SUBSURFACE SOIL EROSION PHENOMENA IN TRANSKEI AND SOUTHERN KWAZULU - NATAL, SOUTH AFRICA.

HEINRICH REINHARD BECKEDAHL

Submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy in the Department of Geography, Faculty of Science, University of Natal, Pietermaritzburg.

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DECLARATION

I wish to certify that the work reported in this thesis is my own original and unaided work except where specific acknowledgement is made of other sources.

This thesis has not been submitted for a degree in any other university.

HEINRICH REINHARD BECKEDAHL

ABSTRACT

Subsurface erosion forms have been regarded as a unique exception to the more common surficial erosion forms such as rills and gullies, and have therefore been viewed as being of little consequence for the total annual soil loss within any given region. A total of 148 subsurface erosion systems occurring at 66 sites in southern KwaZulu-Natal and Transkei were analysed morphologically to determine the significance of subsurface erosion within this region, and to assess the extent to which the observed phenomena may be explained by current theories.

Based on morphological criteria related to the dimensions of the subsurface erosion phenomena, it has been shown that there are five distinct subsurface erosion systems namely scree slope systems; gully sidewall systems; anthropogenically induced systems; systems associated with dispersive soils, and seepage systems. It was further found that, under certain circumstances, the sediment lost through surficial erosion can be increased a *further* 77% by subsurface erosion and that subsurface erosion is spatially restricted to particular slope units which are defined on the basis of the dominant geomorphic processes.

Although soil chemistry, in particular dispersion related to the Exchangeable Sodium Percentage and the Sodium Absorption Ratio, is an important factor in facilitating subsurface erosion, other factors are also important as scree slope systems for example occur in soils which are completely non-dispersive. It has been possible to demonstrate that there is a statistically significant correspondence between the spatial orientation of subsurface erosion systems (in particular soil pipes); the orientation of inter-ped surfaces and the orientation of bedrock joints. This correspondence has enabled the explanation of how the well documented phenomenon of structurally controlled drainage basins may develop.

SAR - NB in facilitating subsurface erosion

PREFACE

Much has been written on the subject of soil erosion, particularly during the past two decades where environmental concerns and considerations centred around the ideals of sustainable land use practices have again been emphasized. The main body of literature, however, is directed towards agriculture and agricultural practice and it is therefore not surprising that considerations of subsurface erosion processes have received relatively little consideration, although a significant body of literature has developed on the subject during the past decade. Many contradictions however still remain in the literature. These discrepancies revolve primarily around the following three related questions:

- ❑ How significant is subsurface erosion when viewed against the total annual soil loss of a region?
- ❑ What are the causative processes triggering subsurface erosion and, once initiated, how does it progress and at what rate? and
- ❑ Although there is general consensus that soil chemistry and dispersion are important aspects of subsurface erosion, much conflicting information exists as to whether dispersion is a pre-condition for the phenomena to develop, or whether it merely accelerates the process.

The present research was undertaken with the aim of addressing these three issues. To this end the research is placed within the historical context of the study of soil erosion in general and the associated geographical paradigms in Chapter 1, and within the context of the relevant work on subsurface processes in Chapter 2. As subsurface erosion processes are inextricably linked to the regional climate, topography, soil and vegetation characteristics, the physiography of southern KwaZulu-Natal and Transkei are discussed briefly in Chapter 3 before presenting an analysis of the morphological characteristics of the 148 subsurface features. By making reference to representative field sites, the five types of subsurface system are discussed in detail in Chapter 5. More detailed analysis of trends follows in Chapter 6, in which the relationship between structure and subsurface erosion, as well as the significance of subsurface erosion forms, are discussed. Conclusions drawn from the study are presented in Chapter 7.

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TABLE OF CONTENTS:

* * * * *

LIST OF FIGURES:

Chapter 1

Chapter 2

Chapter 3

Chapter 4

Chapter 5

Chapter 6

* * * * *

LIST OF TABLES:

Chapter 3

Chapter 4

Chapter 5

Chapter 6

Chapter 7

* * * * *

Chapter 1

1. Introduction

1.1 The Historical Context of Erosion Studies

Soil erosion is a familiar topic for much of the world's population, from subsistence farmers in developing countries to the executives of multi-million rand agricultural cooperative companies, and from scientists and economists to politicians. An analysis of the writings of early geographers and philosophers shows that they were aware of many of the consequences associated with the washing away of the soil, as is evident from the writings of *inter alia* Homer in *ca.* the ninth Century BC. and Plato (427 - 347 BC), while Strabo (64 BC to ca. AD 25) discussed aspects of soil erosion in Greece and Turkey.

Little evidence of a concern for soil erosion is available for the period of the Middle Ages, although an increasing body of evidence now suggests that parts of Europe experienced at least occasional, if not sustained, near-catastrophically high rates of soil loss during the period from *ca.* AD 1100 to *ca.* AD 1300 (Bork, 1988). The later works of Hutton (1788) and Playfair (1819), according to Tinkler (1985), also show insight into the importance of soil erosion phenomena; these works probably reflect the beginnings of a resurgent interest in the topic. Continued interest and research into the topic did not, however, occur and the warnings of Marsh (1864), Dokuchaev (1877) and Bennett and Chapline (1928) that soil loss was occurring at unsustainably high rates went unheeded.

It has been argued *inter alia* by Mannion (1992) that the contemporary research interest in soil erosion phenomena stems directly from the American '*Dust Bowl*' experience of the early 1930s and subsequent similar environmental disasters, as is illustrated by the prompt publication of the original works of Ayres (1936), Sharpe (1938), Bennett (1939) and Jacks and Whyte (1939), with more than 20 topical scientific texts having appeared during the last three decades. The '*Science of erosion studies*' (Zachar, 1982) now spans the disciplines of Geography, Geology, Soil Science, Economics, Hydrology and Agronomy, each of which have made notable contributions to the present body of knowledge on the subject.

1.2 Soil Erosion and Sustainable Land Use Practice

The continued interest in soil erosion and in related research is explained by considerations of the ever-growing need for sustained resource utilization, particularly with reference to the demand for increased agricultural production in relation to the growing world population. Allied to this interest is the demand for sustained supplies of fresh water for both domestic and agricultural needs, notwithstanding the recognition that the earth's resources pertaining to crop production are finite and, for all practical purposes, non-renewable. Further compounding the problem is the realisation that much of the arable land has marginal agricultural potential as it is either inaccessible, too steep, too shallow or has too much or too little water for sustained crop production. The emphasis on agricultural sustainability is further emphasized by the widespread problem of soil degradation and the rapid deterioration of soil quality (Lal and Pierce, 1991). These considerations are illustrated by the projection that, whereas in 1986 the global *per capita* arable land area was approximately 0.3 ha, this is projected to decline to 0.23 ha by the year 2000 and to 0.15 ha by 2050 (Brown *et al.*, 1990); the equivalent values for South Africa are a *per capita* reduction from 5.5 ha in 1970 to some 1.5 ha by the year 2000 (Beckedahl *et al.*, 1988).

It is however essential that, when considering generalised values such as these, one does not lose sight of the complexity of soil erosion phenomena and the associated impact of salinization, nutrient and soil moisture depletion and the concomitant changes in soil structure. The consequences of such secondary environmental impact is to enhance, further, the losses in soil fertility due to erosion, and hence to reinforce the increased susceptibility of the soil to erosion, thereby reinforcing the downspiralling of crop yield and economic productivity of the affected region as outlined by Dudal (1981), Millington (1992) and Blaikie *et al.* (1994).

1.3 Soil Erosion, Geographical Paradigms and Environmentalism

The debate on environmental issues during the first half of this century has tended to follow the pattern of 'Western Intellectualism' (Mannion and Bowlby, 1990), modelled after Strabo (64 BC to 25 AD) in his *Geographica*, and the teachings of Bacon (1561 - 1626); Varenius (1622 - 1650) and Kant (1724 - 1804), in which society is viewed as being independent of the environment, and where nature is subjugated to considerations of human benefit. Since the late 1960s by contrast there is a growing understanding of the interactions between human society and the physical environment - a realisation that human behaviour affects the physical environment and the consequences which such impacts in turn have on society. Mannion and Bowlby, (1990) argue that this awareness is reflected in the shift of Human Geography away from *Environmental Determinism* and the advent of *Human Possibilism*; *ie.* that, although the environment presents limits to human activity, it also offers a range of possibilities within these constraints.

This approach has developed into an analysis of the manner in which social and economic relationships play themselves out spatially, thereby affecting societies at different localities. The concepts about ***locality*** have refocussed attention on the distinctive characteristics of particular places in so far as these resulted from the impact of successive phases of economic organization (Massey, 1984). In essence this approach says little about the relationships between people and the environment; it could however be used to provide an elementary framework for analysing the impacts of social, economic and environmental changes on the social and environmental relationships in a particular place.

A further development from the above locality-based approach is that of the *Political Economy*, which suggests that to understand people-environment interrelationships it is necessary to examine how the social relationships of power relate to the control and use of environmental resources - an approach exemplified by the work of Blaikie (1985). The conceptual developments which have occurred within Geography and the Environmental Movement as a whole in the past decade or so are of particular relevance when viewed against the postulate of Harvey (1973) that conventions and methodology are, at least in part, dependent on locality. This postulate is all the more significant in that, not only is there a tendency to make direct transference of observations from Europe and North America and to apply them to Africa at large and southern Africa in particular, but environmental responses and dependancies are likely to differ with locality too (Bowlby and Lowe, 1990).

Such notion of locality is directly relevant within the context of soil erosion: in developing regions, soil erosion and the associated environmental consequences may well result in starvation and even death of a significant percentage of the local population. By contrast, the worst consequence in highly developed nations is often slight increases in national unemployment figures. Such considerations then are clearly of direct consequence to South Africa - a developing country in which more than 60% of the population are still directly or indirectly reliant upon adequate agricultural yields (Fuggle and Rabie, 1992). The succinct reviews of Garland (1990) and Clarke (1991) illustrate that the dichotomy alluded to above is not only pertinent when comparing developed and developing nations, but exists between different regions within South Africa itself.

Cooke and Doornkamp (1990) cite four common elements in the response of communities threatened by soil depletion, namely:

- scientific efforts to understand and predict the nature of the erosion dynamics;
- investigations into methods designed to alleviate the problems;
- application of research results to land management practices; and (though less common)
- reviews of the effectiveness of existing conservation measures.

The authors argue that soil erosion continues to pose a serious problem despite the intense research which has been undertaken, and which has provided the now very extensive literature on the subject, because soil erosion is not merely a scientific problem but is closely allied to social, economic and political realities (see *inter alia* the work of Stocking (1981, 1995), Blaikie (1985), Darkoh (1987), Blaikie and Brookfield (1987) and Cooke and Doornkamp (1990)). Much of soil erosion research is concerned with measuring and comparing variables that aid or resist particulate detachment in order to predict the nature and extent of the erosion problem. Ultimately the aim is to facilitate a reduction of soil loss and sediment yields with associated implications for potable water supplies. Such considerations have prompted El-Swaify (1981) to lobby for 'Conservation-Effective Planning' in order to safeguard *both* the available soil and water resources, although his efforts have not met with much success to date.

The term 'soil erosion', according to Zachar (1982) was first introduced in the 1930's and was apparently derived from Penck's (1894) use of the term *erosion* to describe the wearing away of solid material under fluvial processes. It now refers to the destruction of soil by the action of water and wind. Difficulties arise in that the Central European school of earth scientists in particular view the term as referring to the destruction of soil by the action of water and wind *under anthropogenic influence* (Schultze, 1952, Richter, 1965 and Bork, 1983; 1988). They argue that, under the natural deciduous forest biome prevailing in Central Europe during the Holocene, no natural soil loss occurred. One consequence of such a narrow definition is that the interpretation given to certain erosion forms differs according to region. In the present context, this is of particular relevance to subsurface erosion, as some researchers argue that "subsurface erosion belongs among the normal soil forming processes and should therefore not be classified as erosion" (Holý, 1980; p27). It is, however, postulatd in this study that such an interpretation is not necessarily valid, irrespective of the definition of erosion used.

The Central European terminology accords with the definition of *accelerated erosion* given by Bennett (1939), a concept which has been reinterpreted as referring to an essentially natural process occurring at an increased rate under conditions of ecological disequilibrium (Holý, 1980; Shakesby and Whitlow, 1991). Although the theoretical distinction between *geologically normal soil erosion* and *accelerated soil erosion* is useful, it lacks practical applicability as process rates fluctuate greatly in both space and time. It would appear that a more suitable interpretation of the concept of *accelerated soil erosion* is that implicit in the review presented by Boardman *et al.* (1990), namely, soil erosion which is perceived to be detrimental to a community or region. Such definition circumvents the difficulty of quantifying 'normal' erosion rates, and will be adhered to for the purposes of the work presented here. It is not the intention to pursue the issue of nomenclature in depth as a full discussion of the issue has been given by Zachar (1982).

There is general consensus in the literature that the critical limit with respect to the intensity of soil erosion is given by the balance between the rate of soil loss and that of soil formation. The difficulty arises as to how to quantify these rates and how representative the values are which are determined from, for example, field plots (Schmidt, 1987). Further complications relate to the recognition that erosion severity is both spatially and temporally dependent, and is clearly affected by magnitude-fequency dependence and by climatic change (Thornes, 1976; Morgan, 1986).

