		2				6	2		
Eragrostis superba	2				2			1	1						1
E. rigidior	1				3		4	5	5	6	1	4		2	
E. gummiflua	3					3	10	15		8	3				
E. trichophora															10
Heteropogon contortus	1			10					8	4		1	2		
Themeda triandra		2							35	12		4		4	
Dactyloctenium aegyptium					18		17	20	12	15	28	4			17
Chloris virgata					13		1				8	1		7	11
Setaria sphacelata						2				4				1	1
Sporobolus ioclados			2		5				1				2	1	
S. nitens													13	19	
Bothriochloa radicans									4				1		
Cenchrus ciliaris													4	4	
Cynodon dactylon													13		
Tragus berteronianus	1								1						

The pattern of vegetation, which is typical of the region as a whole, is discussed in Chapter 4. Here it is noted that plant community stratification corresponds closely with the repetitive catenary soil pattern (sandy, hydromorphic, duplex and alluvial) from interfluve to drainage channel.

Walker (1985) notes that savanna structure on any one site is determined primarily from below ground by soil water and nutrients. Leonard et al. (1988) have observed that the relationship between vegetation and soil morphological characteristics are most distinct where the landscapes involved contribute to a pattern of soils with distinctly different moisture infiltration and retention characteristics. These remarks are particularly applicable to the Ripape catenas where abrupt soil textural and structural changes are clearly demarcated at the surface by the presence of distinctive vegetation communities. This relationship reaches maximum expression on granitic catenas under the climatic conditions which prevail in the study region.

Soils with the highest recorded hydraulic conductivities have textures characterised by low clay and high coarse fraction percentages. They are located in the crestal and in the upper horizons of the hydromorphic slope units. These soils have the lowest CEC values when compared with the mid and lower slope units and reflect the high rates of soil water movement and leaching that occurs at these sites.

The sandy crests support broad-leafed savanna vegetation in which *Combretum zeyheri* and *Combretum apiculatum* are numerically dominant. Apart from the sub-canopy areas where *Panicum maximum* and *Digitaria eriantha* occur the herbaceous layer is composed of low palatability grasses of low nutritional value such as *Pogonarthria squarrosa* and *Aristida* spp.

The down-slope limit of the fringe of *Terminalia sericea* marks the ecotone where broad-leafed savannas give way to open hydromorphic grassland and defines the point at which the B horizons become dominated by impermeable, dispersed clays. At this point marked changes in hydraulic conductivity paralleled the recorded increasing clay percentages. Changes in the herb layer which characterise the ecotone include the presence of a number of sedge species and less commonly the presence of *Eragrostis gummiflua*.

The herb layer in these seasonally waterlogged, and generally treeless, zones becomes quite dense and appears to be highly productive. The grass species occurring at this point along the slope were notably *Urochloa mosambicensis* and *Dactyloctenium aegyptium*. The latter species becoming more conspicuous with increasing distance down the slope. *Panicum maximum* and *Digitaria erianthia* were also found in these slope units but were confined to the sub-canopy habitats where occasional trees interupted the otherwise open grassland. Trees became more numerous with increasing distance down the slope.

Towards the lower end of the midslope, where restructuring of the B horizon clays resulted in improved permeability the most conspicuous change in the grass layer was due to the presence of dense patches of *Themeda triandra*.

The increasing density of the grass layer followed a gradient of increasing soil nutrient levels which were indicated by the higher recorded cation exchange capacities of the A and upper B horizons that accompanied down-slope progression.

In these slope positions increasing numbers of woody plants were observed to occur. On catenas 1 and 3 the lower midslopes supported conspicuous stands of small (< 2 m) *Combretum imberbe* trees. With these noteable exceptions the woody vegetation was composed exclusively of microphyllus, spinescent varieties such as *Dichrostachys cinerea*, *Albizia harveyi*, *Ormocarpum trichocarpum* and a number of *Acacia* spp. The latter group were numerically dominant in these lower slope positions. The occurrence of this type of woody vegetation points to higher soil matric potentials and decreasing plant available water.

Apart from occasional clumps of *Euclea divinorum* woody vegetation was absent from the eroded sodic areas. The sparse grass cover on these sites was dominated by *Sprobolus nitens, Eragrostis trichophora* with *Cynodon dactylon* being conspicuous on catena 1.

Hillslope hydrology

8.1 The movement of water in soils

According to Selby (1990) the most important agent in promoting change in the hillslope processes of weathering, erosion and soil formation is the gravity-induced movement of water at the surface and within the soil matrix. Precisely which fraction of the water reaching the soil surface will fail to infiltrate, and runoff, as opposed to that fraction that will infiltrate into the soil has been the subject of ongoing debate for several decades. Recent developments in hill-slope hydrology suggest that the control over infiltration and runoff is largely related to vegetation. Infiltration and subsurface flow are now regarded as the dominant processes on most vegetated slopes.

The energy model proposed by Runge (1973) recognises that water reaching the soil surface is partitioned into a runoff component, not available for soil development, and an infiltrating component, the gravitational component of which is available for profile development. The control on, and the integration of soil development that follows the distribution of water on hill slopes is central to the catena concept initially proposed by Milne (1935).

The understanding of the processes of infiltration and runoff has undergone fundamental changes since Horton (1941) developed what Chorley (1978) referred to as the classical model of hillslope hydrology.

Horton hypothesised (Hillel 1980 a) that the soil surface zone determined what is referred to as the infiltration capacity and that any rainfall in excess of the soils ability to absorb it was shed from the slope in the form of overland flow. The logic contained in the statement is considered by many (Kirkby & Chorley 1967, Selby 1990, Cooke & Doornkamp 1990) to be the reason for this model having persisted, unchallenged, for several decades.

The Hortonian model paid particular attention to the hydraulics of overland flow and suggested that it was the sole motor of surface fluvial erosion and the sole provider of the hydrograph peak (Kirkby 1978).

With recent research the focus of attention has shifted from runoff to infiltration and subsurface flow as the most important hillslope hydrological process. Selby (1990) states that with very few exceptions, Hortonian overland flow on vegetated slopes is considered to be rare or nonexistent. De Ploey and Savat (1976) have noted that recent experimental work increasingly invalidates the classical model.

Recognising the role played by subsurface water movement on hillslopes Kirkby (1978) developed an alternative to the overland flow model of Horton. This he referred to as the saturated throughflow model and focused attention on short-term infiltration rates, which he considered to be the most important in governing hill slope hydrology (Carson & Kirkby 1972).

Kirkby and Chorley (1967) appear to have been the first to question the Hortonian theory and claimed that it would only apply in arid and semi-arid areas with minimal soil cover and low infiltration capacities. Israeli researchers (Yair & Klein 1973) working in arid and semi-arid regions found that profile textural anisotrophy was far more important than other slope characteristics in determining the balance between runoff and infiltration.

8.2 The infiltration process

Water reaching the soil surface moves into and through the soil mass under the influence of gravitational and capillary forces. Factors such as wetness and suction, texture, structure and uniformity of the profile are regarded as the major controlling factors in determining the initial rate of infiltration and its asymptotic decay to a final steady rate. Hillel (1980 a) notes that the decrease in infiltration from the initial high rate can result from deterioration of soil structure with partial sealing of the profile owing to migration of pore blocking particles, swelling of clay or entrapment of air. The most important cause of the decrease in infiltration rate is the inevitable decrease in matric suction gradient which occurs as infiltration proceeds.

The profile water distribution during infiltration has been described by Bodman and Coleman (1944). According to Chorley (1978) this was an aspect that was ignored by Horton. During infiltration into a homogeneous profile, under ponding, an upper saturation zone of constant hydraulic conductivity and approximately 80% saturation extends progressively downwards into the profile.

The transmission zone is constrained at depth by a wetting front at which there is an abrupt reduction in hydraulic conductivity. Chorley (1978) notes that the wetting front advances slowly through the conducting pores by a series of jumps (hysteresis) and views it as an effective restrictive layer and a promoter of lateral subsurface flow in the almost saturated transmission zone above.

Freeze (1972) explored the effects of changing hydraulic conductivity in soil profiles on the predicted hillslope hydrograph and concluded that zones of high hydraulic conductivity (cf. transmission zone) would contribute to the quick response subsurface flow and the storm hydrograph.

The concept of the displacement of existing soil water by new rain water (piston effect) has been investigated using a variety of techniques which have been reviewed by Chorley (1978). The modeling of this phenomenon is discussed by Bressler et al. (1982). Chorley (1978) notes that this work has shown that, although blurred by diffusion effects, a distinguishable mass of 'old' water is displaced by a pressure wave of 'younger' rain water entering from above. This observation supports the concept of lateral subsurface flow and reinforces its proposed significance in the overall hydrology of the hillslope.

Of particular importance to the hydrology of granitic hill slopes is the textural anisotrophy of the profiles, which results from the accumulation of dispersed clay. On these slopes the assumption of one dimensional (vertical) flow in the infiltration model becomes invalid.

The accumulation of perched water, due to impeding layers, can be assumed to contribute significantly to lateral subsurface flow. The effect of soil profile anisotrophy in creating conditions where the horizontal permeability of saturated soil is greater than the vertical permeability has been investigated by Reeve and Kirkham (1951). Kirkby (1969) concludes that in multi-layered soils the discontinuous decrease in hydraulic conductivity with depth, leads to perched, saturated, conditions which favour lateral flow.

8.3 Saturated hydraulic conductivity

The steady, gravity-induced, infiltration rate into a homogenous, structurally stable, vertical column of soil is shown by Hillel (1980 a) to be practically equal to the saturated hydraulic conductivity. In this project a constant head, shallow well permeameter was constructed to measure the saturated hydraulic conductivities of the A and upper B horizon soils of the study catenas (Plate 5). Measurements were made in the upper B horizon after removal of the overlying topsoil. Owing to problems encountered with the inter-columnar voids in the duplex profiles during the dry winter months, the final recordings were made during the wet season, after the clays had expanded. At this time of year the clays behaved as a homogeneous body, enabling measurements to be taken. The wells were cut into the soil, to a constant depth, using a purpose-made cutting instrument in order to avoid soil compaction. Different well radii and different muffler sizes were used in order to establish optimum performance of the instrument and the final measurements were made using de-ionised water to simulate rainwater.

Although, as noted, the final steady rate of infiltration is practically equal to the saturated hydraulic conductivity, the process of infiltration is a complicated one which depends, not only on several soil factors but also on the infiltrating solution and the interaction between soil and solution. Hillel (1980 a) notes that the modeling of the infiltration process has shown that, in most instances, the matrix-water interactions cannot be resolved into separate and exclusive properties of the soil and the water. Notwithstanding the complexities of the infiltration process, the saturated hydraulic conductivity, determined under field conditions, provides a useful cor[illegible] measure of the permeability of different soils.

Marshall and Holmes (1979) have indicated the range of saturated hydraulic conductivities that can be expected in soils with different structural and textural characteristics. Values lower than 10^{-7} m/s can be expected for fine textured, poorly aggregated, soils whereas values greater than 10^{-4} m/s are typical in coarse textured soils The values recorded on the study sites ranged from $.01 \times 10^{-7}$ to 9.06×10^{-7} m/s. The conductivities in the A and B horizon soils followed a similar pattern along the slope, with the A horizon soils having higher rates in general (Fig 13).

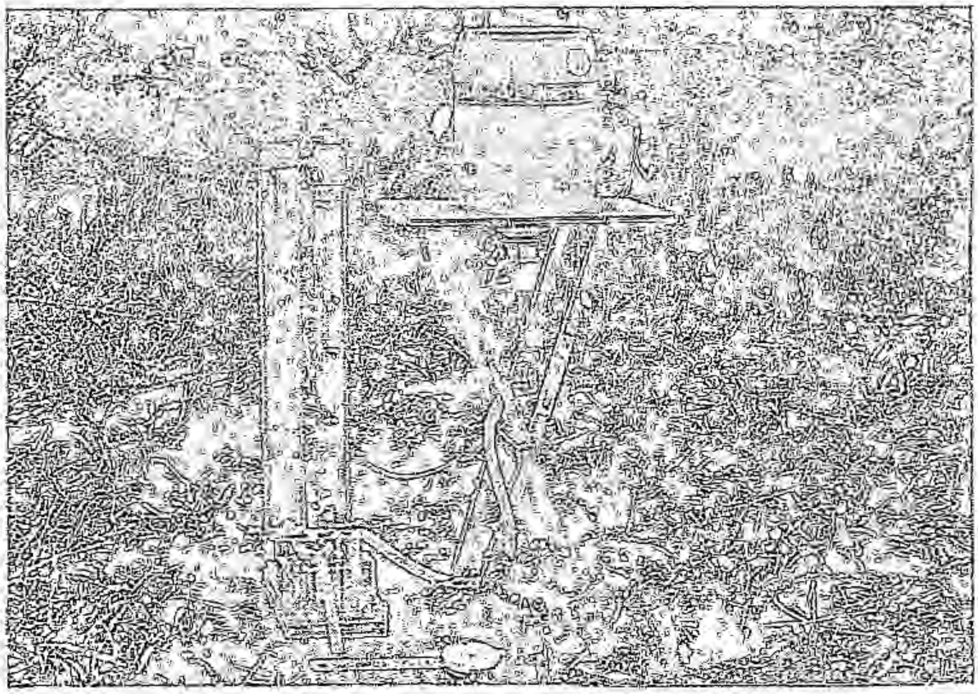
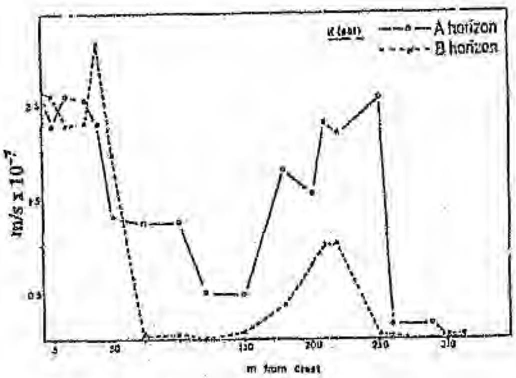


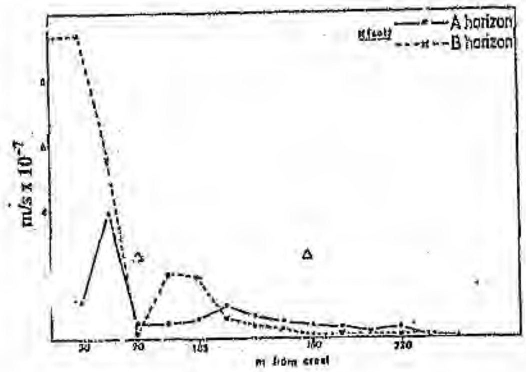
Plate 5 Shallow-well constant-head permeameter
This instrument was used to measure the saturated hydraulic conductivities of the A and upper B horizons

8.4 Results of saturated hydraulic conductivity ($K_{(sat)}$) measurements

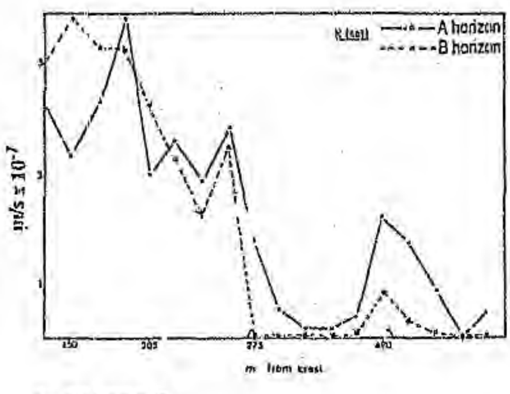
The saturated hydraulic conductivity readings from the A and upper B horizon soils on the study slopes are plotted against catenal position (Fig 19 a,b,c,d.) and demonstrate a pattern of increasing and decreasing values, which is repeated on all slopes.



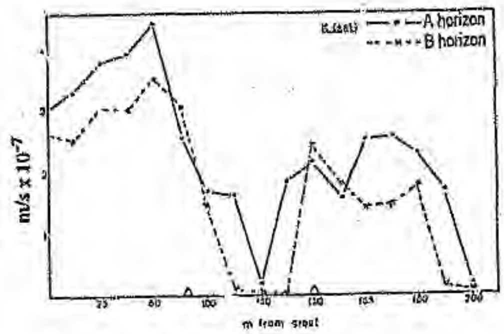
a. catena 1.



b. catena 2.



c. catena 3.



d. catena 4.

Fig 13. Saturated hydraulic conductivity (m/s x 10^{-7}) plotted against distance (m) down the catena

Table 5. Analysis of variance and multiple range tests fr r K(sat) catenas, hillslope units and soil horizons

ANOVA				
K(sat)	MAIN effects	df	F ratio	95% Sig level
	Catenas	1	1.132	P = 0.7547
	Horizons	3	6.179	P = 0.0298
	Units	3	0.399	P = 0.0029
	Residual	24		

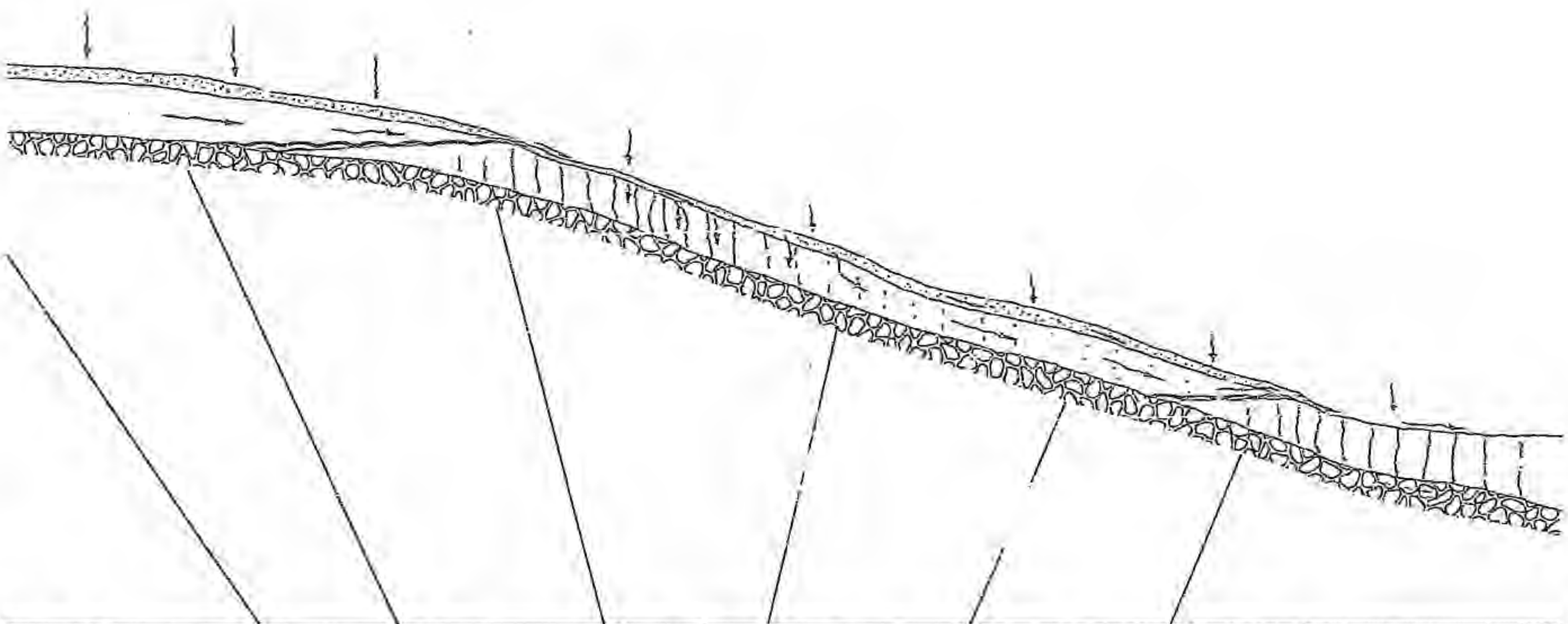
Multiple range test (95% Tukey HSD)		
Contrasts	Units	Sig dif
	Crest -- Mid	*
	Crest -- Foot	*
	Hydro -- Mid	*

No statistically significant differences between catenas, nor between the upper horizons in respect of $K_{(sat)}$ emerged from the study but highly significant differences were recorded between slope units (Table 5). The crests and hydromorphic zones displayed significantly higher values than the remaining slope units but were not different from each other.

A regression analysis of K(sat) versus [Na^+] failed to demonstrate a significant relationship ($P < 0.1498$). The negative correlation between K(sat) and percentage clay was however significant at the 95% level ($P < 0.0456$). A plot of K(sat) versus SAR (Fig 15) shows that there were no high hydraulic conductivities recorded at SAR values above 3. A similar plot (Fig 16) against percentage clay shows that above 27% clay no high K(sat) values were recorded.

Based on the established relationship between clay dispersion and changing levels of monovalent cations (particularly Na^+) in the soil the occurrence of seepline clay accumulations along the catena could conceivably be explained in terms of [Na^+] threshold values at these localities. In the initial project proposal it was suggested that the related phenomena of accumulations of dispersed c critical sodium ion concentrations and low rates of saturated hydraulic conductivity would be closely linked. The conceptual model (Fig 14) that was developed was based on this hypothesis.

Consideration of Fig 15 and Fig 16 points to the co-occurrence of high rates of saturated hydraulic conductivity, low clay percentages and low SAR values. Cause and effect are not unequivocally established. The observed lack of a statistically significant relationship between K(sat) and [Na^+] suggests that it is not an increasing sodium ion concentration, to reach and exceed a critical level at a given point along the slope, that results in clay dispersion and seepline formation at these locations.



profile characteristics	A orthic B apedal	A orthic E leached sands B clay	A orthic B columnar structured clays DUPLEX	A orthic B prismacutannic blocky / granular in structure	A orthic E leached sands B clay	A sandy structureless B structured clay DUPLEX	Sodic site B clay exposed at surface
K(sat)/permeability/ infiltration	high throughout profile	high in A and E low in B	low throughout	high in A increasing in B	high in A and E low in B	low	Low
soil solution electrolyte concentration	dilute	dilute but increasing in residual water above seepline	concentrated	initially concentrated becomming dilute as wet season progresses	dilute becomming concentrated as dry season progresses		
clay status (dispersed/flocculated)	dispersed/ mobile			some degree of reflocculation ?	dispersed mobile		
pattern of water movement	sub-surface	subsurface	surface and through A	into intercolumnar voids when dry	subsurface	perched above B horizon	surface
[Na]/SAR	low	low	high	intermediate	lower	high	high
hydraulic gradient	low			increasing with slope length		high	

Fig 14. A conceptual model relating seepline clay accumulations, critical sodium ion concentrations and saturated hydraulic conductivity.

The work of Thompson 1967, Purves and Blythe 1969, Thompson and Purves 1978 and Thompson 1992 (pers comm.) indicate that the weathering of sodium rich substrates, which in their studies included sodic granites and redistributed Karoo sediments, sufficient sodium is released to initiate clay dispersion immediately following, or shortly after, clay synthesis. This would indicate that clays, in the dispersed state, are widely distributed at all catenal positions and are not only confined to seepline localities.

Dispersed clays are known to be highly mobile soil constituents and are therefore easily translocated by soil water moving from higher to lower slope positions. This process would be facilitated in the coarse, sandy, and highly permeable crestal soils that characterise granitic catenas.

It is therefore postulated that the seepline clay accumulations are not determined by locally elevated sodium ion concentrations producing clay dispersion at these sites. They are more realistically explained in terms of the hydrodynamic processes responsible for the seasonally fluctuating soil water pulses, their effect on the redistribution of the previously dispersed clay fraction as well as their influence on the electrolyte composition and concentration of the soil solution. This hypothesis is developed in the catenal model which is presented in a later section.

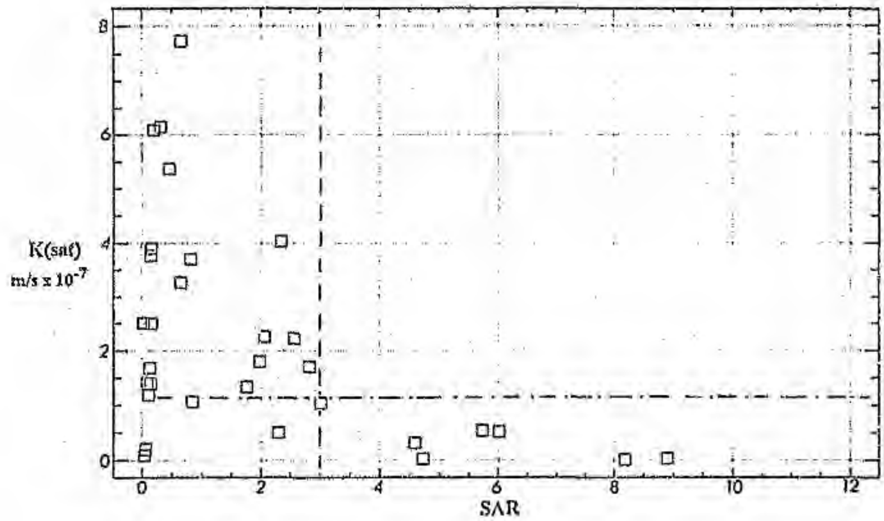


Fig 15. Plot of saturated hydraulic conductivity versus SAR.
no high K(sat) readings at SAR values above ~ 3.

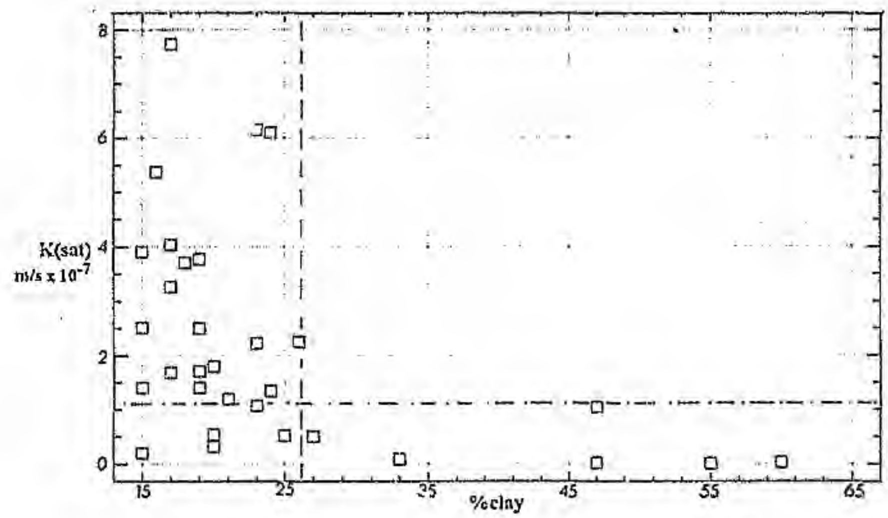


Fig 16. Plot of saturated hydraulic conductivity versus % clay.
no high K(sat) readings above ~ 26 % clay.

Soil erosion

9.1 The erodibility of sodic soils

The erodibility of granitic soils can be explained in terms of those factors responsible for soil aggregate formation and aggregate stability. In his review of the factors determining the susceptibility of a soil to erosion, Thornes (1980) notes that it is aggregate stability rather than textural composition that emerges as the most important factor. According to Hillel (1980 a) a prerequisite for soil aggregation is that the clay fraction should be in the flocculated state and that there should be an appreciable contribution from cementing materials in the soil.

The electrostatic double layer theory, which explains the dispersive behaviour of reactive clays has been described in a previous chapter. It was noted that inter-particle repulsion, favouring dispersion, is maximised when the double layer is fully extended and that this is due to ionic hydration and the osmotic effects resulting from dilute solutions. This effect is maximised when the dominant cation is monovalent and when the soil is fully hydrated. Singer et al. (1977) have shown that significant clay dispersion and erodibility values were recorded at ESP values as low as 2.

Soil erosion in game conservation areas in South Africa has not been studied in any detail. The lack of published data in this regard is noted by Venter (1988) in one of the few documents dealing with this topic. Erosion control measures currently in use appear to be based on experience and studies carried out in cultivated lands, where surface wash is the dominant process, and are inappropriate under rangeland conditions.

The need to develop erosion control strategies based on a proper diagnosis and on an understanding of the relevant processes has been stressed by Beckedahl et al. (1988).

9.2 Erosion on sodic sites

The topographic position and surface characteristics of sodic sites gives the impression that they are erosion features that result from the flow of water that has failed to infiltrate the soil at locations higher on the slope. The use of the term sheetwash (Dye 1977, Tinley 1979) when referring to eroded sodic sites implies that this is the dominant process. Observations and data from the study sites indicates that the erosion, on these areas, is essentially a subsurface phenomenon and that overland flow plays little, if any, part in their formation.

9.2.1 Sheetwash as an agent of erosion

Hogg (1982) defined sheetwash as the selective removal of easily transported material from the hill slope by runoff on relatively homogeneous surfaces. This process leads, according to Selby (1990), to an accumulation of soil and deepening of the profiles in the bottom lands. Sodic sites, however, are characterised by the loss of soil from the footsl oes and a reduction in profile thickness. Gerrard (1980) argues that unconfined flow in thin sheets is only possible on relatively smooth surfaces and that the erosive capacity of un-concentrated flow is in general slight and involves the transport of only the finer soil fractions.

The Hortonian model of overland flow, based on the hydraulics of surface runoff, was considered to be the sole cause of surface fluvial erosion (Horton 1939). The model assumes that flow occurs widely over the slope face and that the depth is related to the distance from the divide. At a critical distance along the slope the depth and the velocity of flow develops sufficient energy to generate a shear strength competent to entrain surface soil particles. According to the model the critical distance is located in the upper midslope and maximum erosion occurs just below this point, usually on the steepest part of the slope . A further prediction is that the lower slope segments are predominantly sites of deposition. Based on these assumptions sodic site erosion does not fit the model since the focus of erosion is in the foot slopes. Recent evidence suggests that erosion caused by overland flow, according to the Hortonian model, is confined to bare unvegetated slopes or to steep slopes with minimal soil cover (Gerrard 1980).

Chorley (1978), one of Horton's severest critics, maintains that on vegetated slopes overland flow can be ignored as a significant factor in erosion. Emmett (1970) noted that in a ten year study in a semi-arid region subjected to periodic heavy thunder storms, overland flow was never observed in the field. He does concede that under the appropriate conditions the erosive action of surface flow can be considerable.

De Ploey and Savat (1976) have shown that downslope evacuation of the coarser fraction by runoff is not an evident phenomenon. This claim finds support in the observations of Gerrard (1980) and Emmett (1970) who have noted that where sheetwash occurs, the continued loss of fine particles leads to domination at the surface by the coarser fraction.

Based on these considerations, trends in mean grain size over the study slope surface soils would be expected to occur if surface wash were a factor in the overall hydrology of the hillslope. Fig 17 reveals little change with respect to mean grain size for the surface soils on all the study slopes throughout the length of the catenas.

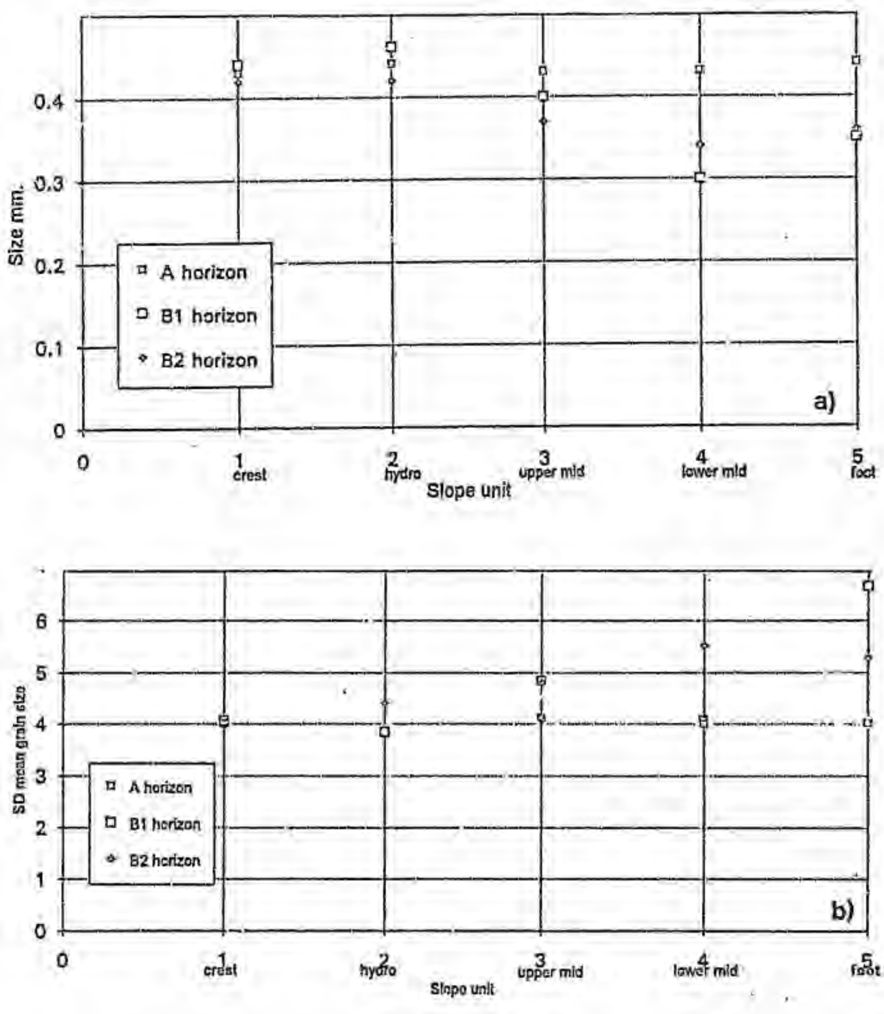


Fig 17. a) Mean grain size at different slope positions (average for all catenas).
b)Standard deviation (mean grain size).

Beckedahl et al. (1988) note that the microrelief of natural vegetated surfaces will tend to promote flow concentration and result in the initiation of microchannel and rill erosion. The hill slopes in the Ripape River catchment are well vegetated and a detailed inspection of the surface features of the slopes that were associated with sodic sites failed to reveal any evidence of either unconcentrated or concentrated flow.

Further evidence of the absence of significant surface water movement on these slopes is related to the presence of the characteristic upslope ledge which characterises most sodic sites. What follows is based on the work of Ireland et al. (1939). These workers studied the erosive effects of water flowing over a fall face and noted that the free fall of water creates a scouring at the base of the fall. In addition, that fraction of the water that is held to the face by surface tension forces promotes undercutting and upslope migration of the scarp. No evidence of undercutting or scouring could be found on the sodic site scarps. On the contrary, where the subsurface pipes discharged onto the eroded surface there was a build up of material in the form of small alluvial fans, which it is presumed would not occur if significant surface flow prevailed.

From the multi-temporal aerial photographs, spanning a fifty year period, the upslope perimeter of the sodic sites appeared to be particularly stable and upslope migration, where it was observed to have occurred, could usually be related to the collapse of subsurface pipes. Some loss of material was noted at the scarp, which appears at first to look like undercutting, but is due to the washing out of unconsolidated material from the exposed A/B horizon junction. The hydraulics of this phenomenon are dealt with under 'piping erosion'.