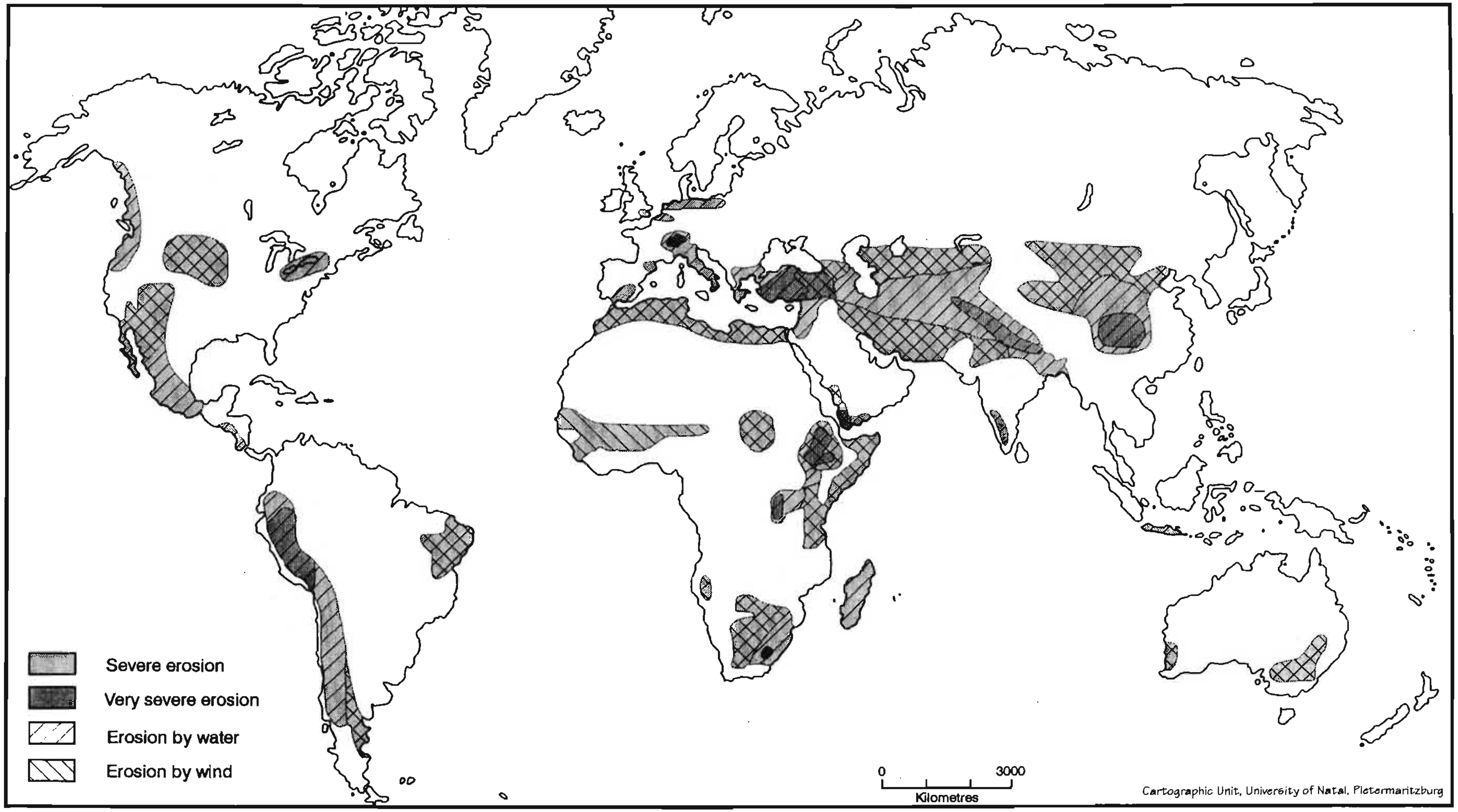


Figure 1.1: World map showing areas of accelerated erosion (after Millington, 1990)

The situation is compounded still further by the recognition that data provided by the field scientist is only one part of a greater social, political and economic reality, and that the answers obtained from geomorphological investigation are as much a product of ideology as they are dependant on the process(es) being studied (Stocking, 1995). This reality should however not be interpreted to mean that the efforts of science are futile - quite the opposite. It is precisely by providing quality data on erosion processes and erosion rates *within* prevailing socio-political and economic settings that applied scientists can have a significant influence on policy formulation and, through the judicious use of descriptive and predictive models, extend geomorphological information beyond their empirical confines.

According to Cooke and Doornkamp (1990) the great majority of soil erosion studies are field-based, empirical studies derived from the detailed monitoring of runoff plots. The annual total soil loss due to anthropogenic influence (Figure 1.1) has been estimated to exceed a global value of 20 billion tons of soil (Kovda, 1977), although some estimates would place it as high as 50 billion tons (Dudal, 1981). By comparison, Adler (1981) has estimated the soil loss for South Africa to be between 360 million and 450 million tons per annum; an average of some 3.5 tons per hectare per annum (t/ha/a) (Verster *et al.*, 1994). These values may be contrasted with a geological erosion rate of 2 t/ha/a or approximately 180 million tons per year (Murgatroyd, 1979). Other than as an indicator of the severity of the erosion problem, estimates such as those cited above are of limited value, particularly in the context of the large range of present day erosion rates reported in the literature. For South Africa alone these vary from as low as 0.5t/ha/a to in excess of 110t/ha/a (Rooseboom, 1978, Stocking, 1984 and Boucher and Weaver, 1991). What is however of significance is that these values suggest that the mean rate of soil loss for South Africa exceeds that of soil formation by a factor of ten. When cognisance is taken of the fact that the rate of soil loss is not uniform across the country but is strongly skewed towards the eastern half, the seriousness of the problem becomes apparent. This realisation has led Verster *et al.*, (1994) to suggest that, erosion may well be the greatest environmental problem facing South Africa.

Most texts on erosion either implicitly of explicitly suggest a progression of surface erosion forms from sheetwash to intense gullying (Figure 1.2) while little attention is paid to sub-surface erosion phenomena. Although these macro pores and conduits within the soil profile, more commonly referred to as soil pipes or tunnel erosion, have been recognised for a long time (see for example the work of Von Richthoffen, 1886), they have been considered primarily within the general context of slope evolution and hillslope hydrology (eg. Schultze, 1952; Yair, 1973; Kirkby, 1978).

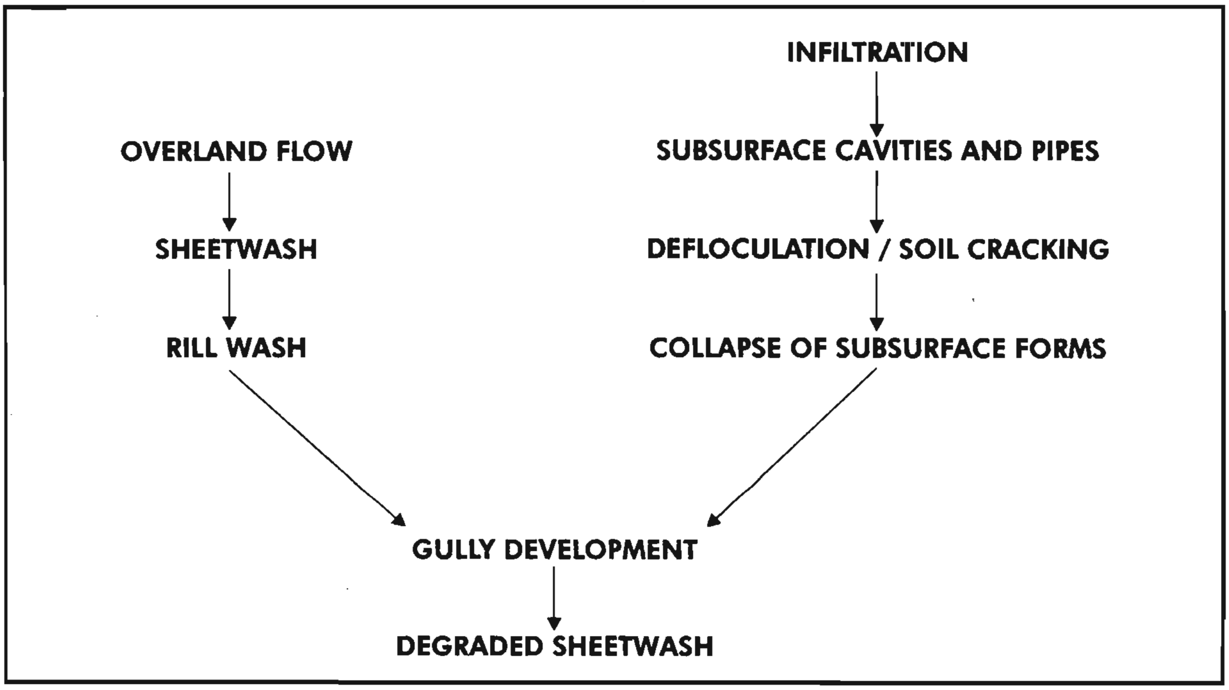


Figure 1.2: The progression of erosion forms, after Beckedahl (1993a).

Subsurface erosion forms, therefore, have been considered to be exceptional phenomena and have not been afforded much attention prior to the publication of two benchmark texts by Gilman and Newson (1980) and Jones (1981) respectively. A significant body of literature has developed on the subject over the past decade, but many questions remain unanswered. Not least is the question of their significance within the overall context of soil erosion phenomena. The degree of uncertainty concerning these features is exemplified by the apparent contradiction in the literature: Bryan and Yair (1982) note in the introduction to their text that subsurface flow can provide the dominant denudational process and that, under high intensity rainfall, pipeflow is comparable in response time and erosional capacity to surface flow. However, under low intensity rainfall, pipeflow may be both more frequent and more prolonged than surface runoff - by contrast, Morgan (1986) argues that subsurface flow can only account for between 15 % and 23 % of the total sediment transport on 8 - 14° slopes.

The aim of the present research is to analyse the role of subsurface erosion phenomena within the southern African context, specifically within KwaZulu-Natal and Transkei, in the light of the above debate.

Specifically, the research aims to:

- determine the extent and frequency of occurrence of subsurface erosion phenomena within the Southern African context as a whole;
- analyse representative case studies to address the question of genesis and geomorphic significance of the subsurface erosion forms;
- show that, under certain circumstances, subsurface erosion may also be due to anthropogenic influence and be detrimental to the surrounding region, hence potentially being a further manifestation of accelerated erosion,
- discuss the socio-economic significance of sub-surface erosion both in terms of water and sediment supply, and
- assess the role of subsurface erosion within the landscape as a whole, giving

particular consideration to questions relating to conservation and the management of areas prone to this type of erosion.

In order to achieve the above aims, the current knowledge pertaining to subsurface erosion phenomena will first be reviewed and then the physiographic setting of eastern southern Africa will be discussed as a precursor to the detailed consideration of representative case studies of sub-surface erosion in the KwaZulu-Natal and Transkei regions.

Chapter 2

2. Subsurface Erosion: A Review

2.1 Terminology

Subsurface erosion refers to the removal of material by water below the soil surface. It therefore encompasses the broad spectrum of processes from chemical removal by solution to the physical removal in suspension. More conventionally within the context of soil erosion the processes of solution are generally ignored, leading Jennings (1971) to define subsurface erosion as the formation of underground conduits by the particulate removal of clay and silt fractions due to water percolating through clastic material.

Jones (1981) has commented on the wide range of terms used to describe subsurface erosion phenomena in the literature, namely pseudokarst (Kosac,1952; Kunsky,1957; Parker, 1963; Feininger,1969; Jennings,1971; Khobzi,1972; Sweeting,1972; Löffler,1974), suffosion (Tricart, 1965), percoline drainage; subsurface gullying (Baillie,1975) and piping or tunnel erosion (Bennett,1939; Downes,1946; Terzaghi and Peck, 1948; Jones, 1981; Nordström,1988). Notwithstanding several, largely unsuccessful, attempts to distinguish between piping and tunnelling (see Rosewell, 1970, and Sherard *et al.,* 1972), these two terms are used interchangeably in the literature from the late 1970s onwards, and now represent the dominant terminology with reference to subsurface erosion processes; these terms will therefore be used in the remainder of this work.

The widespread occurrence of piping across a broad spectrum of climatic zones from arid and semi-arid regions (eg. Bryan and Yair, 1982; Howard, 1994) to humid, rain forest areas (eg. Bremer, 1973; Fränzle, 1976) and from monsoon climates (eg. Starkel, 1972) to periglacial environments (Czeppe, 1965; Smith, 1968) is seen by Jones (1990) to be indicative of both the variety of processes capable of initiating piping, and of the wide occurrence of the minimum criteria for pipe initiation being met.

2.2 Subsurface Erosion and the Hydrological Cycle

Precipitation falling on to a slope either flows over the surface as slopewash, is retained in surface depressions as surface detention storage, or infiltrates through the slope surficial material. Except for the rare occurrence of impermeable rock slopes, some proportion of the precipitation reaching the slope surface infiltrates and either percolates down to the groundwater table to supplement groundwater storage, or will move laterally semi-parallel to the slope surface through the unconsolidated surficial material as throughflow or interflow, as illustrated in Figure 2.2.1. The distinction between throughflow and interflow is generally made on the basis of where the sub-parallel flow occurs - the term throughflow is normally applied to the lateral movement of water within the soil and regolith, whereas interflow usually refers to water moving within the aeration zone above the groundwater table, frequently at the soil-bedrock interface.

The proportion of precipitation entering the slope as opposed to contributing to the slope wash is a function of the nature and intensity of the precipitation, as also of the properties of the surface material of the slope, most commonly the soil mantle. It is these properties which determine the infiltration capacity of soil *ie.* the rate at which it can absorb water. The more important among these properties are texture, organic matter content, biotic activity, antecedent moisture content and the presence and relative abundance of smectitic clays (Jones, 1981; Summerfield, 1991).

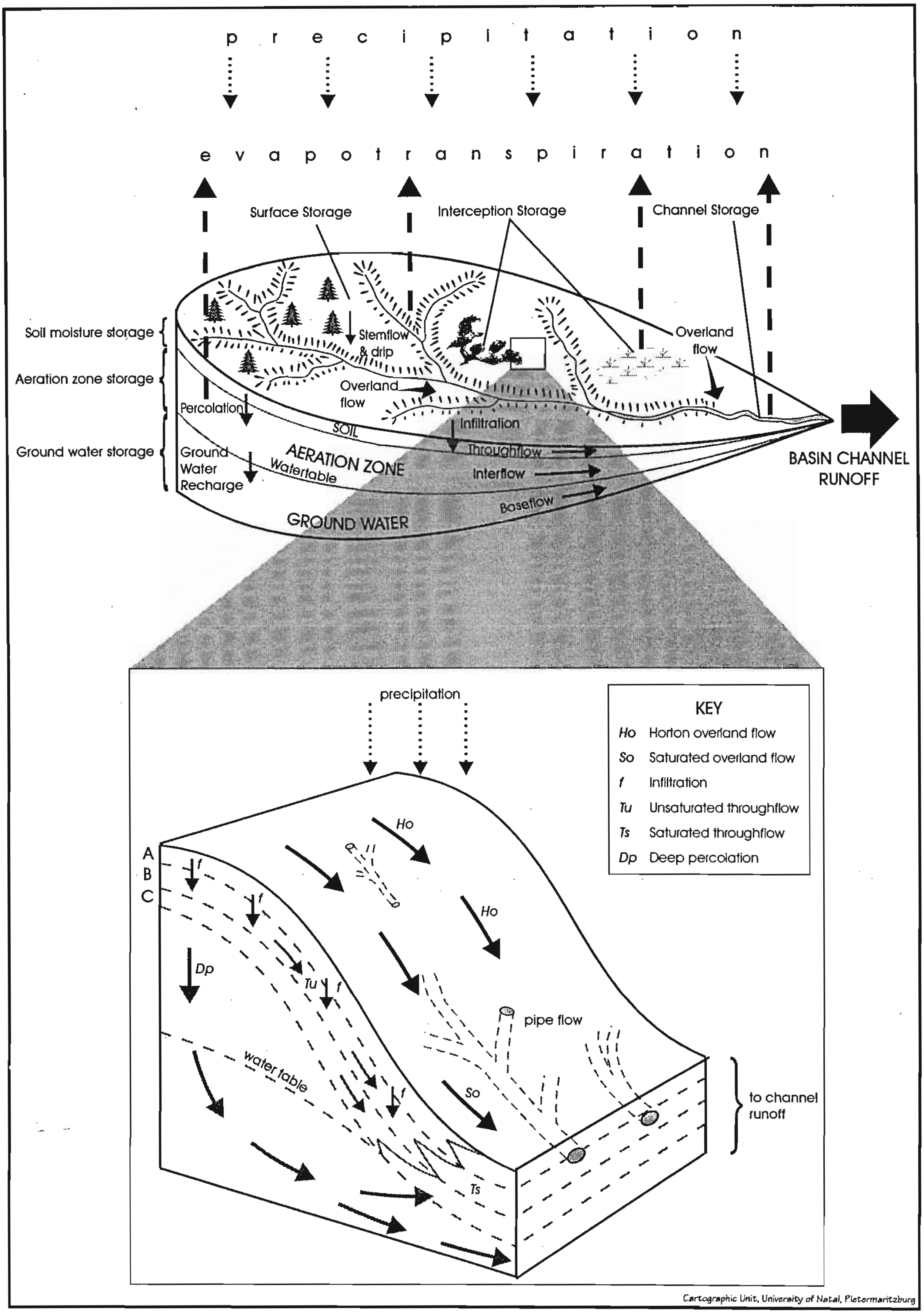


Figure 2.2.1: Diagram of drainage basin showing position of pipes on the slopes.