9.2.2 Subsurface flow

Alternating zones of higher and lower hydraulic conductivity are a feature of the study catenas. High infiltration rates characterise the sandy crestal soils and to a lesser extent the lower midslope regions, low infiltration rates correspond to the upslope seepline and to the duplex horizons at the base of the midslope.

Under the prevailing rainfall conditions subsurface flow predominates on these slopes. An exception to this rule may occur during high intensity rainfall or following several days of continuous rain. At these times water may be seen to emerge at the seepline and flow over the surface. Free surface water is not a common occurrence on these catenas, but saturation of the A horizon soils for brief periods, occurs frequently.

The sandy loams associated with these duplex soils appear to be of sufficient thickness (and storage capacity) to prevent the escape of water in all but above-average rainfall seasons. Their position, higher on the slope, and the fact that they are followed in the sequence by more permeable soils on the slope below, suggests that saturated conditions are of short duration and that this is assisted by downslope subsurface drainage.

In the lower slope the reappearance of strongly duplex profiles, which extend throughout the greater part of the footslope, results in the accumulation of perched water above the impeding layer of the B horizon clays. Unable to infiltrate, and prevented by the declining gradient from rapid lateral drainage, water accumulates in the topsoil layer which becomes saturated throughout its depth.

In many respects the zone of saturation is similar to the wedge of saturated through flow described by Kirkby (1978), but the mechanisms producing it are different. In particular, because of the elevation of the sites, there is little possibility of return flow from a rising stream level and neither can saturation be due to a rising ground water table, both of which sources contribute to the saturated throughflow model of Kirkby (1978). Bore-hole measurements in the area show that the phreatic surface has never been recorded closer than 15 m from the surface and it is generally below 20 m.

The perched water in these lower slope positions is the result of a supply of water from upslope, moving as lateral subsurface flow, and is augmented by rain falling directly onto the site. The reduced rate of drainage, due to the impermeable B horizon, the declining gradient, and the ongoing supply of water from upslope ensures that these soils remain in a state of near saturation for long periods of time during the wet season.

9.2.3 Soil strength and susceptibility to erosion

Soil strength is a measure of its resistance to failure in shear and is determined by its cohesive strength and a number of factors related to friction. The cohesive component of soil strength is largely responsible for aggregate stability and is due, in part, to the presence of cementing materials from both organic and inorganic sources. A considerable contribution to the cohesive component of soil strength derives from the electrostatic forces of attraction between colloidal particles. Selby (1990) reports forces of the order of 7 kN/m^2 in this connection. A further component of cohesive strength, which has been termed 'apparent cohesion' (Craig 1990), is directly related to soil wetness and matric suction and is due to the surface tension forces residing in the films of water surrounding the soil particles in unsaturated soils.

The friction component of soil strength arises as a result of the frictional resistance to displacement between soil particles in contact. It is strongly dependent on the number of point contacts per unit area, on particle strength, surface roughness and packing. One of the most important contributors to frictional strength is the normal component of overburden stress - a gravitational force acting vertically downwards - since it is this component that maintains the point contacts and resists movement.

The low organic matter content, presence of sodium dominated clays and the absence of inorganic cements combine to create a weak aggregate structure in the surface soils that are disposed to sodic site formation. These areas, once stripped of their protective cover, are vulnerable to the effects of trampling and are soon reduced to a structureless mass which is unable to resist displacement.

These weakened soils are subjected to rising pore pressures which further reduce their strength. Under completely dry, or fully saturated conditions, the apparent cohesion that is derived from matric suction is reduced to zero. When saturated, part of the normal component of overburden stress is transferred to the soil water. There is a proportionate rise in pore water pressure and a buoyancy, or up thrust effect, which contributes to a reduction in the effective normal stress.

A further contribution to rising pore water pressure results from the hydraulic head due to the sloping terrain. Pore pressures near the base of the slope may rise to the extent that they negate the vertical gravitational component of overburden stress, rendering the soil particles virtually weightless.

In addition to the 'static' effects of rising pore water pressure the footslope soils are subjected to a displacing hydrostatic force generated by laterally moving subsurface water. Water seeping down the slope does so in response to the hydraulic head difference (ΔH) between higher and lower slope positions. The total head is dissipated as viscous friction, acting in the direction of flow, on the soil fabric. This energy transfer from water to soil particles is referred to as the seepage force.

The combination of the normal body force and the seepage force is the resultant body force acting on the soil particles. It is the resultant body force that governs the effective normal stress (and soil strength) in the plane of seepage.

resultant body force = effective normal stress + seepage force

Under static conditions of no seepage ($\Delta H = 0$) the resultant body force equals the effective normal stress. If seepage is vertically downwards the effective normal stress rises above its static value - a condition which is not possible if there is an impeding layer below. The most likely course of events is that there is a component of upthrust and seepage force acting in opposition to the normal stress component (Thornes 1980).

On sloping terrain where shallow impermeable horizons favor the formation of saturated conditions in the surface soils Thornes (1980) notes that soil water movement is largely due to the potential provided by the hydraulic head differences between slope locations. In the saturated zones of the footslope region flow takes place parallel to the surface or with a vertical component. Contributing to this vertical component is the continuing supply of water from upslope aided by the downslope thinning of the permeable surface layer. A further contributing factor is the convergence of flow lines in this region and the slowing of flow velocities due to the decreasing footslope gradient. These hydraulic parameters are responsible for what Whipkey and Kirkby (1978) refer to as 'return flow', initially described by Dunne and Black (1970).

A special condition of upward seepage is recognised, at a critical hydraulic gradient, which results in the seepage force being equal to the effective weight of the soil. The effective normal stress becomes zero, the contact forces between the soil particles are negated, and the soil will have lost all strength. This is referred to as the 'quick' condition (Craig 1990).

The mechanisms underlying the formation of sodic sites can be explained in terms of the engineering principle that recognises that if, in any plane within a soil mass, the shear stress becomes equal to the shear strength of the soil, failure will occur along that plane. The soil strength measurements obtained on the study slopes confirm the overall reduced soil strength in the A horizon and a distinct plane of weakness along the junction of the A and B horizons.

Under these conditions it is possible that water moving from higher up the slope could easily displace the saturated, cohesionless, and virtually weightless soils across the low gradient footslopes and initiate sodic site formation.

A point that should be stressed is that the major effect is below the surface rather than at it. While contributions to displacement from overland flow cannot be completely excluded, the low gradient and the restricted reach over which this flow could gain the necessary velocity places this region in the 'zone of no erosion' according to the Hortonian model of hill slope erosion.

The velocity of subsurface water movement is in general slow, of the order of 20 cm/hr (Kirkby & Chorley 1967). These authors show that in near-saturated porous soils it increases rapidly in response to increasing rainfall intensity, slope length and gradient and is sufficiently rapid to contribute to the storm hydrograph peak.

Based on these considerations adequate amounts of energy would be available to displace the structureless soils and initiate sodic site formation.

The rate and direction of spread of sodic sites

In order to quantify the rate of soil loss from eroding sodic sites, use was made of remote sensing techniques based on standard aerial photographs. The white quartz clasts that cover established sodic sites constitute a high-albedo surface easily recognised in the field by its bright appearance, and on remote sensing images by a very high overall albedo in all wave length ranges. Other surfaces in the surrounding area have some vegetative component which has a markedly lower albedo in all visible wavelengths. Areas of bare sandy soil that are not eroded may have albedo values approaching that of the eroded areas, being predominantly composed of quartz clasts albeit of finer grain size. Mature erosion areas that have had the quartz clasts stripped away, to expose the underlying clay, or have been re-colonised by pioneer grass species, sedges or cryptogamic plants loose the bright appearance in the visible wavelengths.

The images used to measure the extent of erosion were pan-chromatic aerial photographs. This choice was due to the following factors

- Photographs ranging from 1:20 000 to 1:50 000 scale provide the requisite detail necessary for monitoring of the present study areas.
- Multi-temporal aerial photographs are available over a period of 50 years, encompassing over half the life span of the Kruger National Park.
- The areas of erosion are the brightest areas on the photographs and are therefore easily discriminated from other surface types on panchromatic photographs.

Photographs from four periods were used in the study. The photo sorties were flown in the winters of 1944, 1965, 1974 and 1985. A large difference between the appearance of the area in 1944 and more recent times is clearly visible (air photo split 1944/1974 Plate 6.).

Plate 6. Air photo split 1944/1974

10.1 Scale and albedo problems

The photos from each period differ in scale, orientation and image density/contrast, making it difficult to carry out visual estimation and comparison of the amount of erosion present at each time (Plate 7.). These problems were overcome using digital processing techniques.

10.2 Digital Image processing

Image processing was carried out on an IBM-compatible 486 33 MHz Pc using the Microimages MIPS (Map and Image Processing System) software. This software is particularly suited to this application, with routines for registration of data to map projections and measurement of surface categories. Digitisation of the aerial photograph prints was by means of a Howtek Scanmaster 3 digitising scanner directly driven from MIPS.

One photo from each set was chosen for digitisation. The chosen photo contained the study area as close as possible to the nadir. The study area was then digitised from each photo using a spatial resolution of 150 dpi and an 8 bit grey level range (0 to 255). The limit of the study area digitised from each photo were chosen from the limits of the largest scale photo. This was the 1944 image at approximately 1:20 000 scale. The 1944 image was also used as the bench mark for registration and resampling of the photos to the same projection and pixel size to facilitate measurement and comparison of eroded areas from each period.

Ground control points were chosen from this photo and from 1:50 000 scale topographic maps. The 1944 digitised photo was then resampled to a Universal Transverse Mercator projection using the Clark 1880 ellipsoid. Resampling was performed by the nearest neighbour method with an output pixel size of 1.3 metres. Ground control points were chosen from the georeferenced 1944 photo and the photos from 1965, 1974 and 1985. These were also resampled to a UTM projection at 1.3 m pixel.

The resultant set of four georeferenced photos now represented the same area at the same scale so that direct measurements and comparisons of areas of ground surface type could be made.

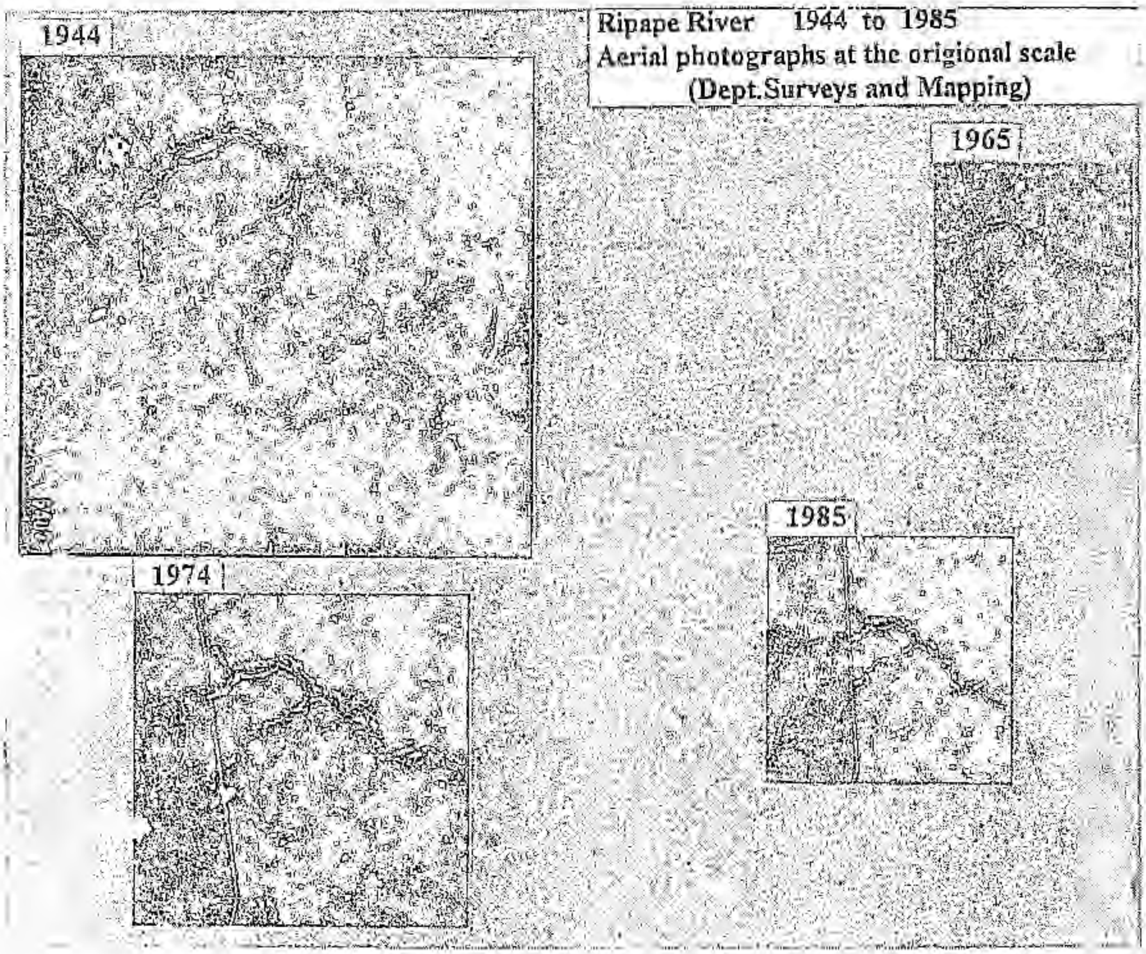


Plate 7. Photographs at original scale

10.3 Measurement of areas

The overall albedo of three surface types was established by interactive image analysis for each of the four photos. The areas devoid of vegetation are clearly the brightest surface types on the digital images and a threshold value equal to the lowest value for the 'bare ground' category was chosen for each image. A binary image was then generated with a value of 0 for any pixel below the threshold value and a value of 1 for any pixel equal to or above the threshold.

Vector polygons were then drawn around the erosion areas on the binary image using an 'automatic boundary' feature of MIPS. The resulting vector object could then be plotted and interrogated to discover the total area covered by the erosion sites. Vector objects and total measured areas for the four dates are presented in Fig 18.

10.4 Estimates of soil loss

Using the rescaled panchromatic images (Plate 8) the automatic boundary feature of MIPS provided surface area measurements for areas dectected as bare ground. Eroded areas for each time interval are as follows :-

1944 image -- 0.64 hectares
1965 image -- 6.50 hectares
1974 image -- 9.70 hectares
1985 image -- 5.50 hectares

The eroded area locations in 1985 are practically identical to the 1974 imagery but the areas are smaller. This is not interpreted as an indication that topsoil had been reformed in a period of 10 years but possibly that the erosion process had advanced one stage further and that the dark underlying clays had been exposed thus reducing the high albedo areas detected in the photograph. There is also the possibility that at the margins of the previously eroded sites cryptogamic plants and sedges were producing cover in previously bare areas. Both these types of encroachment have been observed in the field.