When the intensity of precipitation exceeds the infiltration capacity of the soil, infiltration-excess (or Hortonian) overland flow results. If the rate of precipitation is less than the infiltration rate but local conditions are such that the upper soil horizons become saturated, the soil water table may be raised to the extent that it intersects the slope surface - the condition of saturation overland flow. Aspects of such local soil saturation are of great importance in understanding the initiation and genesis of subsurface erosion phenomena. The position of the pipe-system within the other components of the drainage basin hydrology is shown in the flow diagram in Figure 2.2.2.

It is essential to acknowledge that piping is only an end-member of a continuum of forms of interflow and throughflow (Jones, 1981); hence the definition of pipes as subterranean channels existing as a consequence of the movement of water in currents (Parker, 1963; Kirkby, 1978). Implicit in the definition is the idea that pipes are sculpted by water; consequently their geometry would be expected to reflect the hydraulic flow conditions. The recognition that this expectation is not always met, has led Jones (1971; 1981) to use the term 'pseudo-pipe' - a term which, on the basis of evidence presented in later chapters, is probably not valid for southern African conditions. Although soil pipes form an integral part of hillslope hydrology and represent routes of preferential soil moisture movement, as will be shown in the following section, water is not the sole determinant of pipe development.

2.3 Mechanisms of pipe formation and genesis

A large body of literature exists on piping, much of which has been extensively reviewed by Jones (1981;1990). The factors favouring the initiation and development of the piping process may be summarized as follows (Heede, 1971; Jones, 1971, 1981; Crouch, 1976; Beckedahl *et al.*, 1988; Nordström, 1988); it must, however, be stressed that not *all* factors will necessarily co-exist at any one site:

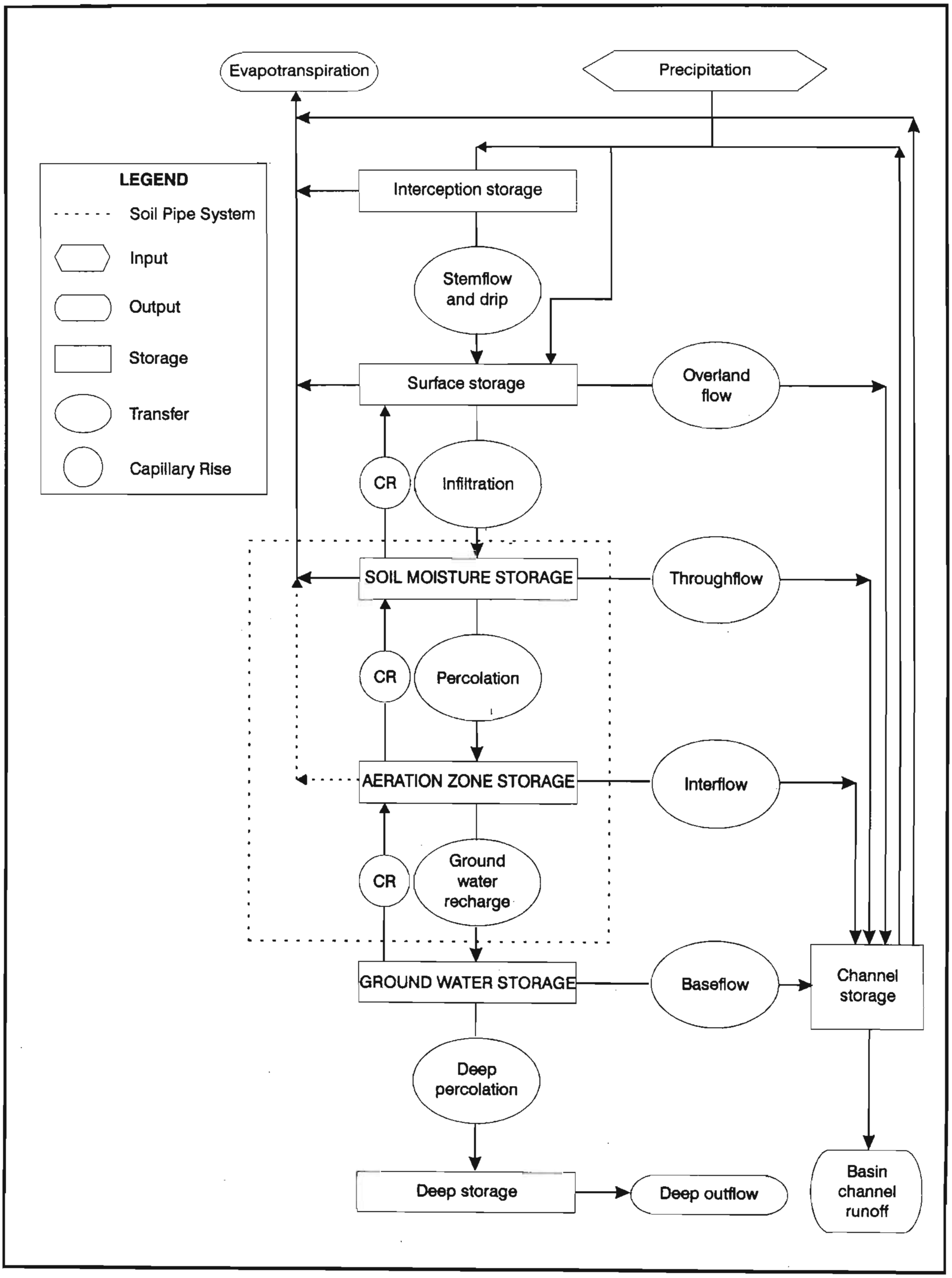


Figure 2.2.2: The soil pipe system in relation to the other components of the basin hydrological cycle (modified after Summerfield, 1991).

- high infiltration rates
- a zone of soil moisture concentration within the profile
- a zone of preferential subsurface water movement in response to an hydraulic head
- a high percentage of swelling clays and associated cracking of the soil profile
- high intensity rainfall
- an erodible layer above a relatively impermeable horizon within the soil profile
- a change in the vegetation cover of the slope
- a high cation exchange capacity (CEC)
- biotic factors such as rodent burrows and root channel networks.

Broadly, and providing that it is recognised that there are interdependencies, the above factors may be grouped into four categories:

i) Chemical soil properties and associated dispersion,

ii) Physical soil properties including swelling and desiccation cracking,

iii) Biotic factors, and

iv) Soil-hydrological factors.

Each of these categories will be reviewed briefly.

2.3.1 Soil Chemical Properties and Dispersion

The control exerted by soil chemistry with regard to pipe development has been discussed extensively (see for example: Charman, 1969; Bryan and Yair, 1982; Jones, 1981,1990; Stocking, 1981; Bryan and Harvey, 1985; Watson *et al.*, 1987; Nordström, 1988). The primary role of soil chemistry is the weakening of interparticulate bonds in alkaline soils - a zone of critical instability develops in response to the exchangeable sodium potential (ESP) of the soil and the ionic concentration of the throughflow. The available sodium within a soil is indicated by the ESP, defined as:

$$ESP = \frac{Na^+}{\text{Cation Exchange Capacity}}$$

(meq/100g of soil)

The Cation Exchange Capacity or CEC is defined as the total electrostatic charge on a mineral, particularly a clay mineral, which is balanced by exchangeable cations of Al, Ca, Mg, K, Na, and H on the crystal surfaces (Rowell, 1994).

The zone of instability represents a transition from stable, flocculated clays at lower ESP and higher ionic concentrations to a stable, deflocculated state in which the process of deflocculation has reduced the soil permeability to a point where throughflow velocities are below the threshold for erosion. The boundaries of such a zone of instability vary with clay mineralogy, to the extent that montmorillonite has the broadest zone (Jones, 1990; Benito *et al.*, 1993). It is generally agreed that dispersion of soil is likely to occur when the ESP is greater than six (Ritchie, 1963).

It has been argued by Stocking (1981) that the sodium responsible for high ESP values in soil is derived from *in situ* weathering of parent material, and distributed into the soil during moisture cycles associated with alternating dry and wet seasons. An alternative hypothesis suggesting that sodium has been replenished by salts dissolved in rainfall has been proposed by Charman (1969, 1970a,b). Both of these mechanisms are seen as possible pathways for replenishing sodium lost from the soil profile by leaching.

Dispersion is accompanied by cationic exchange on the surface of the clay micelles. Bonding divalent cations such as Ca^{++} and Mg^{++} are replaced by the monovalent ions of Na^+, K^+ or hydrogen bicarbonate in the percolating water, increasing the forces of repulsion on the micelles (see Figure 2.3.1). Of the cations, Na^+ is the most effective dispersant. The relationship between the Na^+, Mg^{++} and Ca^{++} content in the soil is generally expressed by the sodium absorption ratio (SAR) defined as:

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Mg^{++} + Ca^{++}}{2}}}$$

(Nordström, 1988)

In general, a soil is considered to be prone to piping if the SAR exceeds 15 (Heede, 1971). A low salt content in the soil water increases the potential for cation exchange, and hence the susceptibility of the soil to dispersion (Sherard *et al.*, 1972).

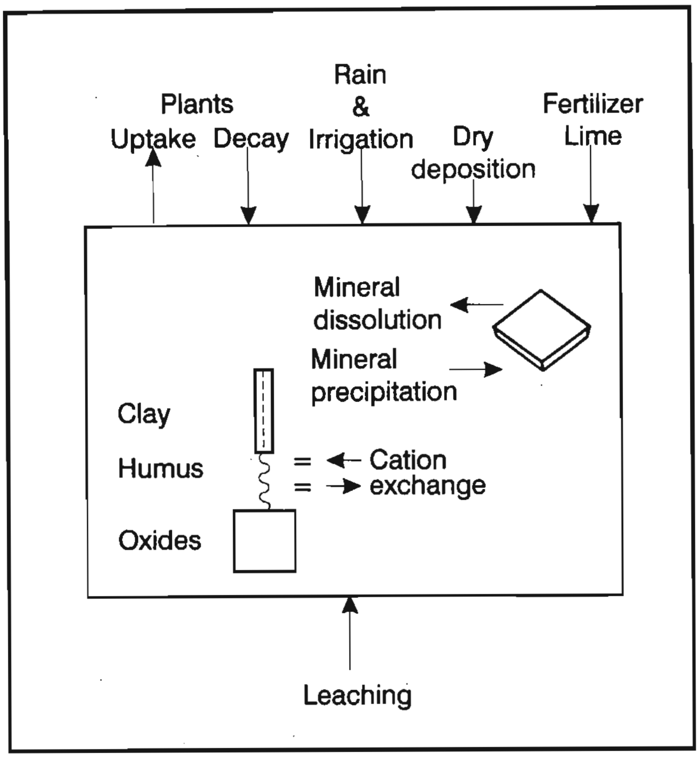


Figure 2.3.1: The processes which influence the amounts of exchangeable cations in soils(adapted from Rowell, 1994).

In summary, the higher the ESP and SAR values, the greater the availability of sodium to cause dispersion and hence the more susceptible the soil is to piping. Recognition of this relationship has resulted in the simplistic assumption that the converse must also hold, *ie*. that soils with low ESP and SAR values have a low susceptibility to erosion and piping. The error of such interpretation has been expounded in the literature (see for example Yaalon, 1984). As indicated above, it is generally accepted that ESP values of at least six meq/100g are needed before dispersion of soil occurs. It has, however, been shown that such a value does not necessarily hold for southern Africa as ESP values ranging between 4 and 68 have been found in Lesotho and Zimbabwe, and that potentially a better erosion index for this region is given by the ratio (Mg^{++} + Ca^{++})/Na^{+}; the higher the ratio, the greater the erodibility (Stocking, 1981b; Rooyani, 1985, Nordström, 1988).

When dispersion of the clay fraction occurs within the soil, the rate of such dispersion is dependent on the ionic content of the soil, and on the chemistry of the water and the rate at which this percolates through the soil. This rate is likely to fluctuate widely in response to micro pores within the soil being clogged by elluviated clays from further up in the profile, and in response to new pores or voids opening as particles are removed by dispersion. The percolation rate is affected still further by the fluctuation in pore size brought about by the swelling of smectitic clays within the soil (Childs, 1969; Sherard and Decker, 1977). The behaviour of dispersive soils with regard to pipe initiation may be summarised by the flow chart shown in Figure 2.3.2, proposed by Stocking, (1981).

The difficulties of conclusively relating soil chemistry to piping have been highlighted by Imeson (1986), who argued that the collection of samples from piped soils in the field for subsequent laboratory analysis may not reveal the true pedogenic conditions, especially where threshold conditions exist. Values characterising such conditions may be ephemeral, may be related to parameters which could not be sampled because conditions have changed subsequent to pipe initiation, or may be related to parameters which need to be measured continuously and with great accuracy in the field (such as critical electrolyte concentrations in throughflow) at various points of the pipe system.