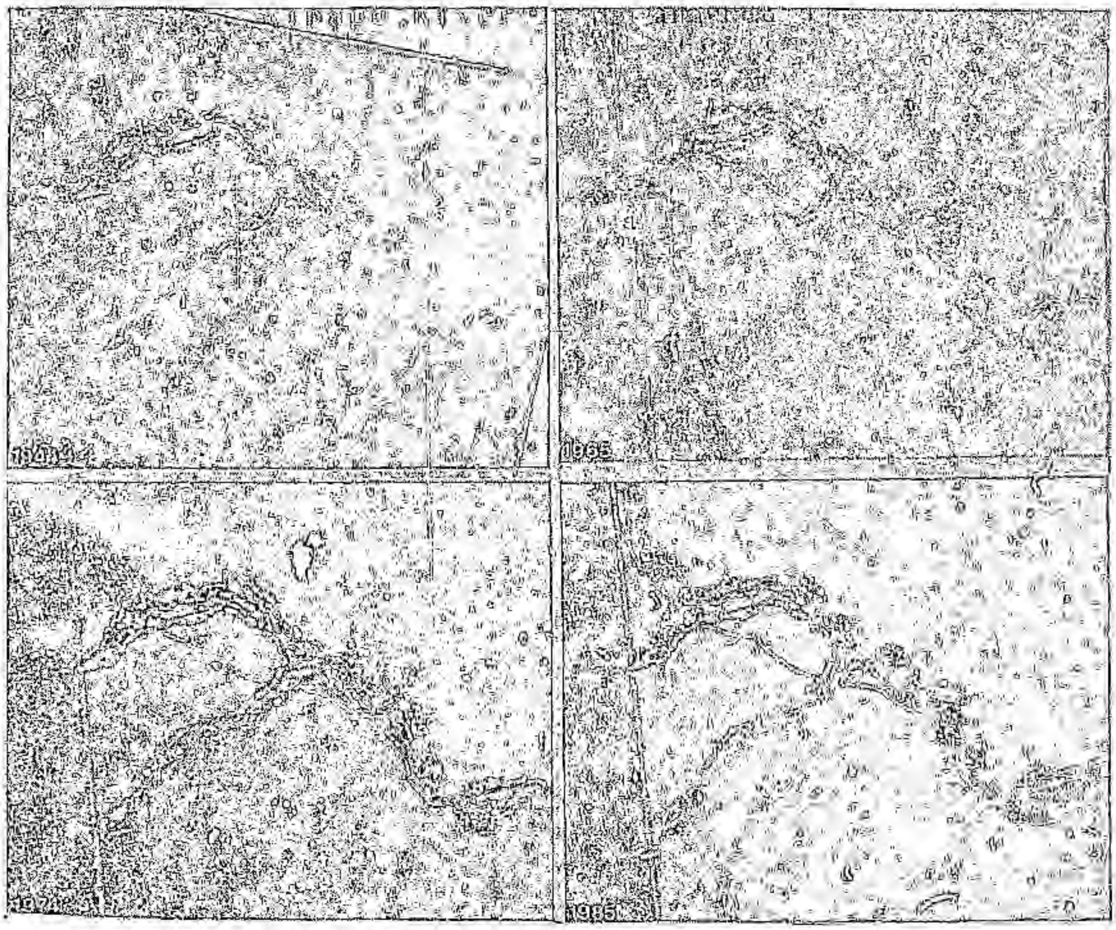


Plate 8. Photo split showing images rendered at the same scale

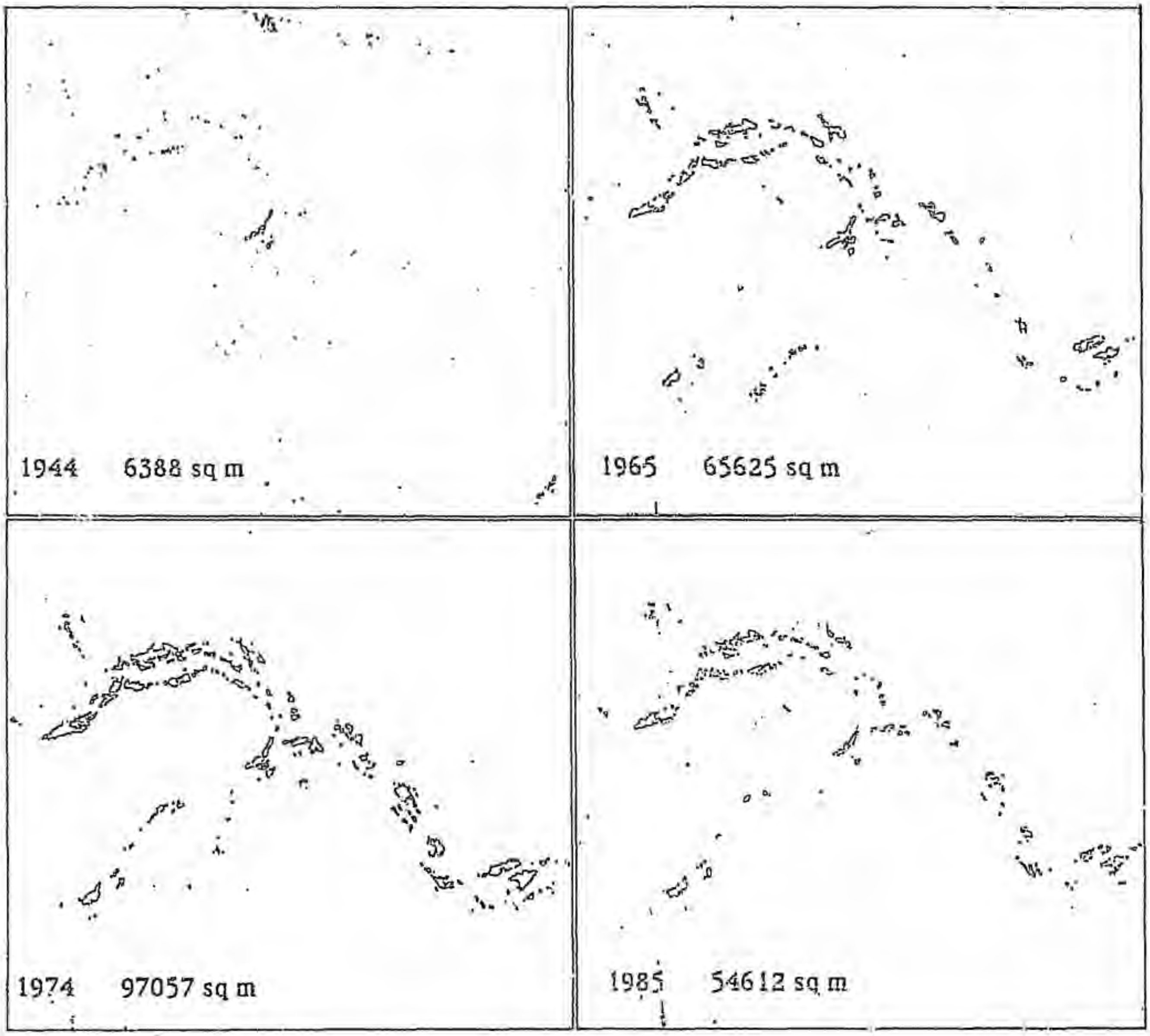


Fig 18. **Vector objects for the four time intervals**
The sum of the areas for each vector object indicates
the total area of bare ground for that period

In order to calculate the amount of soil lost from the eroded areas the mean of 200 measurements of the scarp height were obtained, using a theodolite. The average height was 29 cm over approximately 0.5 kilometres of sodic site upslope margin. The mean dry bulk density of the A horizon soils was 1.67 g cm^{-3} (Table 6).

The increase in area of sodic site involvement during the period 1944 to 1974 was approximately 9 hectares. Assuming a steady rate of increase over this time span an additional 0.3 hectares of sodic site area was added each year.

Table 6. Sodic site scarp height and soil dry bulk density

	scarp height (cm)	dry bulk density (g cm^{-3})
Mean	29.00	1.67
SD	5.92	0.32
VAR	35.06	0.10

The calculated volume of soil lost is 870.0 m^3 per annum and the mass of this soil is 4843.0 kg per year for each additional hectare of sodic site erosion. The rate of surface lowering of the eroded areas over the 30 year period (1944 to 1974) averaged 0.97 mm per year.

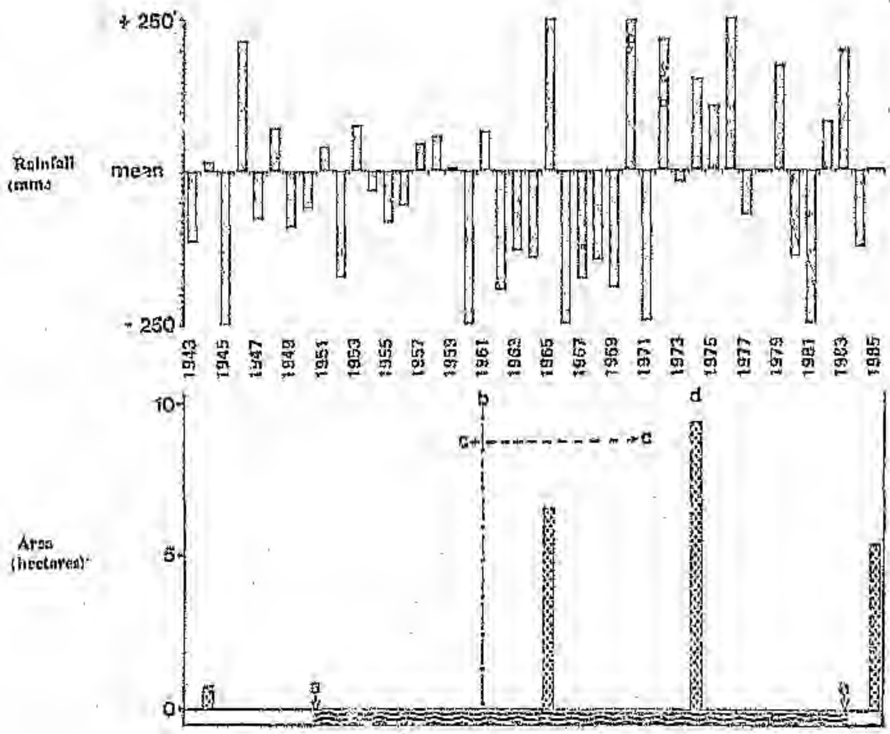
The remote sensing technique gives a conservative estimate of the extent and rate of progress of sodic site involvement and an order of magnitude indication of the total mass of soil lost to this process.

Kirkby (1978) notes that current soil conservation practice argues that the loss of 0.02 to 1.0 mm of soil per year will keep pace with the rate of bedrock weathering and new soil formation. This author considers that the loss of 1.0 mm per annum is too high to maintain the balance between soil erosion and soil formation and requires careful re-examination. Selby's (1990) estimated rates of bedrock weathering which range from near zero to 0.02 mm per year lends support to Kirkby's (1978) conclusions.

Smith and Stamey (1965) regard the maximum permissible rate of soil loss to be 0.5 [illegible] ^{1}, whereas Hudson (1971) notes that where the soils are v[illegible] figure should not exceed 0.2 $kg.m^{-2}.y^{-1}$. This latter figure is [illegible] with the findings of Arnoldus (1977) on soils with a rooting [illegible] 0 cm. The recorded loss of soil from the Ripape sodic [illegible] ler of 0.5 $kg.m^{-2}.y^{-1}$.

The rate of soil loss in tonnes per hectare per annum cannot be calculated accurately for the entire landscape from this single study. It is unrealistic to assume that the progress of sodic site advancement was a steady one and that, depending on prevailing conditions, the rates were probably considerably higher during some periods and less during others.

Without attempting to draw definite conclusions regarding cause and effect relationships, the data in Fig 19 shows the progression of the sodic site erosion, the rainfall over the 40 year time interval and some of the management practices that were implemented during this time. It is the opinion of the author that all of these factors are to a varying extent causally related to sodic site expansion, either acting alone or in concert.



rainfall (1943 to 1985) above and below the long term mean of 61mm
permanent water available
boundary fence
sodic site - relative extent at four time intervals

Fig 19. Sodic site progression, rainfall and management input

a The borehole was sunk in 1951 and continued to supply water into the late 70's after which the supply became erratic and failed completely during 1981/82. The windmill was removed in 1984.

b. The western boundary fence was completed in 1961 and stopped the annual migration of grazers to the gabro sills, to the west, during winter.

c. A prolonged dry cycle prevailed from 1960 to 1971.

d. The area assessed as bare ground reached a maximum of ~9 hectares in 1974.

10.5 Direction of spread of sodic sites

Using the same technique described for determining the area of involvement, the ploygons were defined, at comparable scales, and superimposed in order to determine the direction of spread of the erosion process (Plate 9). The results indicate that the most stable limit to an established sodic site is its upslope margin and that spread is largely due to an increase in length. This indicates that additions to the eroded area occur along the contour and that their upslope limit is determined by the seepline profile morphology occurring at this point.

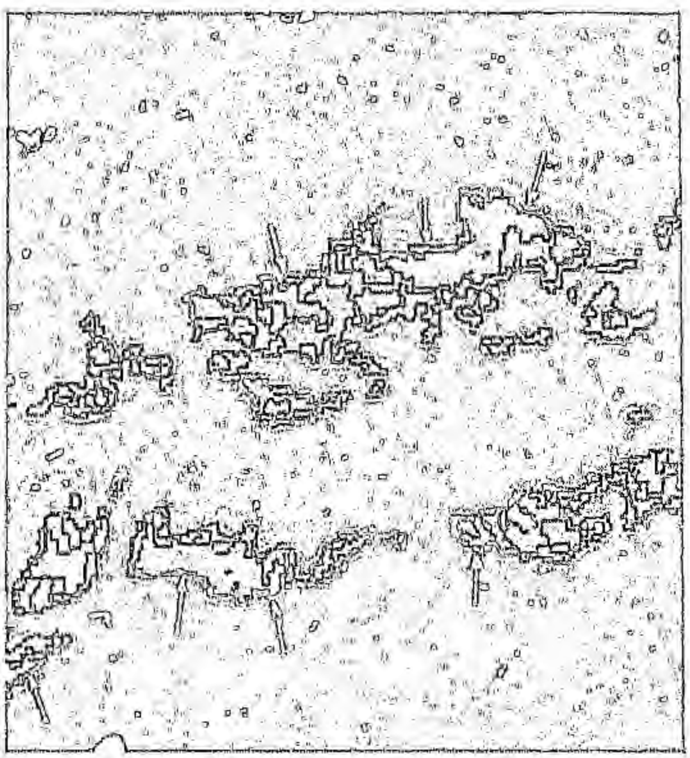


Plate 9. Superimposition of the vector polygons for three time intervals
Although somewhat subjective the overlap of the polygons appears to be more consistent at the upslope edge of the bare areas, suggesting that this is the most stable boundary

10.5 Factors associated with the initiation of sodic site formation

The findings of this study indicate that sodic site erosion is not the natural, geomorphic, land sculpturing process that has been claimed. The magnitude of soil loss is consistent with an accelerated process of erosion that progresses at a rate in excess of the rate of soil formation.

The natural processes that are involved in sodic site development act only to predispose the area to erosion. To initiate the erosion process it would appear that a combination of precipitating factors are required. The most notable predisposing factors to emerge from the study are those associated with hillslope hydrology and a multi faceted complex of factors related to soil erodibility. It has been noted that sodic site erosion responds to the hydrodynamic forces generated naturally by the subsurface flow of water that is concentrated in the upper profile due to the presence of deeper impermeable layers on sloping land.

Soil strength measurements that were carried out in the Ripape River catchment demonstrate a layer of reduced soil strength in a plane immediately above the junction of the permeable A horizon and the impermeable B horizon (Table 7). These recordings were made in exposed profiles in the soils immediately above the sodic site scarp during the wet season and are plotted in Fig 20.

Table 7. Soil shear strength (n = 10)
(Units = kg/cm^2)

Depth in cm	10.0	15.0	25.0	30.0
Mean	0.13	0.15	0.02	0.95
SD	0.07	0.06	0.01	0.02

Table 7 indicates the presence, at 25cm depth, of a zone of reduced soil shear strength which corresponds with the upper surface of the B horizon. It is through this layer that preferential movement of subsurface soil water takes place and, owing to its higher soil water content, can be expected to have higher rates of hydraulic conductivity as compared with the soils below and above. This plane of reduced soil strength is regarded as one of the important factors predisposing these footslope soils to erosion and to the later development of soil piping.

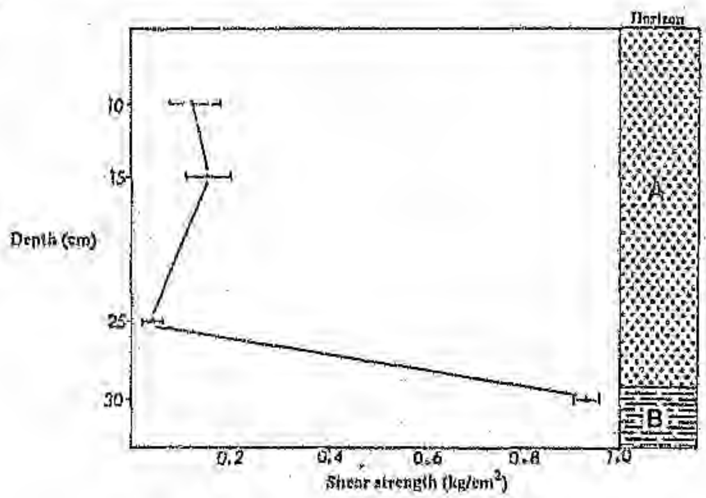


Fig 20. Soil shear strength at four depths

Sodium plays a central role in the predisposition of soils to erosion by adversely affecting the state of flocculation or dispersion of the clay fraction. Dispersed clays contribute nothing to soil aggregate formation and stability. A non-aggregated soil is one which is vulnerable to displacement by moving water.

Rainfall erosivity is often cited as an important factor in soil erosion. In the case of sodic sites the disruptive effects of high energy raindrop impact is secondary to the destabilising effect of alternating periods of saturation and desiccation on the already weak soil aggregates.

The apparent close link between geomorphology and hillslope hydrology has not been examined in detail in this study but the possible relationship between stream order and the occurrence of sodic sites has been mentioned. It appears that the areas most susceptible to sodic site erosion are those associated with well developed footslopes, and accordingly with the lower order streams.

Interposed between an uneroded duplex soil and an eroded sodic site condition is the presence of an intact, protective, grass layer. It is the loss of this grass cover that is seen as the trigger that initiates the erosion process. The apparent attractiveness of the grazing on these base saturated and sodium-dominated soils, [illegible] been noted. The short grass grazers in particular are implicated in initiating the erosion cycle. Where these animals are locally over-abundar [illegible] he high grazing pressures soon result in the deterioration and ev[illegible]ual loss of soil cover.

An important factor leading to local game concentrations is the presence of permanent water in the area. The trampling ,distruction of the grass layer and pulverisation of the soil resulting from the injudicious location of waterpoints becomes very apparent during the long dry periods. It is noteworthy that all the extensive s[illegible]dic patches in the Lowveld, as detected on satellite images, are near to permanent introduced water.

Where fences disrupt the former migratory behaviour of certain species of game and cause a temporary local build-up of animal numbers, the overgrazing and trampling which follows is sufficient, to initiate the erosion process on susceptible soils.

In situations where artificially high hydraulic gradients are created it is possible for the erosion process to be initiated without the prior loss of grass cover. It has been observed that where road design or badly positioned mitre drains discharge large volumes of water onto vulnerable footslope areas the energy of the increased flow is sufficient to dislodge the grass cover and initiate sodic site formation.

The concept that sodic site erosion is the result of sheetwash is not supported in this study. For reasons previously outlined, overland flow, in the Hortonian mode, is not regarded as a common occurrence on these slopes. Significant sheetwash has been observed only where an early burn has resulted in loss of cover and exposed the soils to the effects of the first heavy storms of the rainy season. Generally this is a rare occurrence.

Piping erosion in sodic soils

Discrete pipe openings or incipient piping defects can be seen in the face of the scarp at the upslope boundary of established sodic sites. During the wet season, following a thunderstorm or several days of continuous rain, water can be seen emerging from these points as a milky suspension of silt and clay (Plate 2).

Piping erosion has been treated until recently as an unusual phenomenon. According to Gregory and Walling (1973) it has only recently been accorded a role in hillslope erosion and drainage basin dynamics. Lustig (1970) notes that as an erosion process it is underrated except as a cause of failure in earth dams.

In extensive review of soil piping research Jones, (1981) has devoted a chapter to discussing the conflicting terminology and definitions which have become associated with the process and states that these have become as confusing as the processes they seek to define or describe. Contributing to the confusion, and the divergence of views, is the fact that the phenomenon is widespread and is not confined to a unique set of climatic or edaphic conditions.

Beckedahl et al. (1988) state that confined erosion is a serious environmental problem in southern Africa and that the most widespread form of confined soil erosion is due to soil piping. The process has been the subject of detailed studies in Zimbabwe, Lesotho and the Transkei (Stocking & Elwell 1973, Stocking 1976, Beckedahl et al. 1988 and Rooyani 1985) but no references could be found which deal with this form of erosion in the Eastern Transvaal Lowveld.

In semi-arid and arid climates, where the soils contain appreciable amounts of sodium, there is general agreement that the following factors play a role in soil pipe development.

- seasonally variable water supply and seasonally high hydraulic heads.
- impermeable layers in the soil profile.
- an erodible layer above the impermeable layer.
- reactive clays in the soil.
- the presence of an unrestricted outlet.

Not all reports nominate high sodium levels as an essential requirement, but the majority concede that the SAR value at which clay dispersion will occur depends largely on the electrolyte concentration of the soil solution (Jones 1981). A definition of the soil piping phenomenon that has been offered by Chorley (1978) refers to the formation of natural soil pipes by eluviation or other processes of subsurface erosion.

Several different forms of soil pipes have been recognised by Crouch (1976). This author has identified shallow piping, occurring at the base of the A horizon, where water is arrested by the sharp textural and permeability contrast in the profile (Fig 21), and a deeper process occurring at the base of the B horizon where cracks have penetrated to depth in the impermeable clays (Fig 22). This deeper form of piping is referred to as tunnel-gully erosion since it is believed to be associated with the initiation of gully development.

The third form of piping described by Crouch (1976) occurs in gully walls where its development appears to be secondary to gully development. The first two types have been identified in developing and heavily eroded sodic sites and the third type has been seen to occur where road ramps have been cut into the footslope clays.

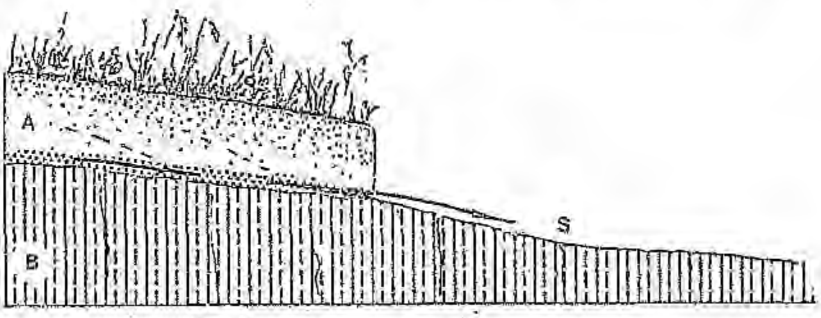


Fig 21. **Shallow soil piping**

Hydraulic conditions imposed by impermeable B horizon (B) and resulting in a concentration of laterally flowing water in a layer of low cohesive strength,at the base of the A horizon (A). Piping is initiated following a reduction in resistance to outflow consequent to sodic site (S) formation

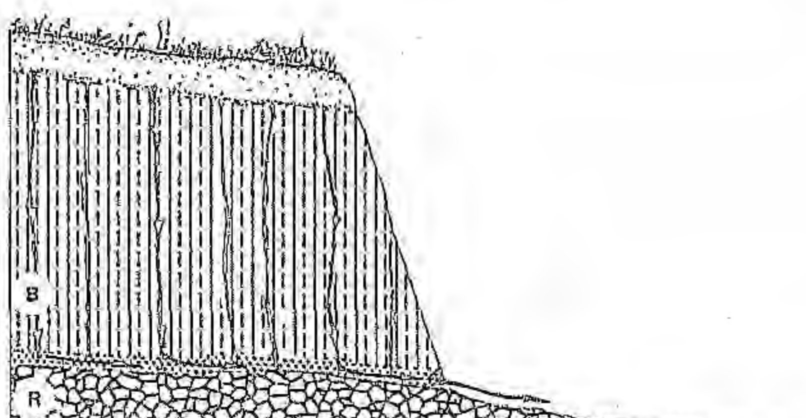


Fig 22. **Deep soil piping**

Vertical water infiltration into inter-columnar voids in th B horizon clays (B). Flow direction changes in the permeable saprolyte above decomposing rock (R) and follows a reduction in resistance to outflow due to gully formation, or the creation of a road cutting.

11.1 The role of hillslope hydrology in soil piping

As previously noted the rate of movement of water through the soil is slow, and flow is assumed to be laminar. Under these conditions the linear relationship between flux and hydraulic gradient, described by Darcy's law holds true (Appendix A 3).

Where flow rates increase, either due to an increase in the driving force or a reduction in the resistance to flow a point is reached beyond which turbulent flow sets in. At this point the hydraulic potential becomes less effective in inducing flow, due to a 'waste' of effective energy which is absorbed by turbulence. The inertial forces of turbulent flow act directly on the walls of the conducting channels displacing soil particles. Application of these principles serves to explain how the process of piping erosion is initiated and how, once started, it becomes self perpetuating.

The unrestricted outlet to flow at the erosion scarp, which follows the loss of topsoil from the sodic site, sets the process in motion. Erosion is assisted by the ease with which dispersed clay particles are dislodged from the walls of the soil capillaries. As the radius of the conducting pores increases the resistance to flow decreases and an increase in flow rate will follow. Eventually turbulent flow will replace laminar flow and the eroding forces will tend to enlarge the conducting pores even more, creating a further increase in flow velocity.

Conditions at the lower end of the midslope are ideal for the piping process to become established. The impermeable B horizon, the seasonal concentration of water and the zone of reduced soil strength in the saturated lower A horizon are all conditions that have been associated elsewhere with the process of shallow soil piping erosion (Jones 1981). The trigger that initiates the sequence is any removal of the A horizon which provides the unrestricted outlet to flow. The motor that drives the system is the piesometric head generated in the slope above.

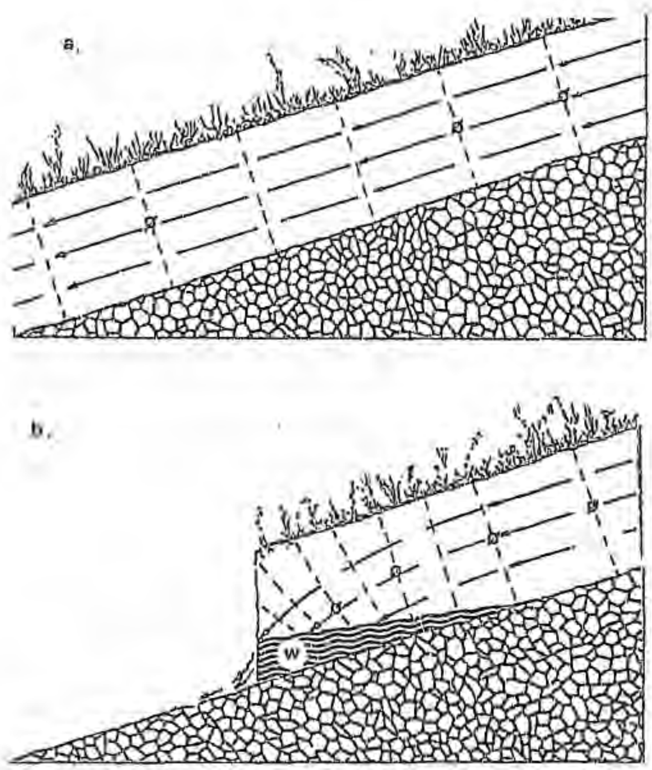


Fig 23. Flow net distortion due to an unrestricted outlet
a) Unsaturated flow perpendicular to isopotentials (ϕ).
b) Saturated wedge (w),corresponds with the vertical extent of outflow. Changing isopotentials (ϕ) result in a distortion of flowlines and concentrate the flow in the lower part of the free face. (modified from Atkinson 1978)

The effect of the creation of an unrestricted outlet was well demonstrated in soil pits excavated at the base of the midslope and highlights a number of features that are pertinent to piping erosion in general. Initially, at the upslope face of the pit water will not emerge until the soil is saturated i.e. until the matric potential equals the atmospheric pressure. This has been demonstrated by Atkinson (1978). Once saturation is reached the hydraulic conductivity increases, but not over the whole face. A saturated 'wedge' develops and extends only as far up the face as is necessary to accommodate the flow from upslope. The reduced resistance to flow at the pit face, which is analogous to the sodic site free face, results in a distortion of the flow net such that water, flowing from upslope, is deflected downwards and contributes to the saturated wedge, as depicted in Fig 23.

Seepage in the soil pits located near the base of the mid slopes resulted in collapse of the lower part of the upslope wall and corresponded with the seepage face of the wedge of saturation as described above. This was particularly well demonstrated on catena 3 where a well defined E horizon, of cohesionless sandy soil was present on the slope, just above the lower duplex zone.

A second effect of a pit (or pipe) is seen when the hill slope hydrograph is viewed in plan. Here a similar distortion of the flow net has been shown to occur (Terzaghi & Peck 1948) and is one of the reasons why soil pipe development is a progressive process. As demonstrated by Atkinson (1978) the net of hydraulic potential is distorted so that down slope drainage, above the pit (or pipe), is captured over an increasingly greater contributing area (Fig 24), and increasingly larger flows, from areas not directly in line in an upslope direction, are received at the outlet point.

It is clear that once initiated a soil pipe can exert a profound affect on the subsurface drainage over wide areas of the slope and result in considerable subsurface erosion which goes unnoticed until late in the process.

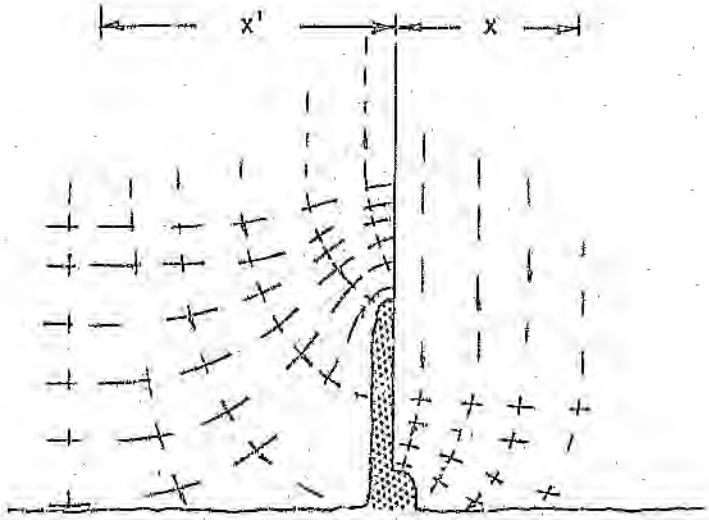


Fig 24. Flow net diagram for a developing soil pipe
Extension of the soil pipe in an upslope direction captures an increasing contributing area, from x to x'.

Pipe flow occurs in conduits considerably larger than the capillary sized soil pores. It is a turbulent regime and is a clear indication of the breakdown of Darcy's law. Atkinson (1978) has shown that the appropriate equation under these circumstances is that which is employed for open channel and pipe flow.

It has been noted (Scholes pers. comm.) that not all points of discharge at the sodic site scarp face are in the form of open pipes and that many appear as seepage points in a weakened soil layer. The author's belief is that these points are initiated as true voids but that, owing to the poor cohesive strength of the overlying superficial layer, collapse of soil into the pipe leads to its apparent blockage.

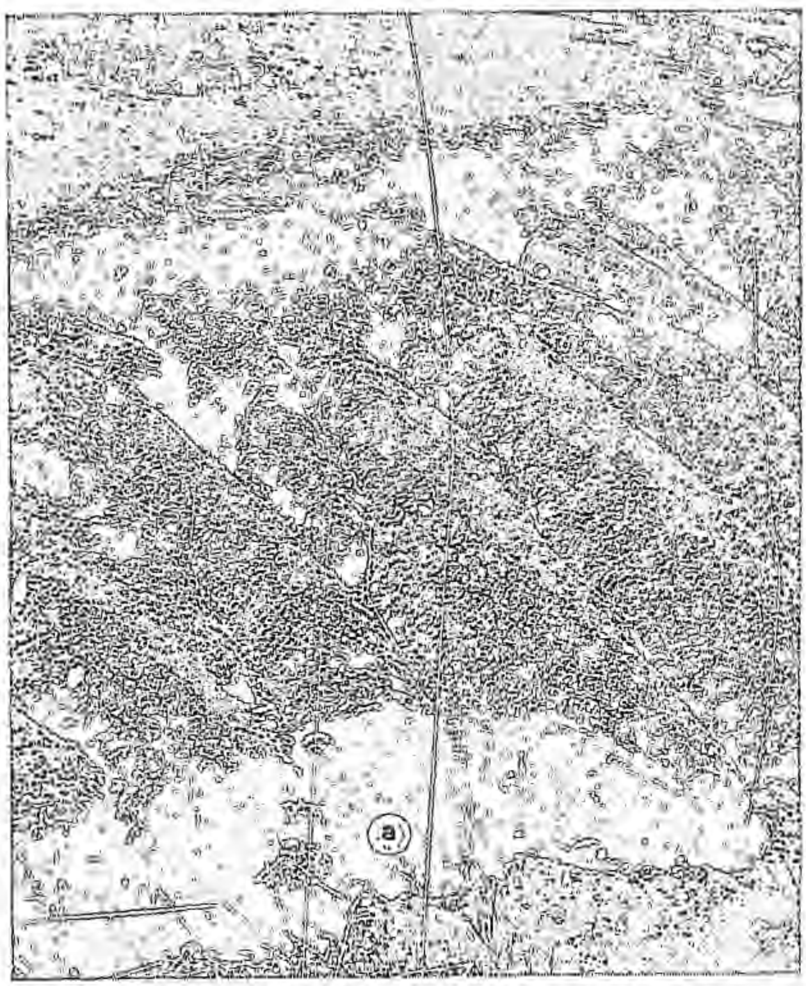


Plate 10. The development of piping erosion at the base of the B horizon (a). This form of erosion is initiated by unrestricted lateral flow at this level in the profile following the construction of an 'un-sealed' road cutting.

The deeper form of piping, referred to as tunnel-gully erosion, is frequently observed where advanced erosion has occurred on sodic sites. These much larger pipes form below the B horizon clays, in the cohesionless saprolite layer above the decomposing rock. In some cases they can be seen to develop within the B horizon where a cemented, impermeable, carbonate layer is present in the profile.

An essential in all piping erosion is the presence of an unrestricted point of outlet at a level in the profile below which a layer of decreased permeability leads to the build up of perched water.

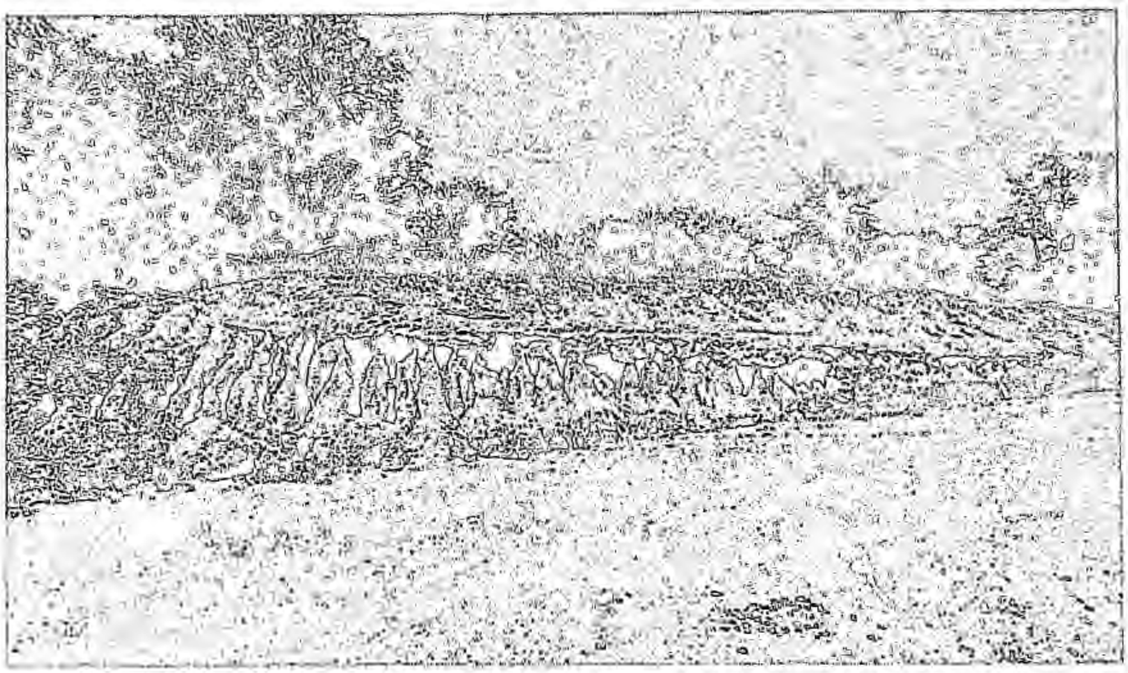


Plate 11. Soil piping in the exposed clays of a road cutting.