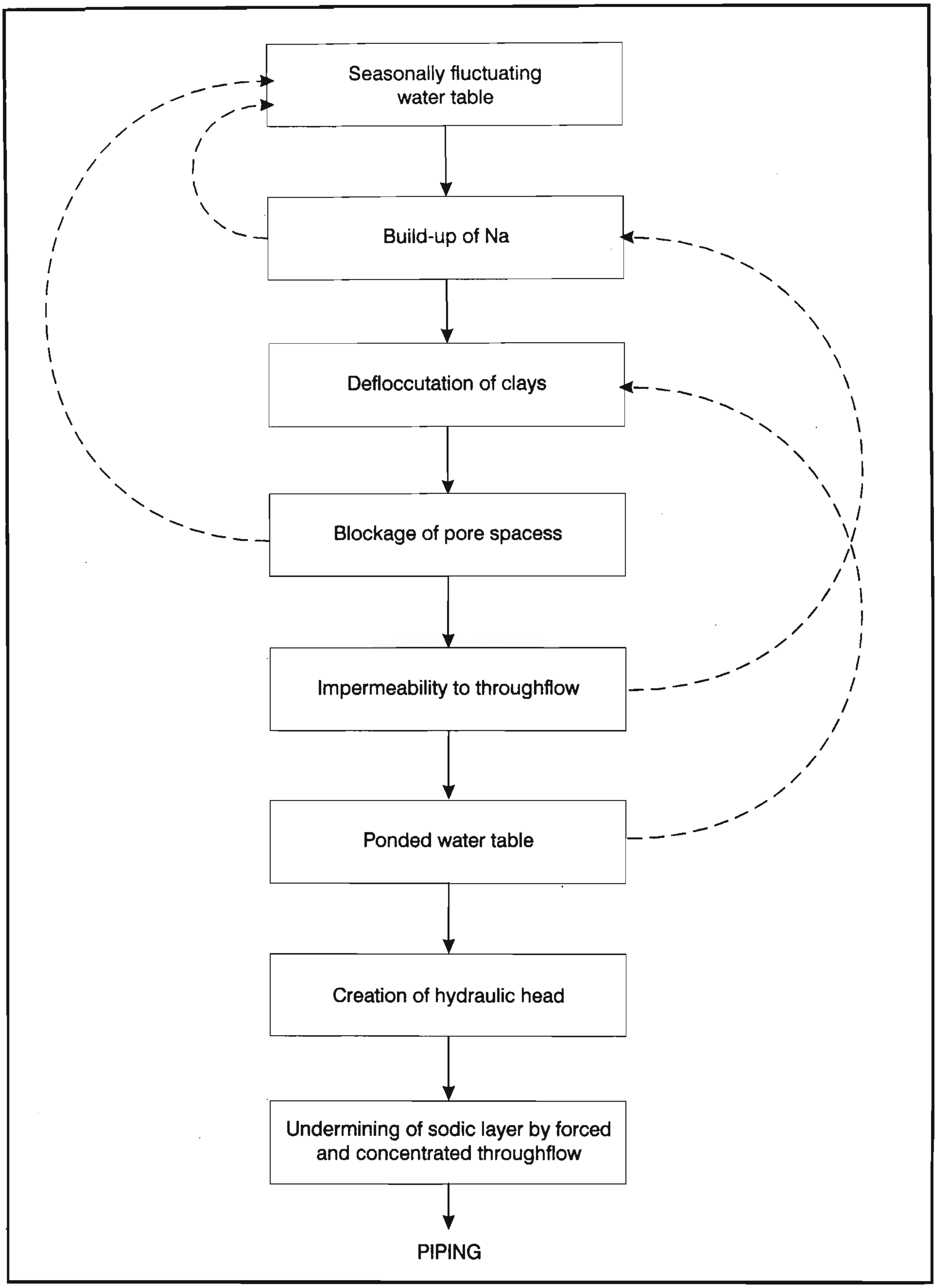


Figure 2.3.2: Flow chart showing the conditions governing the development of pipes in dispersive soils (after Stocking, 1981b).

Notwithstanding the above discussion and the emphasis placed in the literature on the role of salinity and sodicity, piping is also widespread in soils where the sodium ion can have no significant effect on soil erodibility. This is illustrated by published pH values for piped soil horizons ranging from 9.4 in lignitic material in North Dakota (Bell, 1968) to 3.9 for brown earths in the English Peak District (Jones, 1971; 1981), despite Heede's (1971) observation of a significant statistical difference between the mean pH value of 8.9 for piped soils and of 7.6 for unpiped soils.

2.3.2 Physical Soil Properties - Swelling and Cracking

As with other erosion forms, incipient pipe development requires a threshold erosion force that can overcome the resistance of the soil. Irrespective of the actual mechanism of pipe formation, a necessary precondition for pipe development is that those soil horizons which will ultimately form the roof of the system must have a sufficiently high inherent shear strength to support their own weight. As is evident from the discussion of soil strength by Rose *et al.,* (1990), shear strength is the threshold value determining the maximum attainable pipe diameter. When the cohesive shear strength of the material comprising the pipe roof is exceeded, either due to the excessive mass of material involved coupled with the antecedent moisture content, or due to the lateral extent (*ie.* pipe diameter) being such that the span width exceeds the cohesive strength, roof collapse will occur. Although percoline drainage may occur under totally cohesionless conditions, no pipe development will be initiated as no roof can be maintained over the system. For similar reasons the strength of the sidewall is important, yet both parameters have received very little qualitative treatment in the literature (see Carrol, 1949; Jones, 1981).

Many authors have commented on the generalisation that a textural precondition for pipe development appears to be a high silt-clay content in the B or sub-B horizon of the soil profile, overlying a less permeable horizon at greater depth (see for example Rathjens, 1973; Beckedahl, 1977; Crouch *et al.*, 1986). Again, this textural constraint, while common, is not absolute, as shown by Smith (1968) in his discussion on the development of pipes in periglacial environments. This further illustrates the need for caution against broad generalisations with regard to piping. Further evidence in support of this view is the work of Heede (1971) and Jones (1975) who observed no significant differences in texture between piped and unpiped soil profiles.

A consequence of the generally high silt and clay content observed in many piped soils is the preponderance of the soils, particularly those high in smectic clays, to exhibit marked structural discontinuities, fracturing and desiccation cracking (Hosking, 1967; Rathjens, 1973; Crouch, 1976; Lynn and Eyles, 1984; Trzcinka *et el.*, 1993). Although the swelling clays such as montmorillonite and illite are also dispersive, the swelling and cracking upon desiccation is not limited to these clays alone, but has also been reported in peat rich soils of the English Peak District (Jones, 1971). It has been argued that surface water flowing into soil cracks reaches the subsoil, particularly in highly permeable soils, and initiates the formation of a cavity (Crouch *et al.*, 1986). Once a continuous cavity has been established beneath the surface, enlargement will occur whenever water is available to flow along it and to entrain particles. Vertical fractures have been interpreted as desiccation cracking from a parched surface in strongly seasonal wet-and-dry climates or, as has already been mentioned, the presence of swelling clays. A further cause is seen as desiccation in a horizontal direction due to proximity to a gully side wall - a cause which has been invoked to explain short (*ca.* 3 - 5 m) pipe systems along gully sidewalls (Crouch *et al.,* 1986; Masennat, 1980; Dardis and Beckedahl, 1988). It will be shown in Chapter 4 that regional structure may also play a significant role in creating vertical discontinuities within the soil.

A further physical characteristic of soils prone to piping is that by far the majority of piped soil profiles exhibit a markedly layered pattern such that they are frequently described as duplex soils (Jones, 1981,1990; Trzcinka *et al.*, 1993; Fernandes *et al.*, 1994). Porosity and permeability are physical properties which clearly play a role with respect to duplex soils. As their influence is, however, of primary importance within the realm of soil hydrology, they will be discussed in the next section.

2.3.3 The Hydrology of Soil Pipes

2.3.3.1 The Nature of Soil Moisture Movement

Water may enter the soil through the soil surface in a roughly uniform manner associated with precipitation or ponding of surface runoff, or it may enter preferentially along furrows or crevices. Although water may also enter the soil profile by capillary rise from below (originating from the phreatic zone) this process generally does not contribute significantly to subsurface erosion, and will therefore not be reviewed here.

The movement of water into a soil profile is described primarily by two parameters (Hillel, 1980): The *infiltration rate* - the volume flux of water flowing into the profile per unit of soil surface area, and *infiltration capacity* which may be regarded as the limiting equilibrium value of the infiltration rate. The two terms are frequently (erroneously) used as synonyms (Childs, 1969). Infiltration rate will vary markedly as a function of the antecedent moisture content of a soil, whereas the infiltration capacity is regarded as an approximately constant value governed only by the localised soil characteristics, independent of antecedent moisture due to the constraints of the limiting equilibrium values. In reality, although infiltration capacity shows considerably less variance than infiltration rate for the reasons outlined, it is by no means totally constant for a given soil due to factors such as variation of pore size and air entrapment within the void spaces of the soil matrix. In an attempt to overcome some of the difficulties of nomenclature, Hillel (1971) coined the term '*infiltrability*' to denote the infiltration flux when water at atmospheric pressure is freely available at the soil surface. Although the term has some merit, it has not been widely adopted in the literature other than in concept.

The behaviour of soil moisture in conjunction with infiltration is highly complex. It is accepted that initial infiltration is rapid, but shows a characteristic swift decline toward some constant rate (Hillel, 1980; Gerrard, 1981). Such a view is a generalisation which does not necessarily hold. Some soils, dried extensively by evaporation, exhibit initial hydrophobic behaviour (Knapp, 1978). More significant, however, is that water in an unsaturated soil will move through a capillary film adhering to the surface of soil particles. Only when the films have thickened to the extent where they virtually fill the larger voids can water move at the maximum rate for a given soil (Selby, 1982).

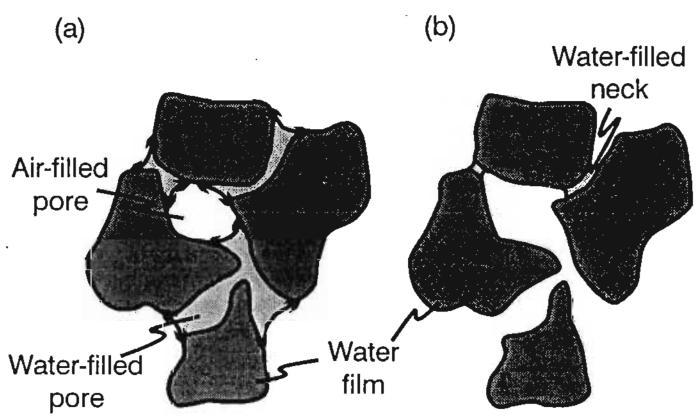
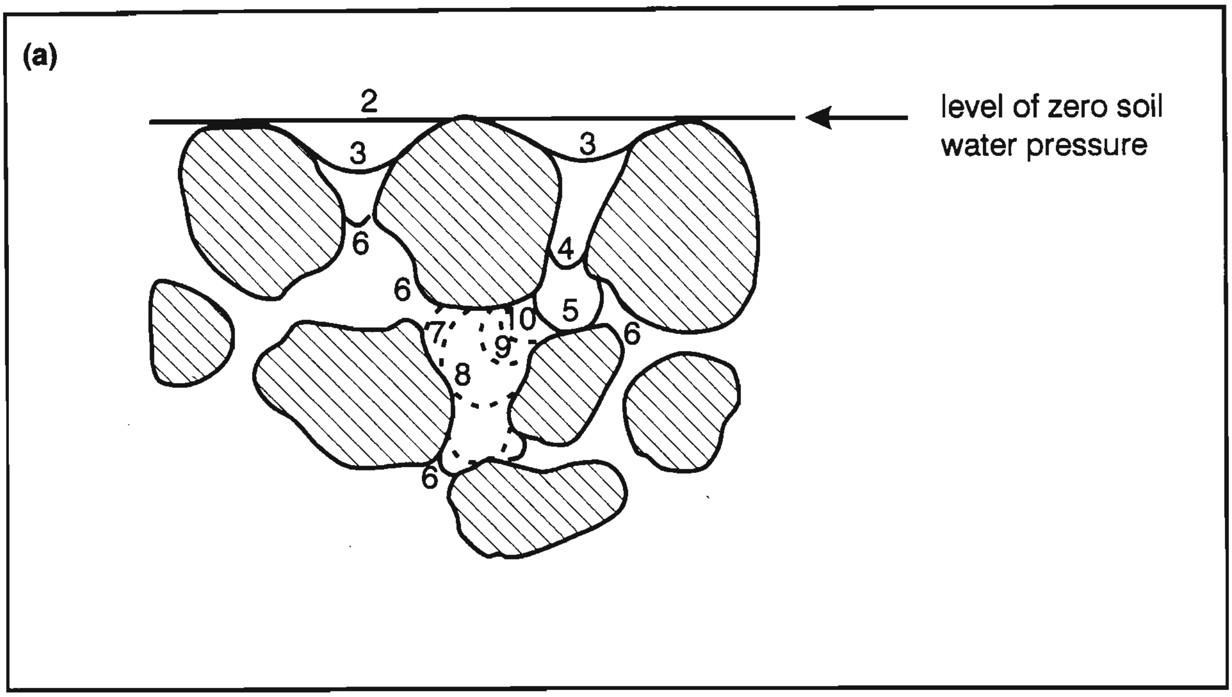


Figure 2.3.3: The distribution of water in soil (after Rowell, 1994).

The complexities of the soil water film and the entrapment of air in the soil macro pores (or voids) as illustrated in Figure 2.3.3 is a partial explanation for the variability in infiltration capacity as also for the hysteresis behaviour of a soil on repeated partial wetting and drying cycles as discussed by Childs (1969) and illustrated in Figure 2.3.4 a and b.