The mechanism underlying the development of these deeper pipes appears to depend on the presence of desiccation cracks or inter-columnar voids, which develop in the B horizon clays during the prolonged dry season. A further assumption is that with the onset of the rainy season the initial ingress of water, arriving by way of subsurface flow or by way of shallow pipes, contains a high concentration of electrolytes. These conditions would allow the 'concentrated' water to penetrate deeply without materially affecting clay swelling, at least initially.

Where the outflow of water is unrestricted, as for example at the stream bank or in the walls of deeply incised game tracks or roads a flow pattern is established which draws on water in the inter columnar voids. Increasing flow rates and accompanying turbulent flow results in erosion between the vertical clay columns and prevents them from becoming occluded by the eventual swelling that occurs later in the season.

At the base of the columns, in the saprolite layer, the flow direction changes to horizontal (Fig 22) and within a short space of time large soil pipes are formed at this level. Progressive enlargement of these pipes leads eventually to roof collapse and gully formation. The erosion shown in Plate 3 is of this type and typically runs at right angles to the long axis of the sodic site.

In the Lowveld granitic soils, almost without exception, where road cuttings cut through the footslope clays these banks become the focus of piping erosion. The road cutting provides the necessary condition of an unrestricted outlet (Plate 10 and 11).

These pipes develop rapidly and tunnel back into the hillside, eventually to become gullies (Plate 12). They are fed by subsurface water from the slope above, often reinforced by surface ponding due to the injudicious placement or poor design of mitre drains. The surface accumulation of water, directed off the road surface by the mitre drains, increases the hydraulic head significantly. A similar type of sodic soil piping is to be seen in the walls of earth wall dam spillways. Here as with road cuttings the disruption of the soils continuity provides the necessary outlet to flow and the process is essentially similar. This process is probably the single most important cause of erosion in the Lowveld, and is entirely avoidable.

Plate 12. Deep soil piping progressing to gully formation following roof collapse. The process is exacerbated by poor mitre drain placement and design.

Reclamation of sodic sites

The complete absence of topsoil on established sodic sites is the reason why, once established, they remain as bare unvegetated areas in the landscape. Dye (1977) has noted that the major factor preventing the re-establishment of plant cover is not the soil salinity *per se*, but rather the textural and structural characteristics of the exposed clays. In their deflocculated state the clays effectively prevent the infiltration of rain water and are an unfavourable medium for seedling establishment and root penetration.

The approach to sodic site reclamation is directed at bringing about a reversal of those chemical processes that have resulted in clay dispersion. The salt sieving effect due to water passing through the soil pores behaves in accordance with the principles of cation exchange. Kemper and Maasland (1964) have noted that this effect is greater with monovalent than with divalent cations in the exchange complex owing to the greater extent of the hydrated double layer with monovalent ions. It has been proposed (Blackmore1976) that in this way gypsum opens up pathways for salt removal when calcium replaces sodium in the exchange complex.

Sites that can be expected to respond most favourably are those where the B horizon is still intact and the process of erosion has not progressed to the point of donga and gully erosion. Once this has occurred reclamation is a difficult and costly process and may in fact prove to be virtually impossible.

Under agricultural conditions, successful rehabilitation of sodic soils has been achieved by manipulation of the ionic balance between the clay fraction and the soil solution, in order to bring about clay flocculation. To achieve this it is necessary to replace the sodium in the exchange complex with a divalent ion such as calcium and to elevate the electrolyte concentration in the soil solution. The degree to which flocculation of the soil colloids occurs will be reflected in an improved aggregate structure and an increased permeability and hydraulic conductivity of the soil. The improved penetration of water into these soils allows for the removal of the displaced sodium to depth. Under extremely dry conditions the lack of deep drainage may prove to be a limiting factor in the overall success of the treatment.

Several different chemical ameliorants have been used with success to achieve the desired cation exchange. These have been discussed by Richards (1954) and Dye (1977). The choice of chemical rests on the soil pH and on the presence of reserves of insoluble carbonates in the soil. Reclamation of sodium-affected soils, under a wide range of environmental conditions, has been achieved by using gypsum ($CaSO_4 . 2H_2O$) as the source of calcium ions for exchange. Gypsum appears to be particularly appropriate in the context of sodic site reclamation under rangeland conditions. Shainberg (1985) has shown that the sparing solubility of gypsum has resulted in the maintenance, over extended periods of time, of high hydraulic conductivities in treated soils. This author has shown that the ability of gypsum to replace sodium from the exchange complex is similar to the more soluble salts such as $CaCl_2$, but that the impact of solubility is less important than the superior ability of gypsum to bring about beneficial changes in the electrolyte concentration of the soil solution.

Frenkel and Fey (1989) have investigated the dissolution rates of gypsum from a number of different sources and have shown that the granular composition of Palaborwa gypsum, with its small fraction of fine material, compares favourably with that from other sources. It has been demonstrated that the fine fraction dissolves rapidly and leads to a quick treatment response whilst the slower dissolution of the coarse fraction prolongs the beneficial effect. In addition it has been noted that a portion of the applied gypsum dissolved by the first rains undergoes evaporative re-crystallisation at the surface, and is available for re-solution during second and subsequent rains.

Much of the research into the effects of gypsum as a sodic soil ameliorant has centered around the prevention of soil crusting (Shainberg et al. 1982, Shainberg 1985, Frenkel and Fey 1989, and Frenkel et al. 1989). Where soil crusting is a problem the method of treatment is by surface application. In the case of sodic sites, under low rainfall and leaching conditions, the method of application requires that the gypsum be distributed both at the surface and at depth (Kamphorst 1990). In order to achieve this deep ripping of the soil is required.

12.1 A pilot study using gypsum on a sodic site

To assess the efficacy of gypsum in the treatment of sodic sites, under Lowveld conditions, a pilot study was set up on a private game ranch in the Hoedspruit district. The main objective of the study was to determine the response of the herbaceous component on sodic sites following treatment. An area within an extensive bare, level, sodic site was fenced off and sixteen plots measuring 4 x 4m were marked out in a continuous strip.

Hydraulic conductivity readings were taken in each plot as well as soil samples for analysis before the treatments were applied. Similar samples and hydraulic conductivity readings were repeated twelve months after treatment.

Three treatments, with four replications, were randomly allocated to the plots. The four control plots had to be located systematically owing to the inability of the ripping implement to be raised between each treatment plot. Accordingly the controls were sited at each end of the strip and in the centre (Fig 25).

All treatment plots were ripped to a depth of between 15 and 20cm. Deeper ripping had been envisaged but this was beyond the capability of the available implement. Gypsum was applied , following the ripping procedure, at the rate of 0, 1 and 5 tonnes per hectare. All plots were seeded with *Cynodon dactylon* at the rate of 3.0 kg per hectare.

plot no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
treatment	C	5	1	0	5	0	1	C	C	0	1	5	1	0	5	C
ripped		↪	↪	↪	↪	↪	↪			↪	↪	↪	↪	↪	↪	

C = control
0 = no gypsum
1 = one tonne/ha
5 = five tonnes/ha
↪ = plot ripped to ~ 15 cm depth

Fig 25. Layout of gypsum trial

The yield response of the herbaceous component was assessed, after ten months by weighing oven dried clippings from two randomly placed 25cm² quadrats from each plot. The dominant grass species present were recorded over the experimental site as a whole. Monthly rainfall figures were obtained from a nearby recording point.

12.2 Gypsum trial results

The total rainfall that was recorded during the duration of the trial was 591.2mm. This was concentrated in the first half of the period during which two of the months received 138.9 and 138.5 mm respectively, that recorded during the final four months totalled 39.4 mm. A dramatic visual response in terms of grass growth was observed (Plate 13), and using the recorded dry mass yields as a measure of grass production, the response was shown to be highly significant when compared with the controls ($P < .0003$).

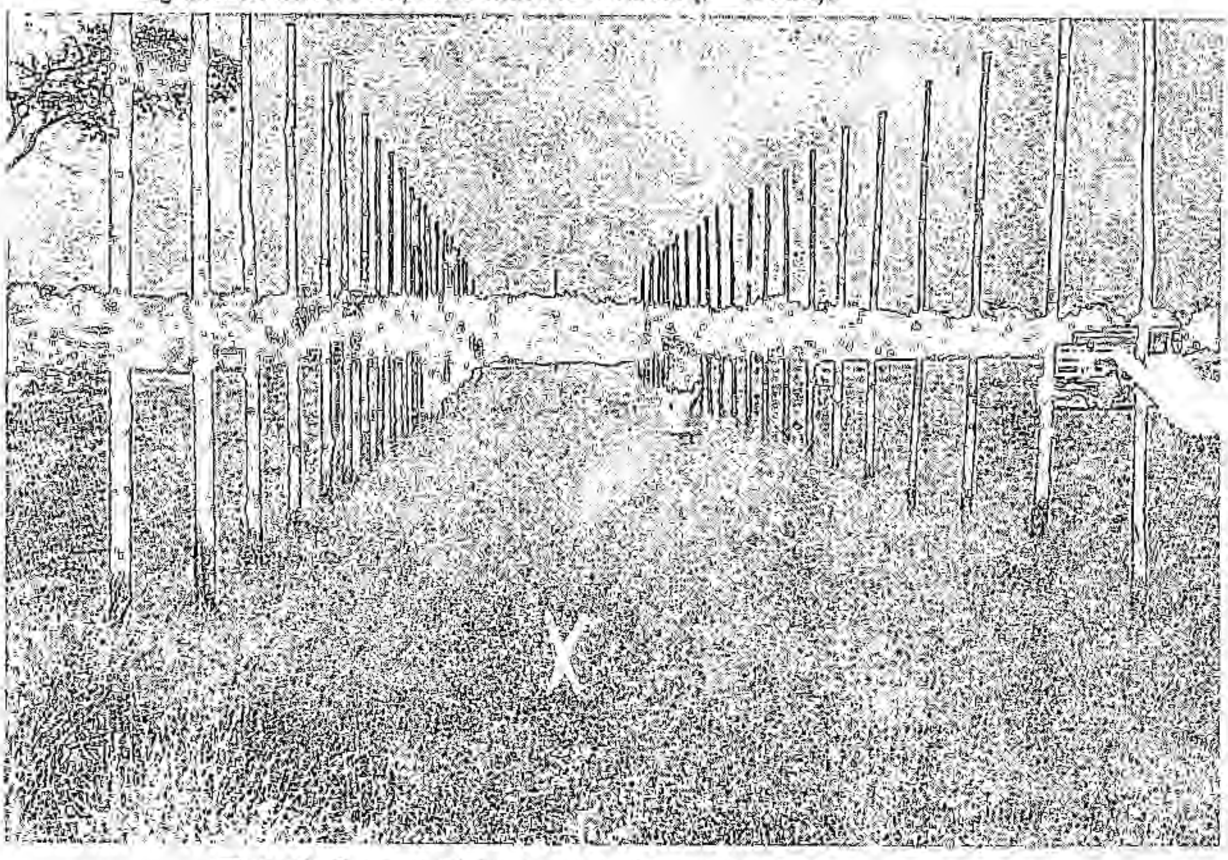


Plate 13. Gypsum trial showing herbaceous response
The photograph was taken eight months after treatment

Table 8. Gypsum trial results
Dry mass yield in kg/ha

Gypsum trial	Dry mass Yield			
Treat	Cont	0 t/ha	1 t/ha	5t/ha
Mean	717.5	964	1627.8	1852.5
SD	95.35	218.91	173.10	61.84
VAR	9091.6	79477.3	29966.6	3825.0
C of V	13.28	29.2	10.58	3.33

ANOVA				
Yield – dry mass	Main effects	df	F ratio	95% Sig level
	treatments	3	13.869	P = 0.0003
	residual	12		

Multiple range test (95% Tukey HSD)		
Contrasts	Treatments	Sig dif
	1 and 3	*
	1 and 4	*
	2 and 4	*

The box plot of treatment versus saturated hydraulic conductivity shows an increasing conductivity over all treatments (Fig 27), and although significantly different from the controls were not significantly different from each other (P < 0.1755).

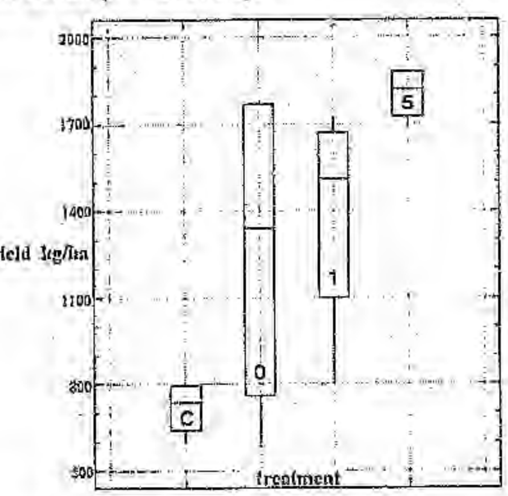


Fig 26. Comparison of treatment yields

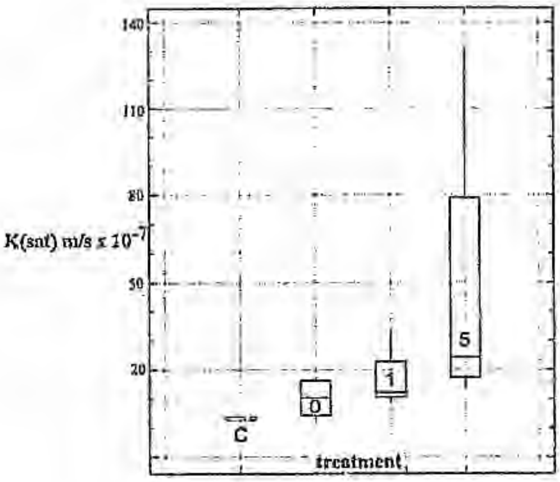


Fig 27. Plot of K(sat) by treatment

An important aspect of sodic site rehabilitation was demonstrated when, owing to a misunderstanding with the land owner, the fence was removed prematurely. This occurred during the height of the dry season when very little alternative grazing was available elsewhere on the farm and within a few days the new grass on the treatment plots was completely destroyed. This shows that if long term success with rehabilitation of the sodic areas is to be successful, measures to prevent overgrazing should be implemented as part of the overall treatment. These measures include paying attention to stocking rates, closing down permanent water supplies in the immediate vicinity the treated sites and brush packing the area for several seasons to allow grass cover to become well established.

The pilot trial showed the rapid response that can be achieved with gypsum but that heavier rates are indicated in order to achieve significant changes in the hydraulic conductivity of the treated soils.

This improved conductivity is regarded as important, not only from the point of view of plant soil water relations but in the longer term removal of excess sodium by leaching when the periodic heavy rains occur.

Since one of the major objectives of gypsum treatment is to bring about an improvement in the permeability of the soil, at the treatment levels applied, the response in this regard was disappointing.

There was no statistically significant improvement in the hydraulic conductivity at the heaviest rate of application of five tonnes per hectare. Assuming that the yield response was related to improved soil permeability this effect could have been solely due to the distruction of clay structure due to the ripping procedure. A plot of yield versus K(sat) does show (Fig 28) that the highest yields were associated with higher rates of saturated hydraulic conductivity but the relationship is too weak for the values to be statistically significant.

For these soils the recorded SAR was 12 and the CEC value was 16 cmol/kg of soil. Based on the method described by Hillel (1980 a) for determining gypsum requirements between 10 and 15 metric tonnes per hectare.would be needed to replace the exchangeable sodium.

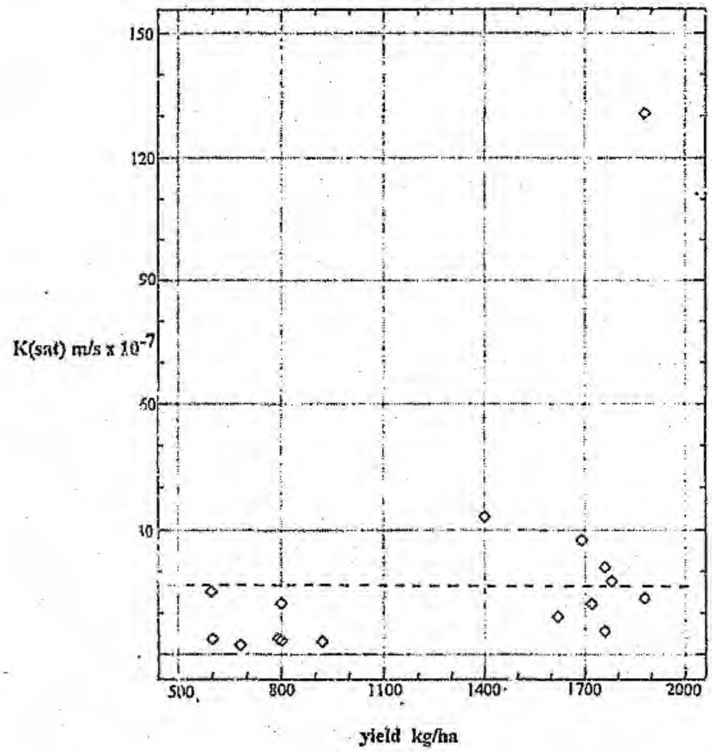


Fig 28. Plot of K(sat) / yield

A conceptual model of the granitic catena

The following model of the granitic catena is proposed as a hypothesis. It differs substantially from previous models of sodic catena formation. It recognises as the major agent for soil differentiation, on these hillslopes, the gravity-induced lateral movement of soil water.

Whilst water movement is regarded here as the primary driving force for pedogenesis there is a strong negative feedback in the model. The changes wrought by moving water are themselves subject to the controls which it initiates. These controls are primarily imposed by decreasing permeabilities and hydraulic conductivities consequent to the selective, water induced, mobilisation, transport and deposition of certain soil constituents.

The variations in lateral subsurface flow that are assumed in the model concur with the findings of Arnett (1976). This author recognises that the major flow variations that occur do so in response to permeability differences and the effects of swelling and shrinking of reactive clays. Slope length and gradient are considered to be of secondary importance.

An important feature of the model is that it assumes that laterally blocked soil water will re-emerge as shallow subsurface flow, or overland flow, by a process of displacement due to the piston action of new rainfall input, in accordance with the hydrological model proposed by Hewlett and Hibbert (1967). In this regard the natural periodicity of the rainfall plays an important role

13.1 Processes

The processes are described below in the order in which they occur from interfluve to footslope.

1. The sandy permeable soils of the crests and hydromorphic areas are the locus of maximum water entry (infiltration) into the hillslope. In this area the rapid influx of water closely parallels the periodic heavy summer rains and results in deep percolation to the weathering front. This promotes the chemical decomposition of the underlying rock and the consequent synthesis of clay and release of ions into the soil solution.

The decomposition of migmatites under semi-arid conditions results in the release of sufficient sodium to cause dispersion of the newly synthesised clay fraction. It is assumed that the periodicity and intensity of the rainfall, coupled with the high rates of flux through these porous soils, leaves little time for diffusion and dispersion processes to procede to equilibrium. The electrolyte concentration of the soil solution, during the rainy season therefor differs little from that of the incoming rain water, and is dilute. Under these conditions (at relatively low sodium ion concentrations and SAR values) significant clay dispersion will occur.

Dispersed clay colloids and sodium ions are the most mobile of the soil constituents and are easily transported downslope in the moving soil solution. Little restraint to this movement is offered by the sandy soils and the process is assumed to achieve its maximum rate in the hydromorphic zone, as witnessed by the leached E horizons which occur in this region.

2. The last significant rainfall event of the wet season generates the final pulse of saturated through-flow which due to lack of follow-up input becomes dissipated at a point on the slope. In response to the declining hydraulic gradient the velocity of flow decreases to the point where the suspended load of the finer soil fractions, particularly the colloids, begins to be deposited within the soil matrix, leading to blockage of the finer soil capillaries, to decreasing hydraulic conductivities and to a further retardation in the rate of flow of the increasingly viscous soil solution.

The model proposes that it is this mechanical rather than chemical process that is responsible for the deposition of the clay that, in time, leads to the formation of the difinitive seepline clay barrier. If this can be shown to be a true representation of the actual process then the concept of sodium ions reaching a threshold concentration and initiating clay dispersion at this particular point on the slope, and therefore determining seepline formation, is no longer valid. Conditions on these slopes tend to suggest that the clays are in a dispersed state shortly after their synthesis and that they do not have to 'wait' for rising sodium levels to become dispersed and deposited in the seepline position. With the succession of wet and dry cycles, the process is repeated year after year. The clay deposit increases in thickness and eventually dominates the entire depth of the subsoil profile.

3. Observations from the study sites (and the Sabi Sand 'exposed' catena) show that the upper surface of the impermeable seepline clay barrier slopes upward (Fig 11 and Plate 4). Thus the last wave of flow of the season is detained in the soil, at this elevated position on the slope (cf. the dam wall of Furves 1975).

This residual body of soil solution, no longer driven by saturated flow from higher on the slope, is in effect macroscopically static. Any movement that occurs from this time, and throughout the dry season, will follow the dictates of unsaturated flow at the capillary level. These conditions are ideal for the processes of diffusion to increasingly concentrate the electrolytes in the soil solution. The loss of water to evapotranspiration, and possibly to deep percolation results in negative pressure potentials, with the water being held at increasing tensions in the adsorbed layers and thin capillary films. From the observations made in the exposed profiles at these sites during the winter, there was no evidence of soil water existing at potentials equal to or above atmospheric pressure, as has frequently been claimed and on which seepline management practices are often based.

4. It has been noted that the clays below the seepline are highly structured and adopt a massive columnar form. During the dry season these clay columns loose water and shrink. The shrinkage pattern is radially inwards so that inter-columnar voids open up and become progressively deeper as the dessication process procedes. These macroscopically large voids are capable of admitting large volumes of water at the onset of the next rainy season but become occluded, in time, as the columns adsorb water and expand radially outwards. In situations where the downward flux of water through the inter-columnar voids is maintained, clay is stripped from the column walls to the extent that swelling of the columns can no longer bring them into apposition with their neighbours. This process occurs when an unrestricted outlet to flow is created at depth and is referred to in the chapter dealing with piping erosion.

5. At the onset of the rainy season the rapid influx of water into the crestal region is repeated and a pulse of new dilute subsurface water begins its journey down the slope. It displaces the old concentrated soil solution from its position above the seepline barrier by piston action (Hewlett and Hibbert 1967). Despite minor degrees of mixing it is reasonable to assume that the initial pulse of displaced water contains a higher concentration of electrolytes due to its prolonged residece time above the seepline. This old water would be the first to penetrate to depth via the patent inter-columnar voids, present in the slope below.

6. The introduction of high salinity water into soils dominated by sodium dispersed clays has long been recognised in irrigation agriculture. The flocculating action and effective restructuring that can be achieved by this practice is discussed by Reeve and Bower (1960). Marshall and Holmes (1979) report that saline waters, with the concentration of sea water, have been used to good effect in the reclammation of certain sodic soils and act directly by increasing clay flocculation and improving the hydraulic conductivity of the soil.

It is suggested that this process prevails in the catenas of the study region and accounts for the observed restructuring that takes place in the mid and lower midslopes. The restructured soils and the improved hydraulic conductivities of this region have further consequences for the catenary sequence in the lower slope positions. These soils, with their improved infiltration characteristics, behave in a similar way to the crestal soils by allowing the rapid ingress of dilute rain water into the profile.

The process of clay deflocculation and accumulation is repeated so that a second seepline morphology is created at or near the base of the midslope. The process is essentially similar to that described for the upper seepline.

It was stated that the major agent for producing changes along the toposequence is the movement of subsurface soil water. In terms of this proposed model it is more accurate to say that not only is water movement important but that the electrolyte concentration of this water is the key to catenal soil differentiation (Fig 29).

The scope of this project did not include soil solution studies and many of the model assumptions are based on theory together with observations in the field. The formal analysis of the soils data indicates that it is not fluctuations in the sodium ion concentration *per se* that determines hydraulic conductivity but rather it is the accumulation of dispersed clay and its subsequent re-flocculation that is important. The proposed model suggests it is the seasonal interruptions to saturated flow, and the consequent impact on soil solution electrolyte concentrations, that determine the catenal soil sequences. The effect of sodium as a clay defloculant is determined by the total electrolyte concentration of the solution. To test the validity of this model a replicated series of soil solution analyses at points along the catena, temporally spaced to coincide with dry and wet seasons will be required.

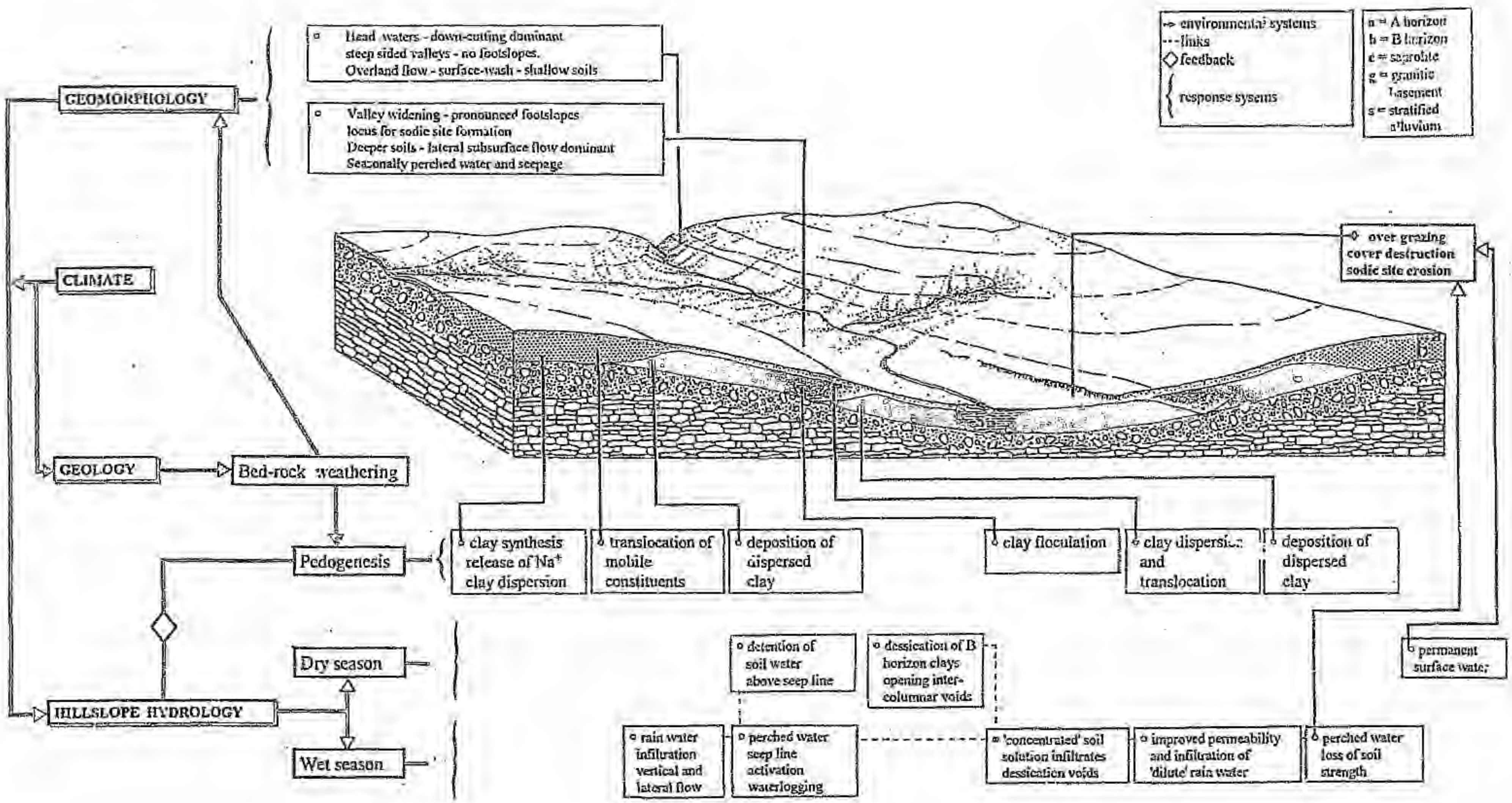


Fig 29. General summary of the development of the granitic catena and of sodic sites

Conclusions

14.1 Study catenas

The processes responsible for soil development were similar over the range of sites studied. Owing to the close proximity of the four study slopes the topography, climatic factors and the weathering environment are similar and differences in soil texture and chemistry can be ascribed to subtle variations in the underlying geology.

Features that were characteristic of the study area soils include the generally high levels of magnesium and low calcium content. The soil pH tended to be more acidic than is expected for sodic soils in general.

Expansive 2:1 clays dominate the catenas in all but those areas where the soil microclimate, due to seasonally elevated soil water content, might be expected to result in a more aggressive weathering milieu. In these positions 1:1 type clays were identified.

The lack of a statistically significant relationship between the sodium ion concentration and the saturated hydraulic conductivity, and the significant relationship between the percentage clay and K(sat) suggests that it is the clay content of these soils that is determining permeability differences down the catena. The low SAR values and the abundance of dispersed clays in the profiles indicate that the dispersion process is primarily determined by changes in the electrolyte composition and concentration of the soil solution, rather than the sodium ion concentration. SAR values (sensu stricto) can be misleading.

The dominant hydrological processes, on these slopes, proceed below the surface. Very little evidence of surface water movement could be detected.

14.2 Sodic sites

The most significant factor related to the formation of sodic sites (Objective 1) that has emerged from this study is that eroded sodic sites develop as a consequence of subsurface water movement in duplex soils. These soils are located in the footslopes of granitic catenas. Loss of the A horizon follows the destruction of the protective grass cover. Erosion occurs at the boundary between the A and B horizon, not at the surface of the A horizon.

The investigations into the rate and direction of spread of sodic sites (Objective 2) indicate that the process progresses at a rate which is inconsistent with the philosophy that exposed sodic sites represent natural erosion. The direction of spread of these areas is controlled by profile morphology and progresses as far up the slope as the duplex horizons will allow. Their lateral spread, however, appears to be unconstrained.

The management of eroded sodic sites (Objective 3) should take account of the subsurface nature of the dominant processes. These are natural hillslope processes, beyond the influence of management, and by themselves do not initiate the erosion. Preemptive management of susceptible areas rests on husbanding the protective, and seemingly fragile, grass cover by avoiding local overabundance of short-grass grazers.

The rehabilitation of eroded sodic areas can be achieved by improving the permeability of the exposed clays. Attempts at controlling the flow of surface water over these sites achieves little and is wasteful of time effort and financial resources. It has been demonstrated that the application of gypsum is effective in achieving improved permeability and a rapid response in terms of grass cover.

The rehabilitation of sodic site erosion should be viewed as a 'complete package', the individual components of which are ineffectual if applied alone. Treatment of the soil to improve its permeability will not achieve satisfactory results alone. The newly established grass cover requires protection from grazers not only initially, but in the longer term as well. Those factors responsible for cover destruction should receive as much attention as the soil treatment.

With regard to the destructive effects of the deeper form of piping erosion, the design and construction of road cuttings, mitre drains and earth-wall dam spillways should, where these are sited in susceptible areas, receive the respect demanded by sodium affected, clay dominated soils.

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Models referred to in the text

1. Gouy-Chapman theory :

This theory is one of several that have been used to explain ion exchange in terms of the charged colliod surface and the diffuse double layer. It describes the ionic distribution within the double layer.
The negative charges are assumed to be constant and to be distributed uniformly over the particle surface (an approximation). The strength of the surface charge is proportional to the charge density.
The Gouy-Chapman equation

$$z = 1/ev.\sqrt{\varepsilon kT/8\pi n_0}$$

provides a means by which the thickness of the double layer can be estimated. z is the characteristic length of the double layer, defined as the distance from the clay surface to where the ionic concentration is very nearly that of the external solution ; e is the elementary charge on the electron ; ε is the dielectric constant ; k is the Boltsman constant ; v is the valency of the ions in solution ; n_0 is the concentration of the ions in the bulk solution and T is the temperature (°K). As the equation indicates the double layer is *compressed* as the valency of the ions in solution is *increased*. Monovalent ions replacing divalent ones will therefore result in a 50% reduction in the thickness of the double layer. Since z is inversely proportional to the square root of n, a tenfold increase in the solutions concentration will reduce the double layer to approximately 1/3 of its original thickness.

2. Gapon equation

An equation that is widely used to describe ion exchange , particularly in the case of sodium-calcium exchange over low to moderate range of ESP values, is expressed in the following form;

$$A_e/B_e = c([A_s]^{1/a}/[B_s]^{1/b})$$

in which A and B are cations with valencies of a and b,respectively and the subscript e indicates the concentration of the ambient solution. The coefficient c depends on the nature of the charged surface and the cation adsorbed. This equation indicates that the adsorbtion mechanism favours cations of *higher valency* and that this preference *increases* as the solution becomes more *dilute.*

For the important case of sodium-calcium exchange, the selectivity coefficient (Shainberg 1973), is given by;

$$C_{Ca\text{-}Na} = n_0 ([Ca_e]\,[Na_s]^2/[Na_e]^2[Ca_s])$$

in which the subscript e denotes the ionic equivalent fractions of Ca and Na in the exchange complex, the subscript s denotes the mole fractions of these ions in the solution phase, and n_0 is the total molar concentration of the solution. In a mixed sodium-calcium system most of the calcium ions are adsorbed tightly in the Stern layer, whereas the sodium ions are relegated to the diffuse region of the double layer (Hillel1980).

3.The Darcy equation

The equation which is traditionally used to describe the flux of water through porous media is similar to the other linear transport equations of classical physics (eg. Ohms law). It is referred to as the Darcy equation and can be expressed simply as;

$$q = K.\Delta H/\Delta X$$

where ΔH represents the hydraulic head drop over unit distance ΔX ,which is termed the hydraulic gradient and is the driving force promoting flow; q is the specific discharge rate or simply the flux and K is a proportionality factor designated the hydraulic conductivity.

This relationship indicates that the flux is directly proportional to the hydraulic head drop and inversely proportional to the resistance. Darcys law is valid for low flow rates where the flow pattern is laminar, but fails at higher rates of flow once turbulence sets in.

4. Mean grain size and standard deviation

The mean grain size is calculated on the assumption that the particle size distribution in soil is approximately log normal (Campbell 1985). Any combination of textural classes can be represented by a log mean particle diameter (d_g) and a geometric standard deviation (σ_g).

dg and σg are calculated as follows
$dg = \exp a$
$\sigma g = \exp b$
where $a = \Sigma\, m_i \ln d_i$
and $b = [\, m_i (\ln d_i)^2 - a^2\,]^{1/2}$

m_i is the mass fraction of textural class i
d_i is the arithmetic mean diameter of class i
the summation is taken over the textural classes sand, fine sand, silt and clay
where $d_{sand} = 0.5$mm, $d_{fine\ sand} = 0.2$mm, $d_{silt} = 0.02$mm
and $d_{clay} = 0.002$mm.