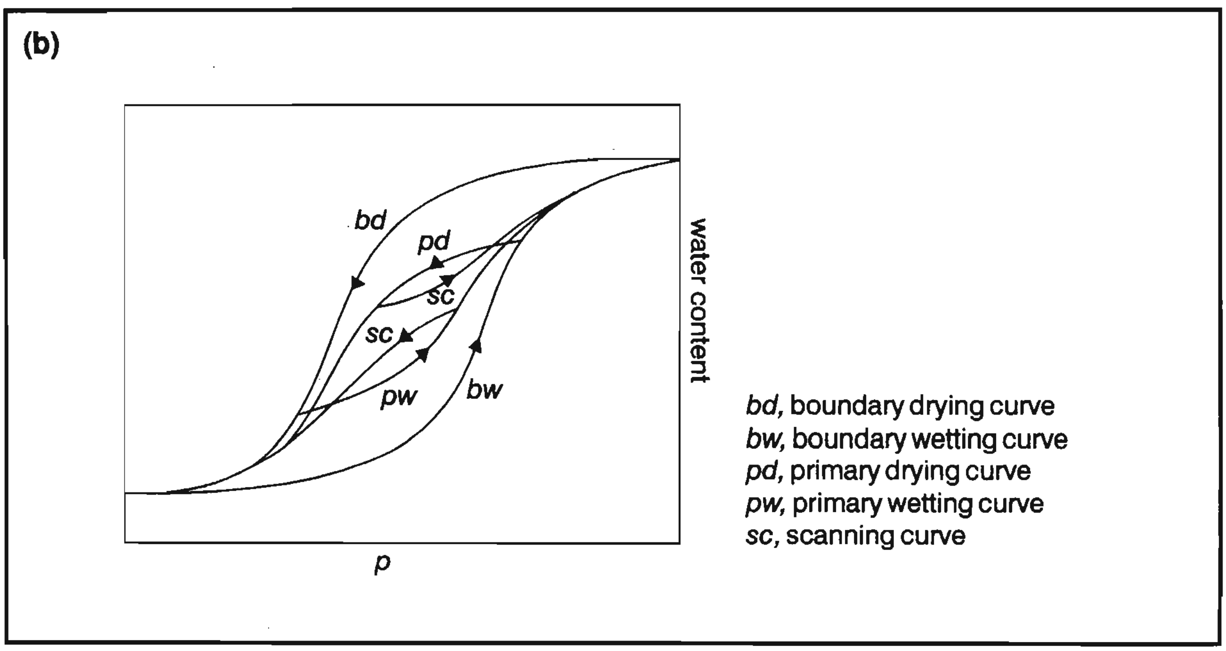


Figure 2.3.4: a) The stages of withdrawal of water from, and its re-entry into, the pore spaces within a soil. Full lines represent withdrawal and broken lines represent advance of water into the soil.

b) The hysteresis curves of the idealised soil moisture characteristic. (Both a) and b) are modified after Childs (1969).

In consequence, it has been observed that maximum infiltration rate into a soil profile may only be attained after some ten minutes to several hours subsequent to the onset of precipitation (Selby, 1982).

According to Knapp (1978), the actual infiltration rate is determined by:

- the amount of water available at the soil surface;
- the nature of the soil surface (vegetation type and density, surface roughness, etc.);
- the hydraulic conductivity of the soil (ie. the ability of the soil to conduct the water away from the surface);
- the antecedent soil moisture present (which partially determines iii above); and
- the size, number and inter-connectivity of voids within the soil profile and their potential change in size and shape due to swelling of clay minerals upon wetting.

As has already been mentioned, if evaporative drying of the soil has proceeded to the extent that the particle - water film has been destroyed, the soil must first be wetted before infiltration can occur other than through macro pores. Once within the soil profile, soil water is subject to the following forces (Childs, 1969; Knapp, 1978; Gerrard, 1981):

i) gravity
ii) the hydraulic gradient, and
iii) soil suction.

Under the influence of gravity, soil moisture will tend to percolate vertically down towards the phreatic zone. Decreases in permeability within the soil profile and/or the throughflow from up slope can cause saturation, resulting in hydrostatic pressures which will in turn tend to create horizontal pressure gradients to dissipate the pressure. Although broadly considered, the hydraulic gradient conforms roughly to the topographic gradient; this condition does ***not*** hold at the local scale - the hydraulic gradient will follow the path of least flow resistance (Gilman and Newson, 1980). The latter consideration is of particular importance with respect to pipe initiation and genesis, as will be shown in later chapters. Although soil suction will act primarily in the vertical, it can also be of significance to piping. Soil suction acts in the direction of the moisture deficit in response to vapour pressure, and will tend to draw moisture away from the surface free water and into the soil profile during the wet season.

During the dry season the direction of suction will be reversed and will tend to draw moisture into the soil profile from groundwater storage in response to moisture loss from soil surfaces. Soil suction attains potential significance with respect to piping once the macro pore has attained the critical size to allow relatively free air movement within and through it. Under these conditions the vapour pressure within the incipient pipe is unlikely to approximate to the saturation vapour pressure, hence potentially initiating soil moisture suction in the direction of the pipe. In this manner pipes have the potential to act as a moisture sink within the soil profile.

2.3.3.2 The Significance of Pipeflow

Despite the low significance accorded pipeflow processes in several of the general texts on soil erosion discussed in Chapter 1, field observations attest to pipes potentially playing a substantial role in hillslope and basin hydrological response. Gilman and Newson (1980) found results for three streams suggested that contributions to the hydrograph ranged from a mere 4 to 72%. In a study over two and a half years (190 storms), Jones and Crane (1984) found a contribution of 49% to stormflow and 46% to baseflow; values of the same order of magnitude as those obtained by Tanaka (1982) in Japan. Data presented by Wilson and Smart (1984) suggest pipe contribution values to stormflow as high as 68%, whereas Roberge and Plumondon (1987) estimate that pipeflow typically transmits 20% to 22% of snowmelt in north eastern Canada. Such variability makes it almost impossible to generalise about the contribution of pipeflow. This is all the more important when such generalisation is based on scaling up from relatively short pipe segments to the landscape scale. In order to understand the formative mechanisms of pipes, the manner by which water may initiate, reach, or modify a soil pipe, needs to be understood.

Following from Section 2.2.1, once water has infiltrated into the soil, it will move either as *matrix throughflow* or as *macro pore throughflow.* Throughflow may be defined as the down slope flow which takes place physically within the soil profile (Kirkby and Chorley, 1967), and can contribute significantly to storm runoff. Gilman and Newson (1980) distinguish between *throughflow* and *interflow* on the basis that the latter has a considerably greater lagtime than the former; a distinction which is rather difficult to infer in practice when interpreting the hydrograph.

In deep homogenous soils, water would be expected to move approximately vertically to the watertable. Most soils in eastern southern Africa, however, have well defined horizons with differing properties; duplex or texture-differentiated soils are common. A soil profile may therefore be considered as a sequence of layers each with a permeability distinct from its neighbours, but potentially also varying within itself in response to the illuviation of clays and iron by, for example, podzolisation. These changes in permeability related to textural differentiation may, according to Gilman and Newson (1980), be sufficient to deflect the direction of infiltrating water down slope. The consequence of an impeding layer within the profile may be the saturation of the soil immediately above, causing lateral saturated flow (or matrix throughflow) through the pore spaces. Although saturation of a part of the profile is not a necessary condition for lateral flow, field studies have focused on saturated flow and have neglected unsaturated flow.

As a soil is not a uniform matrix where behaviour of water within the pore spaces is merely determined by the bulk properties, cognisance must be taken of the existing voids and macro pores within the profile. These voids may be of biological or structural origin, or they may be related to shrinkage and desiccation and, depending on the nature of the soil, will be enlarged by dispersion (see Crouch, 1976; Jones, 1981). An open channel in the soil does not automatically offer a line of least resistance to throughflow. In unsaturated soils water flows preferentially in the smaller pores and throughflow will only occur if the pressure in the soil water exceeds atmospheric pressure (Dixon and Peterson, 1971); large non-capillary pores therefore cannot drain unsaturated soil as illustrated in Figure 2.3.5.

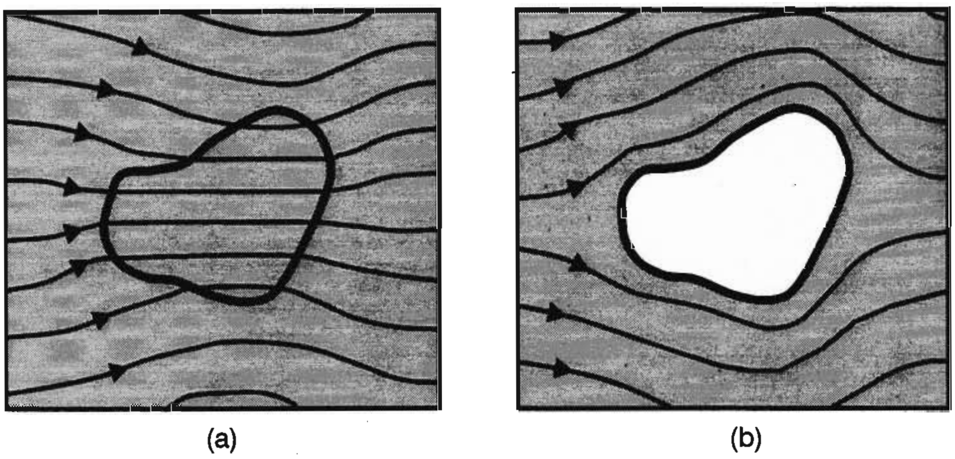


Figure 2.3.5: Representation of macro porosity and throughflow (after Gilman and Newson, 1980). a) In saturated flow a macropore behaves as a zone of locally high permeability; b) In unsaturated flow, it acts as an impermeable zone.

As most soils in the study area are unsaturated in their upper horizons, the rapid transport of water through macro pores is therefore unlikely to occur. Such interpretation is, however, not valid as it has been found that when macro pores intersect the slope surface at a point where concentrated surface flow exists, these pores provide a route for the rapid infiltration and lateral transport of water, even though the micro pores or soil matrix are then often not yet saturated (Whipkey, 1969;

Kirkby, 1985). A comprehensive review of the role of macro pores in hillslope hydrology is given by Germann (1990). Although the qualitative investigations discussed by Germann (1990) attest to the importance of macro pore flow, when dealing with dispersive soils each throughflow episode is essentially unique as the geometry of the macro pores is not stable but will change in response to dispersive and erosive processes along the margins, as also in response to soil activity causing swelling and shrinkage as soil moisture levels fluctuate.

It is recognised that as a consequence of the heterogeneity of many soils, isolated local zones of saturation occur within the soil profile on a hillslope; a situation that is complicated further by the concentration of throughflow by slope form (see for example Kirkby and Chorley, 1967; Anderson and Burt, 1977; Beven, 1977; Daniels and Hammer, 1992). The concentration of throughflow in topographic hollows and the associated potential for saturation is of particular relevance to the present study, as such hollows are also the sites for the accumulation of colluvium, much of which is at least to some extent sodic. This observation accords with the work of Stocking (1976); Crozier *et al*., (1990) and Fernandes *et al*., (1994); and will be discussed in greater detail in Chapters 4 and 5. Most geomorphology and soil texts however, still argue that modification of the landscape by throughflow proceeds at extremely slow rates, and that it is thus of little significance other than in the removal of dissolved colloidal material (see for example, Summerfield, 1991).

There are three ways in which throughflow can exercise a significant geomorphic influence, *viz.*:

- by promoting mass movement on slopes (Crozier *et al*., 1990; Couttes, 1990),
- by removal of fine material in suspension through the soil fabric, leaving behind a zone of increased permeability (Jones, 1981;1990 and Dunne, 1990), and
- by the scouring of subsurface channels or pipes, leading ultimately to roof collapse and gullying (Dunne, 1990 and Trzcinka *et al.,* 1993).

Hydrologically the latter two mechanisms are important, representing processes of both the creation of surface drainage networks and of pseudo-karstic phenomena. They may well also represent the two end points of a continuum in the development of soil pipes, which provide an obvious macro pore network for the rapid transmission of throughflow. Following a detailed analysis of the literature, a problem of definition between macro pore flow and pipeflow becomes apparent. This problem is particularly evident when comparing Gilman and Newson (1980); Germann (1990); Anderson and Burt (1990), and Jones (1990) with one another. The distinction would appear to be primarily one of size, but to some extent also an attempt at differentiating the processes of soil water concentration. Macro pore flow is implicitly *closed conduit* flow (as described by Dardis *et al.*, 1988a), generated by infiltration with some translatory flow from the adjacent soil matrix (compare with Pearce *et al*, 1986; Anderson and Burt, 1990). By contrast, most pipes are erosionally enlarged, consist of a *closed-open conduit*, and are fed by a combination of overland flow (entering the system at a point of roof collapse) and soil water drainage, to the extent that rates are comparable or in excess of those for overland flow (Jones,1987;Torri *et al.*, 1994).

There is an appealing conceptual logic in regarding matrix flow - macro pore flow - pipe flow as a continuum of increasing permeability with a concomitant increase in the potential rates and volumes of flow, despite Anderson and Burt's (1990) argument to the contrary on the grounds that pipe networks may exhibit a greater degree of connectivity in a down slope direction than may be the case with macro pores. Unfortunately there are at present insufficient data to either validate or refute such an objection. In dispersive soils, saturated matrix flow is likely to entrain hydrophilic clay particles and to translocate these along the hydrological gradient, leaving behind enlarged void spaces and hence a potentially more permeable soil. This in turn represents a pathway of decreased resistance to soil water, with the associated possibility of increased throughflow ultimately creating a pathway along which silt- and sand-sized particles can be removed, *ie.* the conditions for turbulent flow, erosion and hence incipient pipe formation have developed as a continuum as illustrated in Figure 2.3.6.

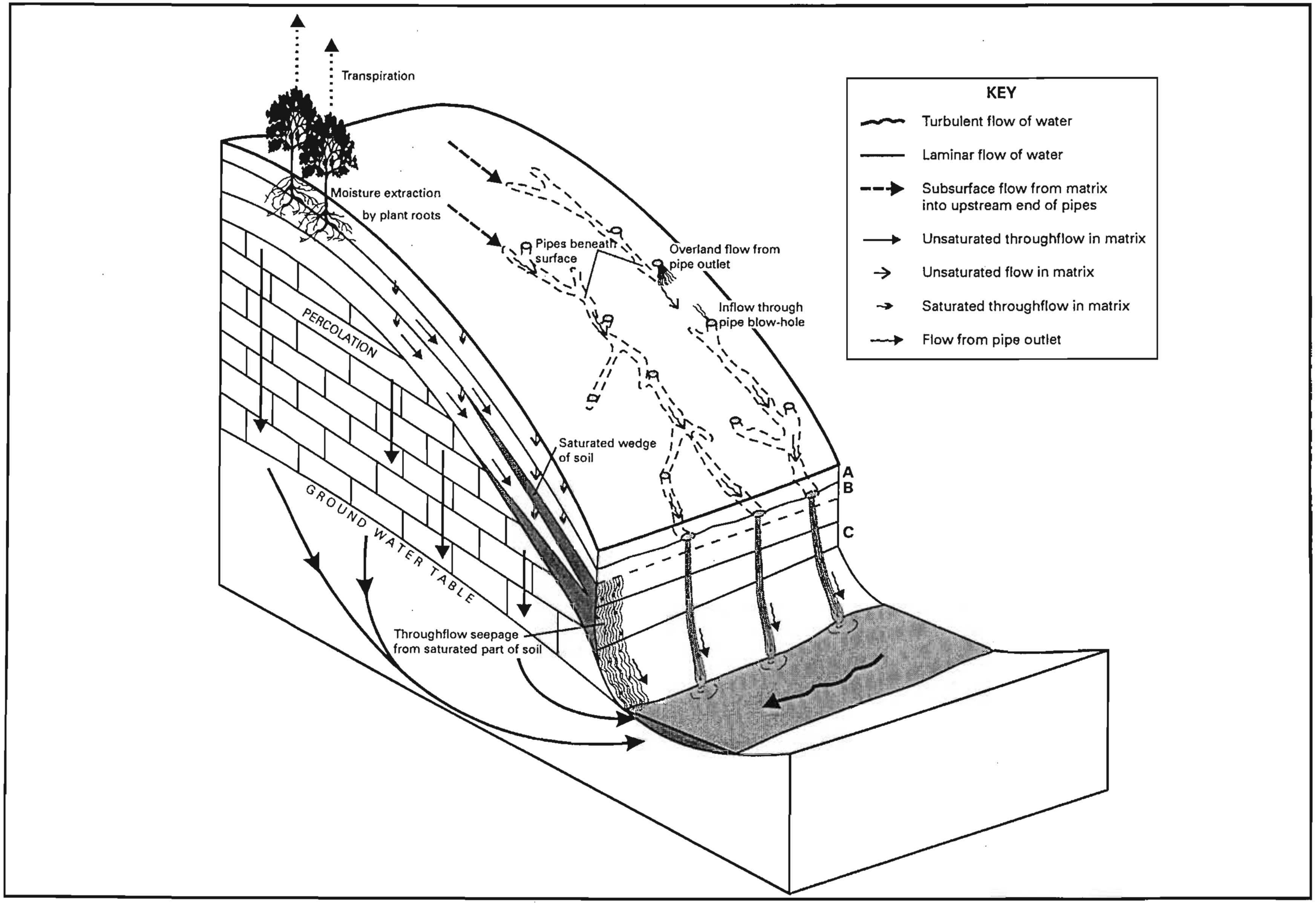


Figure 2.3.6: The continuum of the susurface erosion-soil pipe system. (Adapted from Kirby, 1985; Jones, 1990 and Summerfield, 1991)

2.3.3.3 Conditions for Pipe Discharge

From the afore going discussion and from the work of Kneale and White (1984), Coles and Trudgill (1985) and Dunne (1990), the following conditions act as thresholds governing pipe discharge:

- If rainfall intensity is below the pedal infiltration rate, no flow will occur in a closed pipe system *unless* the piped soil is at field capacity.
- If antecedent soil moisture is too low (*ie.* the soil is too dry) in relation to the rainfall intensity and the rate of macro pore flow, any such flow will cease as the moisture is absorbed preferentially into the soil matrix by soil suction.

Soil pipes have the potential to contribute significantly to the basin hydrological system. As has been shown, pipeflow may provide a significant contribution to stormflow, particularly in situations of moderately high soil moisture content where absorption losses along the pipe are relatively minor. In extreme cases the rate of discharge can be such that the normal flow capacity of the pipe is exceeded, resulting in a positive water pressure causing a *water spout* at the pipe outlet.

As discussed previously, pipes may conduct water through soil which is largely unsaturated and can hence cause larger volumes of surface water to reach the stream channel network than would otherwise be the case. In addition, pipes improve the linkage between distinct source areas and the stream network, effectively increasing the contributing area for stream discharge (Freeze, 1972; Jones, 1979, 1987).

2.3.4 Biotic Factors and Pipe Formation

Biotic activity was initially seen as the primary cause of piping (see for example Sharpe, 1938; Bennett, 1939) but consensus in the literature at present favours a relatively minor role with few exceptions (Jones, 1981). Newman and Phillips' (1957) argument that animal burrows were the *initial* cause of pipe development has also been repudiated. Notwithstanding the above, Löffler (1974) described how rootcasts can act as pedotubules, channelling surface water into the soil profile and so promoting piping in New Guinea. The reasoning is very similar to that favouring the animal-burrow hypothesis: essentially the concentrated flow of water along a soil conduit will be associated with turbulence. The potential therefore exists for erosive scour and consequent enlargement by what are, in effect, fluvial processes.

An alternate argument favouring biotic activity enhancing pipe development is that of Johnson (1976) and Fernandes *et al.,* (1994), who cite earthworm and ant activity respectively as significantly increasing soil permeability and so enhancing infiltration, increasing the incidence of saturated matrix flow and consequently of piping. Biotic factors may also be used as an early indication of the potential existence of piping (see for example Heede, 1971; Beckedahl, 1977) as pipes will themselves modify the moisture regime of soil profiles within the context of hillslope hydrology (Kirkby, 1978). This aspect will be discussed more fully in Chapters 5 and 6.

2.4 Modelling Soil Pipes and Pipeflow

As a direct result of the complexities of soil pipe genesis and evolutionary behaviour, no generally applicable model exists at present for the evolution of pipe networks (Jones, 1981, 1990; Anderson and Burt, 1990), to the extent that Jones (1981) questions whether a single model could totally encompass all potential forms of piping caused by the different initiating processes.

It will be shown in the following chapter that the topic of soil pipe genesis has not been extensively researched in South Africa and, as the pipe systems tend to be ephemeral or episodic and are generally in excess of one metre below surface (in some cases as much as three metres, see Dardis and Beckedahl, 1988), the complexities of measuring flow are increased considerably relative to Europe. As a consequence tracing methods discussed by Drew and Smith (1969) are generally inappropriate and the most reliable survey of a pipe system is still derived from a compass traverse through the system itself, provided that the pipe diameter permits access.

Three attempts have been made at modelling soil pipes to varying degrees of success. Field observations in Britain suggest a generally slow rate of evolutionary development. Following the mathematical work of Shreve (1972), Jones, (1975,1981) suggests an analogy with flowage at the base of glaciers - diffuse seepage at the phreatic surface exploits the existence of voids in the soil which exhibit disproportionate growth of the large voids, concentrating throughflow and the erosion associated with turbulent flow, leading ultimately to stable networks.

If **a** and **b** are the respective radii of two tributary passages of similar length and connected to similar sized source areas and, further, if M is the rate of erosional increase of the pipe down-conduit of the junction of the two passages, and discharge (Q) is given by $Q_a + Q_b = Q$, it may be shown that:

$$\frac{a^{*} - M_{a}}{\mathbf{a}} = \frac{b^{*} - M_{b}}{\mathbf{b}}$$

where $\mathbf{a}^*$ and $\mathbf{b}^*$ are the rates of change of radii **a** and **b** respectively.

Differentiating for Q gives:

$$\mathbf{b}^{*} = -\mathbf{a}^{*}\left(\frac{\partial Q_a/\partial a}{\partial Q_b/\partial b}\right)$$

and

$$\mathbf{a}^{*} = \left(\frac{M_a}{\mathbf{a}} - \frac{M_b}{\mathbf{b}}\right) / \left(\frac{1}{\mathbf{a}} + \frac{1}{\mathbf{b}}\left[\frac{\partial Q_a/\partial a}{\partial Q_b/\partial b}\right]\right)$$

(After Jones, 1981)

Should $\mathbf{a} > \mathbf{b}$, $\mathbf{a}^{*}$ is positive. The larger passage will increase in size more rapidly, hence capturing continuously more of the total discharge. Although a convenient approximation, the above approach essentially assumes a homogenous soil and *quasi* regular discharge, which is not justified. It further does not take cognisance of the field observation of the existence of two or more layers of pipe networks juxtaposed on top of one another.

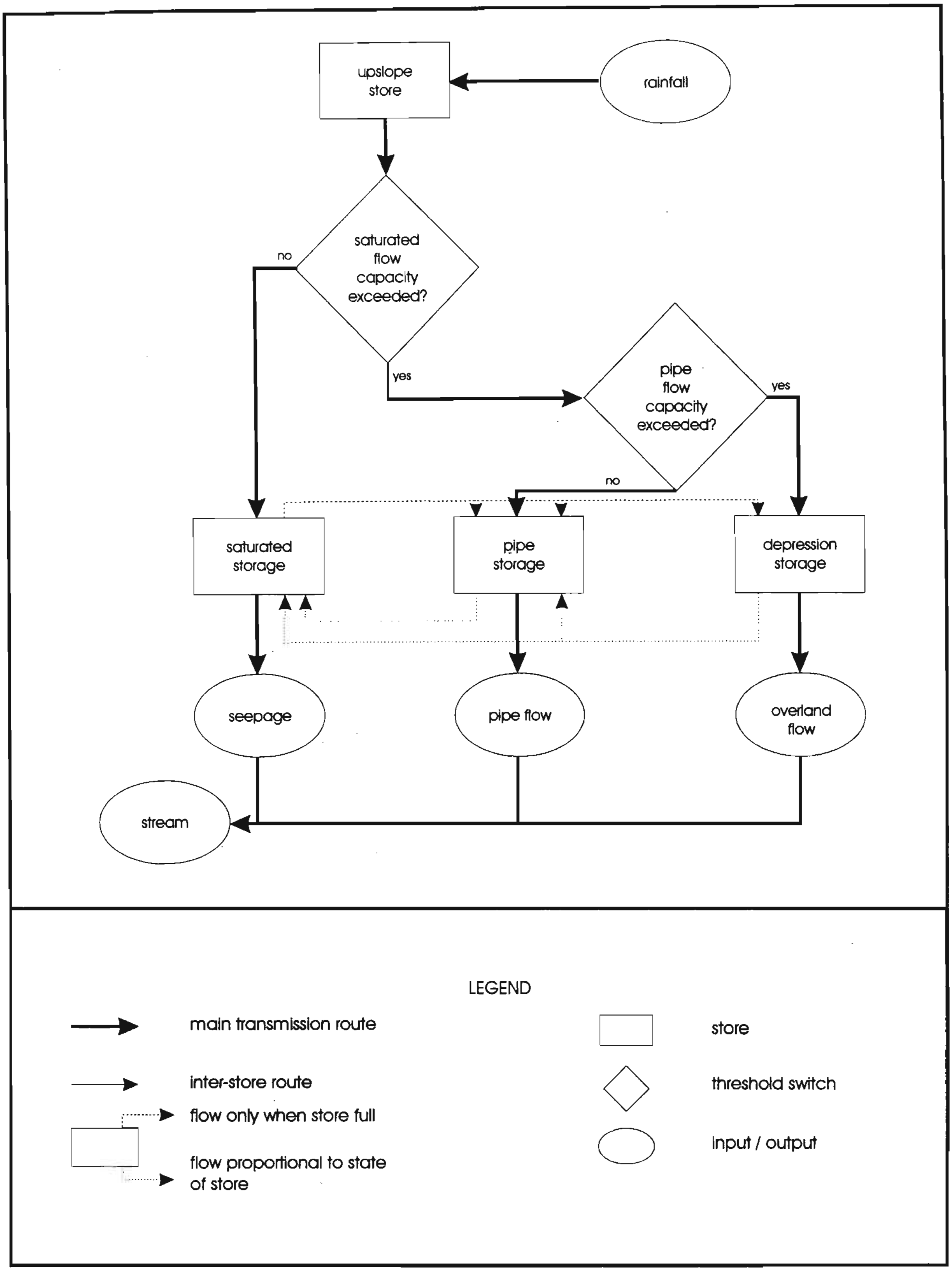


Figure 2.4.1: A conceptual model of soil pipe development, after Wilson and Smart (1984).

The second attempt at modelling soil pipes is the more conceptual approach used by Wilson and Smart (1984), as illustrated in Figure 2.4.1. Although generally valid, this model does not reflect the direct intake of surface runoff into macro pores through collapsed sections of pipe roof. A more complete representation would therefore be the model as shown in Figure 2.4.2.

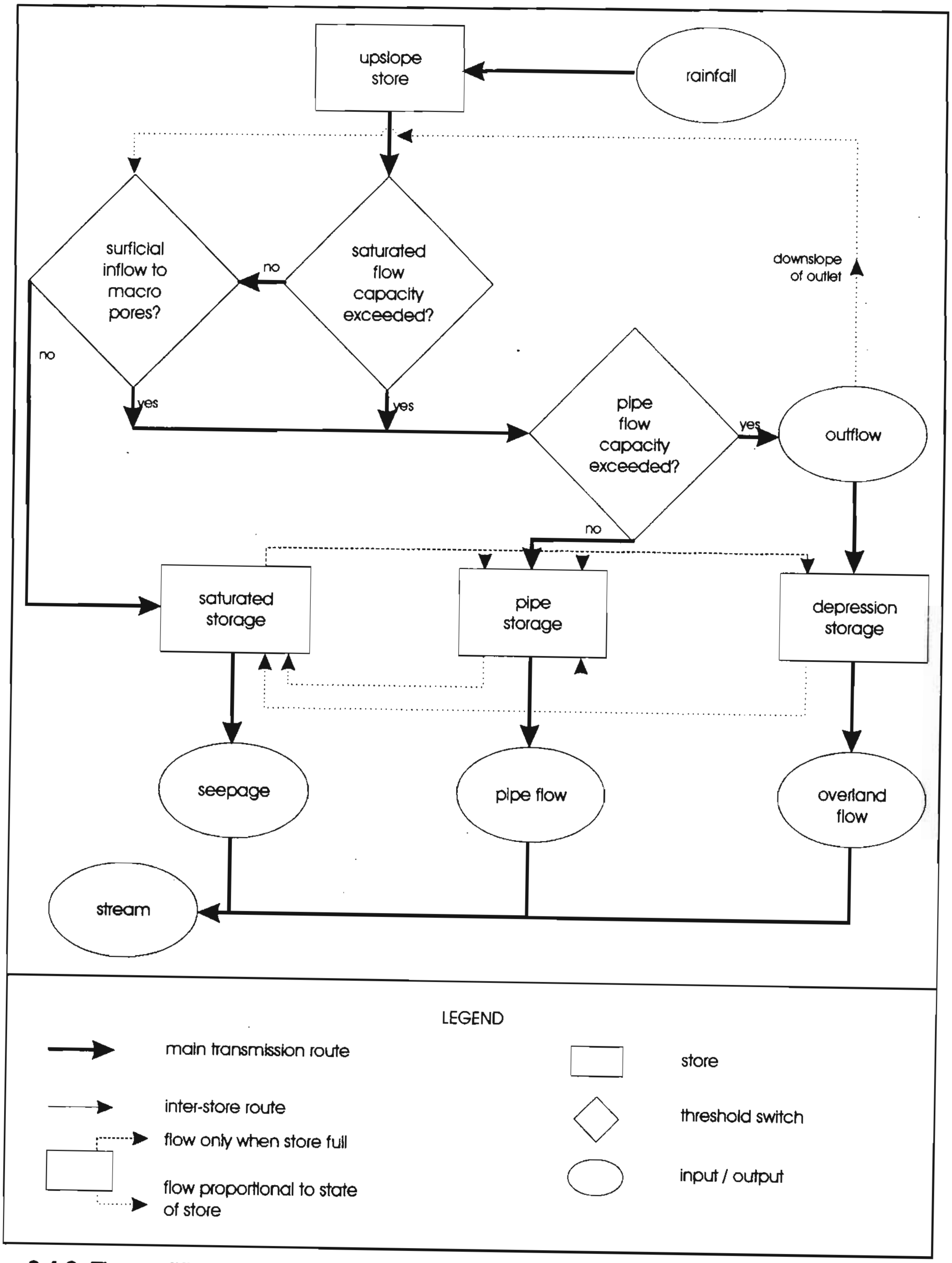


Figure 2.4.2: The modified conceptual model of soil pipe development, based on the original work of Wilson and Smart (1984).