Laboratory analysis of soil samples

1. The data are grouped according to :

a) Catenal position	- Crest zone (Table B i) - Hydromorphic zone (Table B ii) - Midslope zone (Table B iii) - Footslope zone (Table B iv)
b) Soil profile depth	- A horizon - B1 horizon - B2 horizon
c) Catena	- I, II, III and IV

2. Particle size analysis :

   Oven dried samples (~ 100 g) were sieved to separate the following fractions:- Gravel (>2 mm) and coarse sand (2 to 0,5 mm). The remainder of each sample was dispersed by treatment with sodium -hexametaphosphate and the fine sand (0.2 to 0.02 mm), silt (0.02 to 0.002 mm) and clay (<0.002 mm) were determined by the hydrometer method. Medium sand (0.5 to 0.2 mm)was determined by difference. Gravel (as % sample weight) is expressed separately. The remaining fractions are expressed as percentages by weight of the samples minus the gravel fraction. Organic carbon was not determined.

3. Cation concentrations were determined in a 1 M ammonium acetate extract using an atomic absorption spectrometer, and expressed as cmol(+)/kg.

4. pH was determined in a 1:2.5 soil /water suspension and in a 1:2.5 soil / 1 mol/litre KCl solution suspension

5. Hydraulic conductivity of the A and upper B horizon were determined using the apparatus shown in Plate 5 and reported as K(sat)) = m/s x 10^{-7}.

Table B i.

SOILS DATA –(RIPAPE CATENAS)

CREST ZONE A Horizon (0 to 15 cm)

catena	dens	gravl	Crse sand	Med sand	Fine sand	silt	clay	pH KCl	pH H_2O	Ca	Mg	Na	K	SAR	CEC	$K_{(sat)}$
Units	kg/m^3	gm	%							cmol(+)/kg					cmol(+)/kg	$m/s \times 10^{-7}$
I	1.71	9.84	32.98	36.16	5.78	4.98	23.91	4.78	5.18	1.71	[illegible]	[illegible]	0.16	2.07	15.3	2.26
II	1.58	10.79	30.07	33.13	8.95	3.97	22.86	4.74	5.23	2.33	3.80	1.96	[illegible]	0.84	13.13	1.07
III	1.64	3.81	39.82	39.24	1.00	2.99	16.95	4.36	5.28	0.16	3.62	[illegible]	0.16	2.35	7.18	4.03
IV	1.68	6.68	38.25	37.77	4.00	3.00	16.98	4.60	5.33	0.56	[illegible]	1.08	[illegible]	0.65	6.68	3.27
MEAN	1.65	7.78	35.28	35.08	4.99	3.98	20.67	4.62	5.41	1.11	6.59	2.35	[illegible]	1.48	10.57	2.66
SD	0.05	2.25	3.93	3.62	2.91	0.99	3.86	0.16	0.23	[illegible]	[illegible]	1.27	[illegible]	0.74	3.75	1.11
VAR	0.00	7.75	15.43	13.12	8.45	0.98	14.90	0.03	0.05	0.76	5.08	1.58	[illegible]	0.55	13.98	1.23

B1 Horizon (15 to 35 cm)

catena	dens	gravl	Crse sand	Med sand	Fine sand	silt	clay	pH KCl	pH H_2O	Ca	Mg	Na	K	SAR	CEC	$K_{(sat)}$
I	1.6	13.16	32.15	33.47	4.91	5.82	23.58	4.51	7.66	1.57	18.7	0.56	[illegible]	0.20	17.14	2.64
II	1.68	14.18	35.24	29.77	6.00	6.00	23.00	5.35	6.70	1.02	8.36	0.69	2.77	0.31	16.41	9.06
III	1.64	4.03	36.75	38.25	3.00	5.00	17.00	4.60	6.02	[illegible]	3.11	1.05	[illegible]	0.65	7.74	5.08
IV	1.59	8.33	38.83	39.24	1.99	4.98	14.96	6.10	6.15	1.04	9.63	0.07	[illegible]	0.03	14.52	2.51
MEAN	1.63	10.1	35.74	35.18	3.98	5.47	19.65	5.14	6.63	0.98	9.57	0.66	2.83	0.30	13.95	4.73
SD	0.04	4.01	2.24	3.81	1.57	0.45	3.73	0.64	0.65	0.51	3.42	0.39	[illegible]	0.23	3.71	2.73
VAR	0.00	16.11	5.93	14.53	2.47	0.23	15.94	0.41	0.42	0.26	11.7	0.15	[illegible]	0.05	13.78	7.47

B2 Horizon (down to 75 cm)

catena	dens	gravl	Crse sand	Med sand	Fine sand	silt	clay	pH KCl	pH H_2O	Ca	Mg	Na	K	SAR	CEC	$K_{(sat)}$
I	1.68	14.33	43.59	24.09	23.2	5.02	26.19	4.62	7.88	1.04	0.59	0.09	0.13	1.02	2.34	——
II	1.77	51.70	52.83	12.05	4.68	5.85	24.58	4.33	6.39	1.01	0.16	0.07	[illegible]	0.62	2.19	——
III	1.61	6.28	36.15	38.32	1.96	3.93	19.64	4.07	5.65	0.05	0.12	0.62	0.52	2.13	0.80	——
IV	1.59	11.80	36.45	38.91	3.91	4.93	15.77	4.60	6.40	0.05	0.16	0.47	0.01	1.45	0.69	——
MEAN	1.66	21.03	42.26	28.32	8.95	4.49	[illegible]	4.40	6.58	2.04	0.16	0.60	[illegible]	0.30	1.32	——
SD	0.07	17.95	5.80	11.2	9.44	0.60	4.21	0.22	0.81	0.50	0.06	[illegible]	0.20	0.56	0.97	——
VAR	0.00	322.1	46.23	123.7	89.06	0.36	16.34	0.05	0.66	[illegible]	0.30	0.19	0.05	0.31	0.93	——

Table B ii.

SOILS DATA --(RIPAPE CATENAS)

HYDROMORPHIC ZONE

catena	dens	gravl	Crse sand	Med sand	Fine sand	silt	clay	pH KCl	pH H_2O	Ca	Mg	Na	K	SAR	CEC	K(sat)
Units	kg/m^3	gm	%							cmol(+)/kg					cmol(+)/kg	$m/s \times 10^{-7}$
			A Horizon (0 to 15 cm)													
I	1.53	7.59	30.22	34.84	5.99	4.99	23.96	4.78	5.12	1.01	13.91	4.62	0.15	1.76	18.49	1.34
II	1.67	8.30	37.64	34.17	4.97	4.97	18.88	4.80	5.25	2.58	7.56	0.21	0.00	0.15	10.24	3.77
III	1.65	2.96	35.92	38014	5.99	4.99	16.96	5.15	5.25	0.13	1.60	0.31	0.09	0.30	2.51	3.02
IV	1.64	4.68	40.22	36.80	4.00	2.00	16.95	4.65	5.34	0.16	4.06	0.02	0.01	0.01	4.25	4.40
MEAN	1.62	5.94	36.00	35.99	4.74	4.24	19.20	4.85	5.24	0.96	6.51	1.32	0.06	0.55	8.87	4.13
SD	0.05	2.12	3.67	1.57	0.83	1.29	2.86	0.19	0.08	0.90	4.11	1.19	0.06	0.70	6.25	1.14
VAR	0.00	4.47	13.48	2.48	0.68	1.67	8.17	0.03	0.01	0.08	16.88	3.64	0.00	0.49	39.05	1.13
			B1 Horizon (15 to 40 cm)													
I	1.64	14.41	25.34	34.86	8.96	9.95	20.90	5.00	6.96	1.55	12.91	0.30	[illegible]07	0.11	14.83	1.91
II	1.51	7.52	38.79	36.27	3.99	4.99	15.96	5.32	6.75	1.18	7.65	0.97	0.83	0.46	17.63	5.38
III	1.66	2.84	37.43	39.58	2.00	2.00	17.99	5.06	5.95	0.[illegible]	5.78	1.10	0.02	0.73	5.72	4.28
IV	1.57	6.87	41.70	36.32	2.00	4.00	15.99	4.58	5.85	0.33	1.90	0.02	1.48	0.02	3.74	3.52
MEAN	1.59	7.91	34.47	36.76	4.39	5.23	17.71	4.99	6.38	0.97	6.56	0.60	0.60	0.33	10.46	3.62
SD	0.06	4.16	5.34	1.73	2.68	2.93	2.02	0.27	0.48	0.45	4.20	0.15	0.60	0.28	5.88	1.55
VAR	0.00	17.30	28.55	3.00	7.16	8.57	4.07	0.0[illegible]	[illegible].23	0.02	17.62	0.20	0.36	0.[illegible]8	34.5[illegible]	2.40
			B2 Horizon (down to 75 cm)													
[illegible]	1.63	38.82	33.24	18.40	6.17	5.54	39.05	4.[illegible]	[illegible].90	7.59	0.15	6.32	1.07	3.20	15.53	-------
[illegible]	1.69	24.59	43.33	29.14	2.95	4.92	19.67	4.31	6.82	0.02	0.18	3.55	1.33	1.94	2.04	-------
III	1.64	5.98	35.24	37.79	2.00	7.99	16.98	5.42	5.50	0.69	0.12	0.08	0.06	0.08	0.92	-------
IV	1.69	10.34	38.48	32.60	2.99	3.99	16.94	4.35	6.14	0.04	0.10	0.73	0.05	0.77	0.49	-------
MEAN	1.66	19.93	37.07	30.73	3.53	5.51	23.16	4.23	6.34	[illegible].08	0.74	3.77	0.64	1.50	4.75	-------
SD	0.03	12.89	4.43	7.93	1.58	1.50	1.50	0.31	0.57	[illegible].19	0.14	2.59	0.57	1.19	6.25	-------
VAR	0..00	166.3	19.63	62.90	2.46	2.24	2.24	0.02	0.32	20.02	0.02	6.70	0.32	1.41	39.09	-------

Table B iii.

SOILS DATA –(RIPAPE CATENAS)

MIDSLOPE ZONE A Horizon (0 to 15 cm)

catena	dens	gravl	Crse sand	Med sand	Fine sand	silt	clay	pH KCl	pH H_2O	Ca	Mg	Na	K	SAR	CEC	K(sat)
Units	kg/m^3	gm	%							cmol(+)/kg					cmol(+)/kg	$m/s \times 10^{-7}$
I	1.68	5.19	32.75	[illegible]	4.99	5.99	24.94	4.80	5.22	0.57	10.93	16.22	0.03	6.02	30.75	0.52
II	1.47	4.98	42.95	30.12	3.99	5.98	16.94	4.45	5.18	0.07	5.19	0.25	0.09	0.14	5.58	0.92
III	1.63	4.91	38.37	31.71	4.99	4.99	19.55	4.53	5.36	2.44	4.86	9.33	0.02	5.73	14.64	0.54
IV	1.63	3.48	34.46	[illegible]	4.99	5.08	19.94	4.58	5.73	0.36	5.17	2.30	0.10	1.98	8.93	1.80
MEAN	1.60	4.64	37.0	[illegible]	4.74	5.74	20.44	4.59	5.28	1.11	6.72	7.27	0.06	3.47	14.97	0.95
SD	0.08	0.68	4.05	1.16	0.43	0.43	2.87	0.13	0.08	1.43	2.46	6.12	0.03	2.50	9.67	0.52
VAR	0.01	0.46	16.4	2.58	0.19	0.19	8.25	0.02	0.01	2.05	5.60	37.42	0.00	6.23	93.44	0.27
B1 Horizon (10 to 40 cm)																
I	1.90	6.51	24.54	20.65	2.99	5.98	45.84	5.90	8.08	[illegible]	35.36	43.33	[illegible]	11.42	83.23	0.01
II	1.71	7.35	42.24	33.59	4.00	5.00	14.99	4.56	6.14	0.06	4.90	0.13	[illegible]	0.12	4.75	0.58
III	1.88	0.45	22.04	15.98	3.00	4.00	54.98	4.82	6.63	3.25	23.30	29.35	7.96	8.19	63.56	0.01
IV	1.74	3.90	45.15	14.17	3.99	3.99	46.87	4.25	5.50	2.59	20.27	15.97	1.66	4.73	40.45	0.02
MEAN	1.18	4.46	33.74	21.11	3.50	4.74	40.67	4.89	6.59	2.34	13.20	22.26	5.21	6.11	48.0	0.18
SD	0.08	2.63	10.08	7.59	0.50	0.82	15.25	0.62	0.95	1.36	8.17	16.00	4.50	4.19	29.2	0.23
VAR	0.01	6.90	101.6	57.61	0.25	0.68	232.4	0.38	0.90	1.84	66.75	250.6	20.5	17.58	852.7	0.06
B2 Horizon (down to 70 cm)																
I	1.74	1.82	39.02	28.84	3.97	2.98	31.79	5.78	7.19	[illegible]	0.36	25.80	0.04	23.63	40.43	———
II	1.77	35.20	33.39	23.26	5.89	6.67	29.89	4.70	6.75	0.02	0.36	8.20	0.56	17.68	9.19	———
III	1.97	1.58	24.00	[illegible]	4.95	3.96	43.57	5.52	7.00	[illegible]	0.38	39.32	0.96	25.04	45.21	———
IV	1.84	30.76	47.10	24.11	3.97	5.96	18.86	4.43	5.63	0.05	0.15	0.19	0.29	1.55	0.98	———
MEAN	1.83	17.34	[illegible]	24.93	4.72	4.97	30.78	5.08	6.64	7.20	0.32	20.59	0.46	16.97	24.13	———
SD	0.09	15.72	8.24	2.28	0.83	1.58	8.41	0.59	0.61	9.14	0.32	[illegible]	[illegible]	9.32	19.03	———
VAR	0.01	247.1	67.89	5.19	[illegible]	2.49	70.73	0.34	0.37	[illegible]	0.01	[illegible]	[illegible]	86.94	362.0	———

Table B iv.

SOILS DATA --(RIPAPE CATENAS)

FOOTSLOPE ZONE A Horizon (0 to 25 cm)

catena	dens	gravl	Crse sand	Med sand	Fine sand	silt	clay	pH KCl	pH H_2O	Ca	Mg	Na	K	SAR	CEC	K(sat)
Units	kg/m^3	gm	%							cmol(+)/kg					cmol(+)/kg	$m/s \times 10^{-7}$
I	1.66	4.56	34.07	29.97	8.99	4.00	22.87	4.76	5.28	2.22	14.53	7.42	0.47	2.58	24.37	2.22
II	1.73	7.94	36.01	30.08	7.98	5.89	19.94	4.93	5.32	1.33	10.29	11.92	0.05	4.59	22.59	0.31
III	1.67	3.52	41.08	32.09	2.00	5.00	18.98	4.15	5.37	0.04	5.62	4.75	0.01	2.83	10.44	1.07
IV	1.62	10.1	40.74	32.27	2.90	6.00	19.60	4.68	5.39	0.04	3.32	0.22	0.11	0.16	4.19	2.50
MEAN	1.67	6.54	32.98	31.49	5.24	5.25	20.2	4.63	5.34	0.09	8.31	5.15	0.09	2.54	15.40	1.68
SD	0.04	2.76	3.02	1.17	3.26	0.82	1.64	0.29	0.04	0.95	4.16	[illegible]	0.06	1.58	8.40	0.84
VAR	0.00	7.63	9.10	1.37	10.64	0.68	2.68	0.08	0.00	0.86	[illegible]	[illegible]	0.00	2.49	70.61	0.17
			B1 Horizon (down to 35 cm)													
I	1.62	6.81	26.10	20.00	4.99	2.00	46.92	4.53	7.97	[illegible]	26.5	11.82	[illegible]	3.02	53.58	1.04
II	1.80	0.96	22.0[illegible]	12.02	3.00	3.00	59.92	5.15	6.07	3.07	25.60	[illegible]	3.42	8.90	66.77	0.03
III	1.85	5.23	47.92	32.09	2.00	3.00	15.00	4.45	6.47	0.01	2.16	0.62	2.11	0.60	4.90	2.00
IV	1.96	17.82	41.29	31.74	3.00	4.99	18.98	4.30	4.92	0.04	1.29	0.07	1.83	0.09	3.23	1.40
MEAN	1.81	7.71	34.34	23.96	3.25	3.25	35.20	4.61	6.36	1.97	13.90	11.64	4.62	3.15	33.37	1.12
SD	0.12	6.21	10.62	8.45	1.09	1.09	18.64	0.32	1.09	1.95	12.48	12.76	3.79	3.50	29.45	0.72
VAR	0.02	38.62	112.7	71.22	1.18	1.18	345.9	0.10	1.19	3.81	[illegible]	189.4	[illegible]	12.24	867.5	0.51
			B2 Horizon (down to 70 cm)													
I	1.67	9.11	39.14	23.12	2.98	1.99	41.77	5.86	7.28	1.58	0.38	7.64	1.80	[illegible]	14.40	———
II	1.67	6.07	37.92	29.60	5.89	8.84	16.69	5.09	7.30	0.62	0.49	[illegible]	0.01	[illegible]	18.23	———
III	1.85	6.23	47.92	32.09	2.00	5.00	15.00	4.45	6.47	0.01	2.16	0.62	2.11	[illegible]	4.90	———
IV	decomposing rock below 35 cm															———
MEAN	1.73	6.80	38.66	15.48	3.62	4.16	24.49	5.13	7.02	1.74	0.19	8.86	1.31	10.94	12.51	———
SD	0.08	1.67	7.28	3.9[illegible]	1.65	7.02	12.24	0.58	0.39	2.61	0.89	6.89	0.93	11.74	5.60	———
VAR	0.01	2.78	52.96	15.48	2.73	9.12	149.8	0.33	0.15	[illegible]	0.79	[illegible]	0.86	137.9	31.4	———