The most comprehensive (and complex) model is Germann's (1990) adaptation of his 1981 work on a schematic representation of the fluxes occurring during infiltration into macro-porous soil, shown in Figure 2.4.3, and where:

Q and q are different volumes of discharge;

t is time;

I is infiltration or percolation, depending on whether water is moviong in the vertical (infiltration) or horizontal (percolation);

z is a distance measure; and

O is overland flow related to surface wash processes.

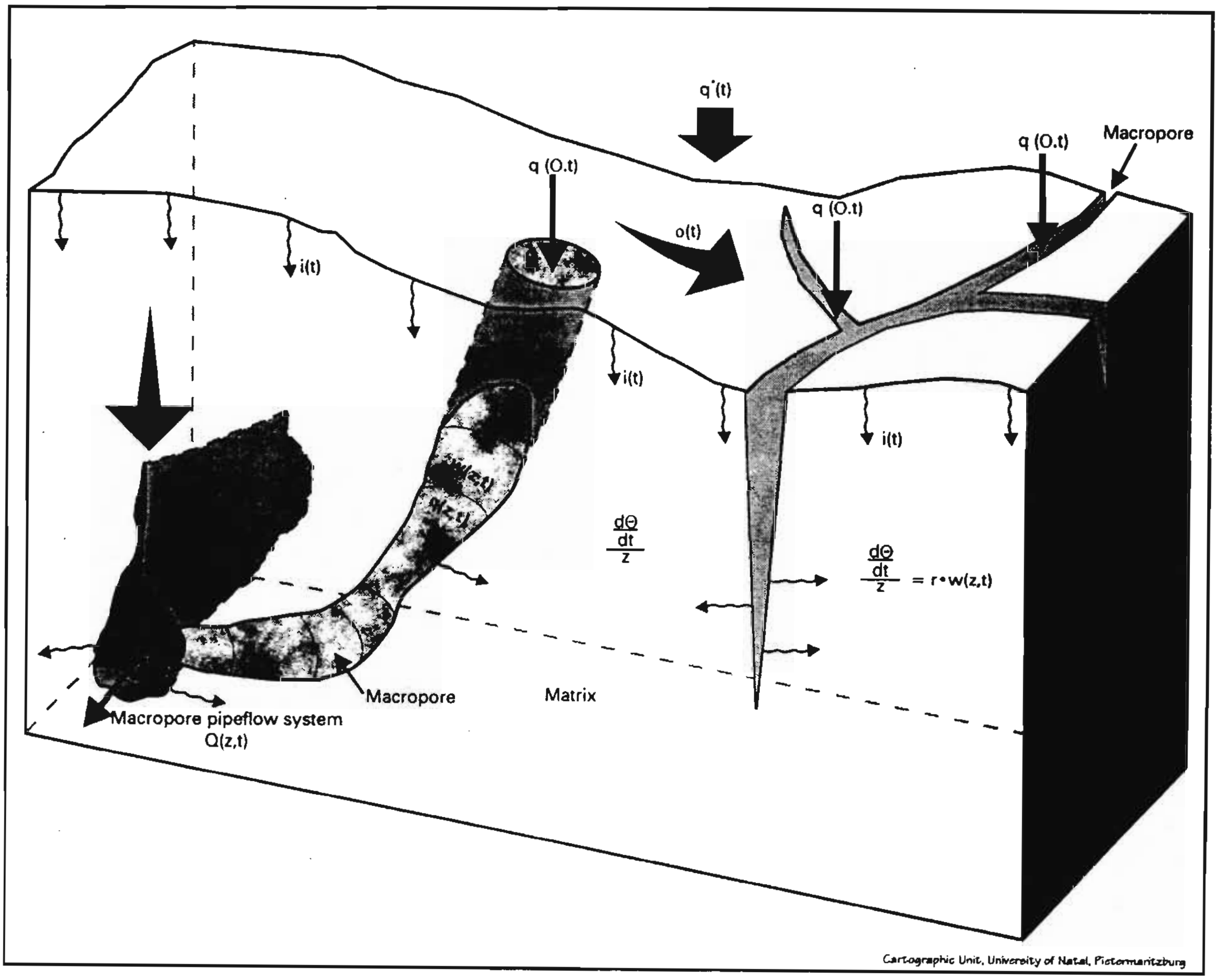


Figure 2.4.3: The model of soil pipe development as proposed by Germann (1990).

2.5 Pipeflow and Sediment Loss

The problems of measuring sediment movement in, and as a consequence of, piping are still more problematic than those of quantifying pipeflow. As discussed in Section 2.3.1, the rate of throughflow affects the extent and efficiency of dispersion. By constructing a weir within a pipe to gauge discharge of water and sediment, the moisture content within the soil matrix of the pipe walls will be affected and hence, too, the rate of throughflow. The danger of which Goudie (1981) warns concerning process measurement *ie.* that values obtained should be a reflection of the process under consideration and *not* of the level of interference introduced into the system, is particularly pertinent here. In highly dispersive soils most attempts at measurement introduce a measure of uncertainty, the significance of which is difficult to ascertain.

McCraig (1979) has indicated that sediment discharge from pipes has a high degree of temporal variation associated with it, as it is related to discrete events such as roof collapse or sidewall spalding. Similar observations have also been reported from the Negev badlands by Yair *et al.,* (1980). A further discrete sediment source is the liquefaction and flowage of soil subsequent to dispersal of the interstitial clays, as described by Trzcinka *et al.,* (1993). Chemically, pipeflow is important: Walsh and Howells (1988) argue that pipes drain solute-rich water from the soil profile near the soil-rock interface.

Despite the constraints discussed, several attempts have been made to quantify the sediment yield associated with pipe discharge. Predictably there is a large degree of variance among the results obtained. Hauser and Zötl (1955) obtained values of 0.5 kg of sand per week associated with a mean discharge of 0.16 $l\ s^{-1}$. When scaled up, these figures suggest an annual erosion rate of 13 dm^3, although the source area from which this material was derived was unfortunately not quantified (Jones, 1981). Work in the Milk River Canyon , Alberta, led Barendregt and Ongley (1977) to conclude that during the summer of 1975, 111 x 10^3 tonnes of sediment were removed from the Canyon slopes. This value led them to conclude that piping is the dominant process responsible for valley slope recession in that area. Unfortunately again no mention was made of the areal extent of the source area.

It is interesting to note that, despite the potentially significant contribution of subsurface erosion to total sediment yield from a catchment, the conventional mathematical soil erosion models such as the Universal Soil Loss Equation (USLE) and its revised version (RUSLE), the Soil Loss Estimator for Southern Africa (SLEMSA) and others (WEPP; CREAMS, OPUS) do not take cognisance of subsurface water flow as pipe discharge. The model produced by the Agricultural Catchments Research Unit (ACRU), does not incorporate it directly (it does consider subsurface water movement, but not as pipeflow (see Schulze, 1995); this problem can, if necessary, be incorporated by relatively minor modifications to the model (Schulze, *pers. Comm.*, 1995). The problematique surrounding the incorporation of piping into soil loss models is centred on the two-fold difficulty of:

- the availability of suitably detailed data sets, and
- the difficulties of obtaining reliable information on pipe flow and pipe discharge in relation to the driving precipitation and antecedent soil moisture conditions.

Notwithstanding these difficulties, subsurface flow (and allied to this, to a very limited extent sediment loss) has been modelled using the physically based distributed model SHE (the *Systèm Hydrologique Européen*, described in detail by Abbott *et al.*, 1986), with some limited success (Whitelaw, 1988). This has led Anderson and Burt (1990) to observe that, while the differing flow processes can generally be adequately described in both space and time by experts when in the field, such knowledge has as yet been transferred to the modelling environment with very limited success resulting in subsurface flow regimes and sediment yields being poorly predicted by available models even after extensive calibration procedures.

It will be shown in Chapter 6 that, although pipe sediment transfer rates vary considerably for South Africa (see for example Garland and Humphries, 1992), the rate of sediment flux due to piping is potentially as significant for South Africa as in the Milk River Canyon of Alberta.

The discussion thus far has shown the potential role of climatic, meso-topograhic and soil conditions in determining both the nature and incidence of subsurface erosion, and specifically soil pipe development. Prior to considering the subsurface erosion phenomena of Transkei and KwaZulu-Natal in detail, it is therefore necessary first to discuss the physiography of the region briefly. This is the scope of the following Chapter.

Chapter 3

3. The Physiographic Setting of South Eastern Southern Africa

3.1 Macro-Morphology

The landscape of the south eastern portion of the subcontinent in many respects mirrors the complex morphological diversity of southern Africa as a whole and has generally been attributed to the cumulative influence of processes active during the geomorphic history of the region since the fragmentation of Gondwanaland more than 200 million years ago (Moon and Dardis, 1988). The rifting process involved in this fragmentation has been cited as the cause of the original form of the coastline (Beater and Maud, 1960).

In essence, the terrain of the south eastern sub-continent consists of a series of dissected steps from the coastal lowlands, through the Natal midlands to the Drakensberg Escarpment and ultimately to the Lesotho Plateau above, reaching altitudes of nearly 3000m over a total distance of just under 200km. The morphology from the Transkeian coast inland to the Drakensberg is similar to that of Natal, except that the coastal margin is comparatively narrow. The Transkei coastline is one of the few rocky shorelines found in South Africa and is characterised by a coastal scarp which rises to an altitude of over 700m within 30km of the coast. A direct consequence of this steep coastal margin is that the streams in southern Natal and particularly in Transkei generally discharge into the sea through straight, narrow, coastal gorges.

The difference in coastal morphology between KwaZulu-Natal and Transkei is a direct result of the combined effects of crustal flexuring along what has been described by King (1982) as the Natal Monocline (although Maud (1961) has presented a more plausible argument in favour of a sequence of seaward-tilted fault blocks) and the influence of the Port Shepstone and Mbotyi Faults.

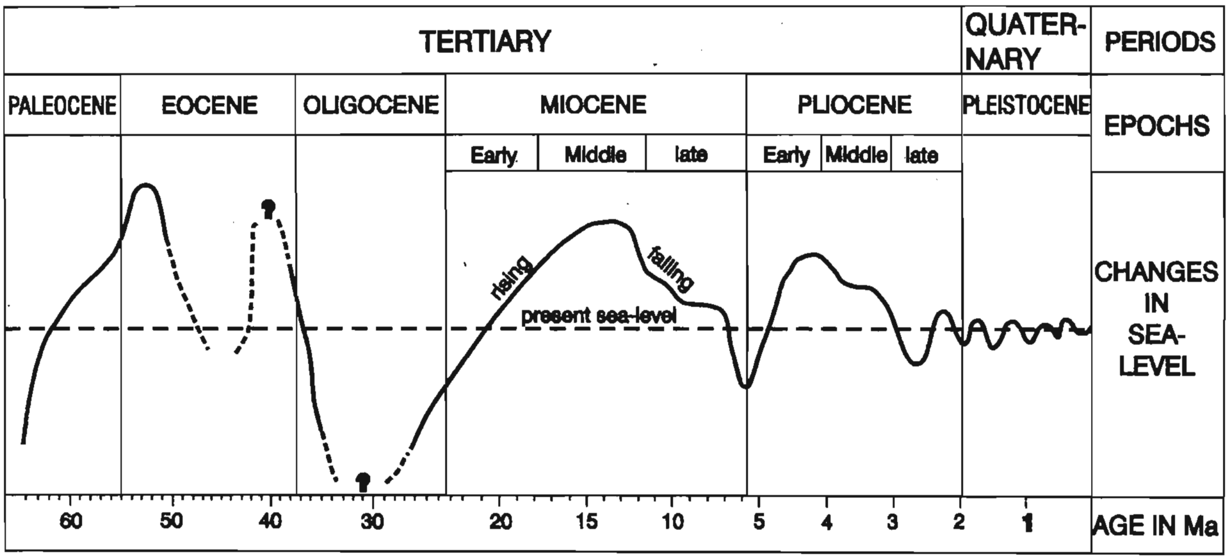


Figure 3.1: South African Cenozoic sea level changes (after Dingle *et al.*, 1983).

Since the time of the continental breakup the actual form of the coastline has been modified by tectonic uplift and flexuring of the subcontinent, including eustatic sea-level movements (Figure 3.1). Relict shorelines occur intermittently along the southern African coastline, reaching elevations of up to 100m above present mean sea level (m.s.l.) along the east coast (Davies, 1978). This elevation has been interpreted as supporting the view that most relict shorelines of the region represent the combined effect of glacio- and tectono-eustatism as well as local epeirogenesis (Davies, 1978). A review of research (see Dardis and Gridley, 1988) indicates that sea levels along the east coast of the subcontinent have fluctuated widely during the past 25 ka, from a minimum of -130m during the northern hemisphere Glacial Maximum (17 - 18 ka) to a maximum elevation of about +6m at 5.5 ka as shown in Figure 3.2.

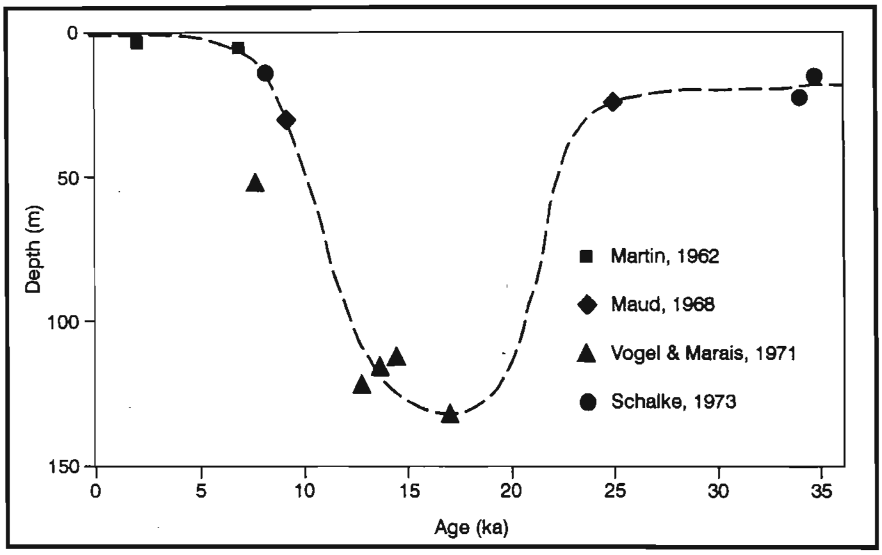


Figure 3.2: Late Quaternary southern African sea level changes (after Tankard, 1976).

Early geomorphic research adopted a regional framework for the interpretation of landscape development, derived from considerations of lithology, geological structure, altitude, and geomorphological history (Wellington, 1955; King, 1963) - an approach also inherent in the work of Kruger (1983) and van Zyl (1985). Much energy was expended on the polemic of explaining the existence and morphology of the Main Escarpment, the feature dominating the eastern Cape and KwaZulu Natal Drakensberg and which is anomalous in that it has developed to an altitude in excess of 2500m within the near-horizontally bedded lithologies of the Karoo Supergroup.

The Escarpment was originally interpreted as a fault scarp (Seuss, 1904); an interpretation questioned by Penck (1908), who argued in favour of a process of scarp retreat. Hypotheses associated with a dominant mechanism of scarp retreat facilitated the theoretical extension of Penck's work and the formulation of a logical corollary in what has become generally known as '*denudation chronology*'. This was first proposed for the region in Dixey's (1942) pioneering work, identifying four erosion surfaces from the coast through to the Lesotho Plateau. The dangers inherent in work centred on a broad acceptance of the philosophy pertinent to erosion surfaces is exemplified by Fair and King (1954) arguing for three surfaces; King (1949;1967;1976) arguing for five surfaces and Partridge and Maud (1987) ultimately again arguing for the existence of three erosion surfaces, albeit different in many respects to those surfaces proposed by Fair and King (1954). Further problems relating to the identification, dating and correlation of erosion surfaces over extensive areas have been discussed by numerous researchers, notably: Young (1972), De Swart and Bennet (1974), Chorley *et al.* (1984), Selby (1985) and Summerfield (1985).

A different dimension was added to the arguments on landscape genesis for the region by the work of Birkenhauer (1985) who proposed structural control as the cause of the distinctly stepped regional topography, and the work of Ollier and Marker (1985) who reviewed the effect of crustal downwarping on the base level of rivers and the associated erosion.

In an attempt to synthesize the research, Partridge and Maud (1987) redefined the denudational history of the subcontinent on a more quantitative basis than had been previously possible. Their interpretation is based on the analysis of key topographic profiles, correlation of erosion with offshore sedimentation, dating evidence from both paleontological and geomorphological studies, and on morphotectonic models relating to uplift of continental margins They concluded that the mountainous regions above the Great Escarpment could not be related to any one particular phase of erosion, but rather that the oldest recognisable surface was the African erosion surface, coinciding approximately with the similarly named surface of King (1967). Two further surfaces were identified by Partridge and Maud (1987) as the Post African I and the more recent Post African II surface (Figure 3.3).

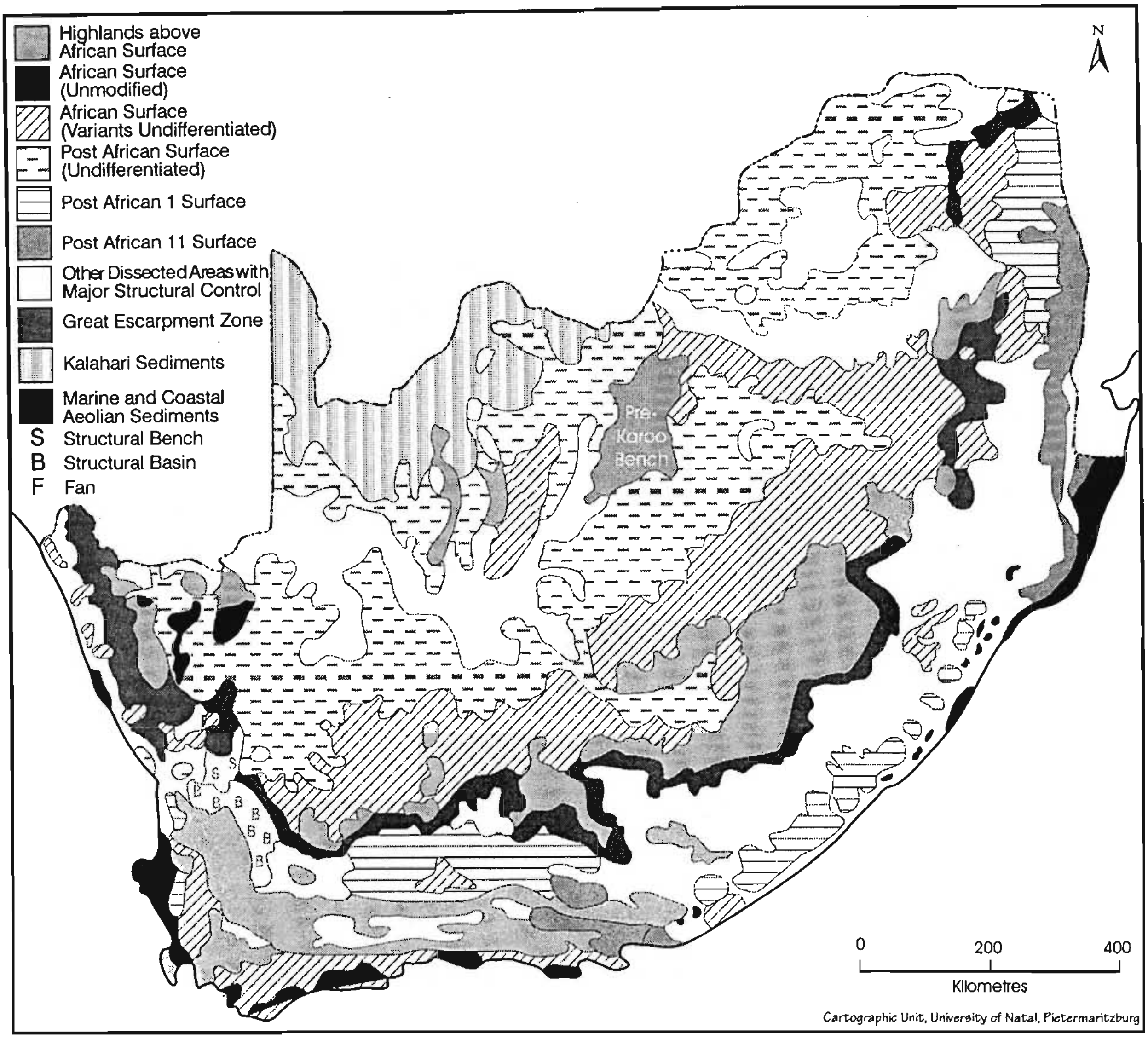


Figure 3.3: The distribution of erosion surfaces and dissected areas on the southern African subcontinent (after Moon and Dardis, 1988).

Notwithstanding the justifiable criticisms of the denudation chronology approach it is argued here that, in keeping with the work of Embleton (1985), such an approach has some merit in providing a spatial context for the control exerted by geomorphic materials, process, structure and temporal-eustatic change at a regional scale, provided that denudation chronology is used judiciously and is not over-extrapolated.

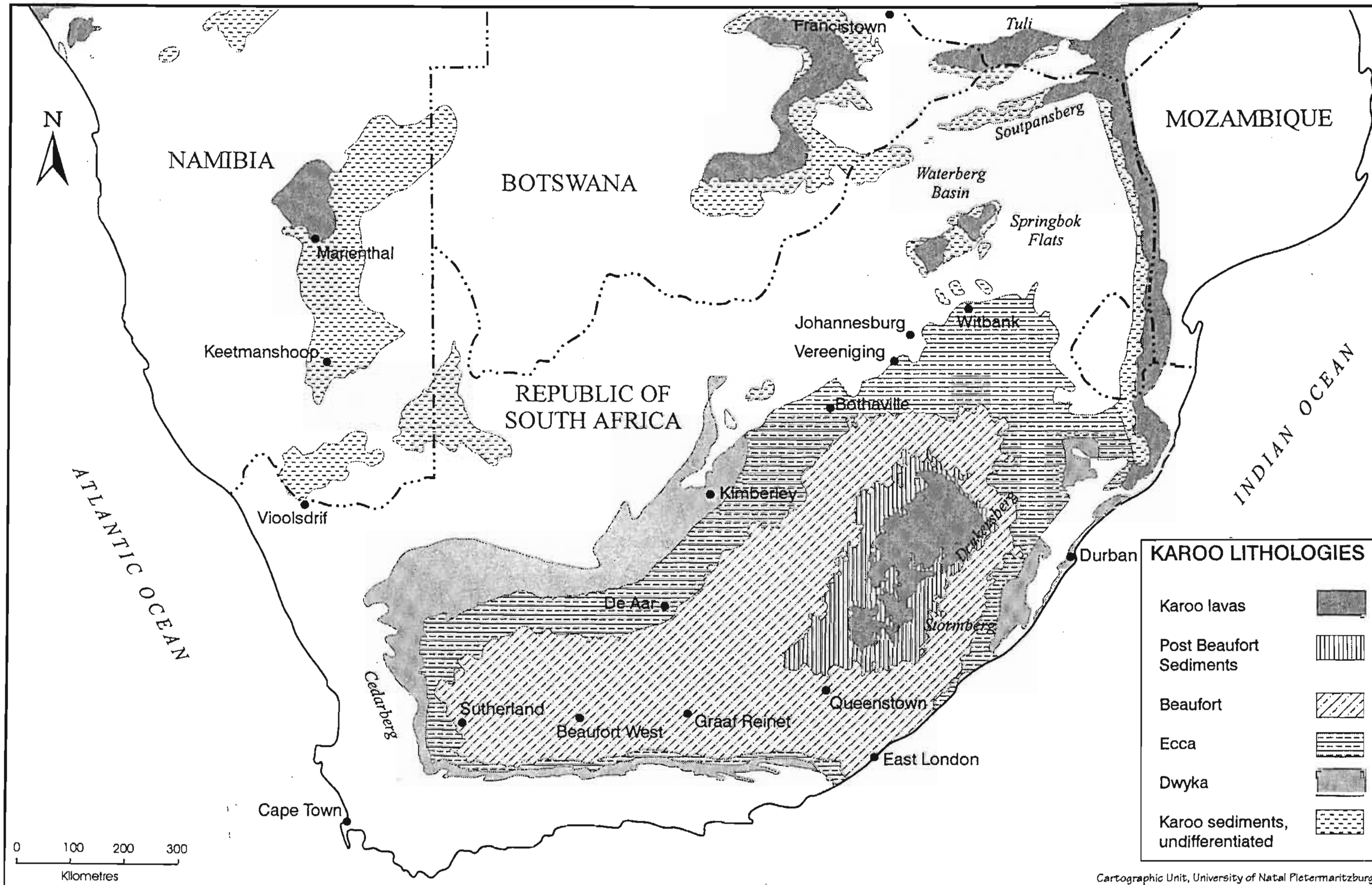


Figure 3.4: The occurence of Karoo lithologies in southern Africa (modified after Truswell, 1977; Tankard et al., 1982)

Although a more detailed review of the geomorphic evolution of the KwaZulu-Natal-Transkei region is beyond the scope of the present discussion, some insight into the geological stratigraphy and structure are pertinent to the later discussion and are thus reviewed briefly in the following section.

3.2 Geology

The geology of the study area (Figure 3.4) consists predominantly of lithologies belonging to the Karoo Supergroup, with relatively minor exposures of the Natal Group sandstones which are believed to be time equivalents to an at present undefined portion of the Cape Supergroup stratigraphy (Hobday and von Brunn, 1979; Kent, 1980). The geological stratigraphy of the region is summarised in Table 3.1. The subsurface erosion forms discussed in this work are found exclusively on the Karoo lithologies within the region; specifically those belonging to the Ecca Group and above, and hence no further discussion of the Natal Group will be presented here.

Transition from the Natal Group to the Karoo Supergroup is evidenced through a succession of interbedded shales, varvites and diamictites, although very little if any of this succession is seen as outcrop in Natal or Transkei (Johnson, 1976). The Karoo Supergroup is characterised by a changing tectonic framework and records the crustal migration of Gondwanaland from polar to tropical latitudes. Karoo lithologies span a period of nearly 200 Ma (Tankard *et al.*, 1982). These deposits form the central nucleus of the final sequence of the Gondwanaland succession which spanned the southern hemisphere continents and India, providing the source material for the piped, now often degraded, soils of the region. Indeed, while it is emphasized that soil pipes have been observed to occur to a limited extent on other lithologies elsewhere in South Africa (Figure 3.5), there is some evidence suggesting that the soils developed from middle and upper Karoo Supergroup sediments are more susceptible to pipe erosion than those from most other lithologies - an hypothesis that is given some support by the occurrence of pipes on Karoo-age lithologies from India, Madagascar, Australia and

South America (see for example: Banerjee, 1972; Singh and Agnihotri, 1987; Wells *et al.*, 1991; Wells and Andriamihaja, 1993; Trzcinka *et al.*, 1973; Crouch,1976; Lynn and Eyles, 1984; Fernandes *et al.*, 1994). Although the relationship will be discussed in later chapters, it would appear that this correspondence is at least in part a function of mineralogy.

Table 3.1: Generalised stratigraphy of southern KwaZulu-Natal and Transkei (modified after Truswell, 1977; Kent, 1980; Tankard *et al.* 1982 and Eriksson, 1983).

SUPERGROUP	GROUP	SUBGROUP/ FORMATION	MEAN MAX. THICKNESS (m)	LITHOLOGY	AGE	
					PERIOD	APPROX. YRS
KAROO	**Drakensberg**		1200	basalts	Jurassic	180ka
	Stormberg	Clarens	150	sandstone	Upper Triassic	200ka
		Elliot	100	siltstone and mudstone with sandstone lenses	Upper Triassic	215ka
		Molteno	50	sandstone, mudstone and shale	Middle Triassic	235ka
	Beaufort	Adelaide Subgroup	100 - 1000	sandstone, siltstone and mudstone	Permo -Triassic	250ka
	Ecca		300	greywacke, mudstone, shale, coal, and some immature sandstone.	Permian	280ka
		Dwyka Formation	> 1000 (variable)	tillite, diamictite, shale and mudstone	Permo - Carboniferous	350ka
not defined	**Natal**		900	coarse conglomerate, arkosic sandstone, fine micaceous sandstone and quartz aranites	Ordovician to Silurian	500ka

The base of the Karoo Supergroup consists of the Dwyka Formation of Permo-Carboniferous age and represents the last time that the African subcontinent was subjected to extensive glaciation (Savage, 1972). Although more recent glacial events roughly coincidental with the northern hemisphere Pleistocene glaciation have, on occasion, been postulated (see, for example, Lewis,1988; Hanvey and Marker,1992 and Hall,1994), there is very little field evidence to support such hypotheses. To date they have not been generally accepted by the scientific community in southern Africa.

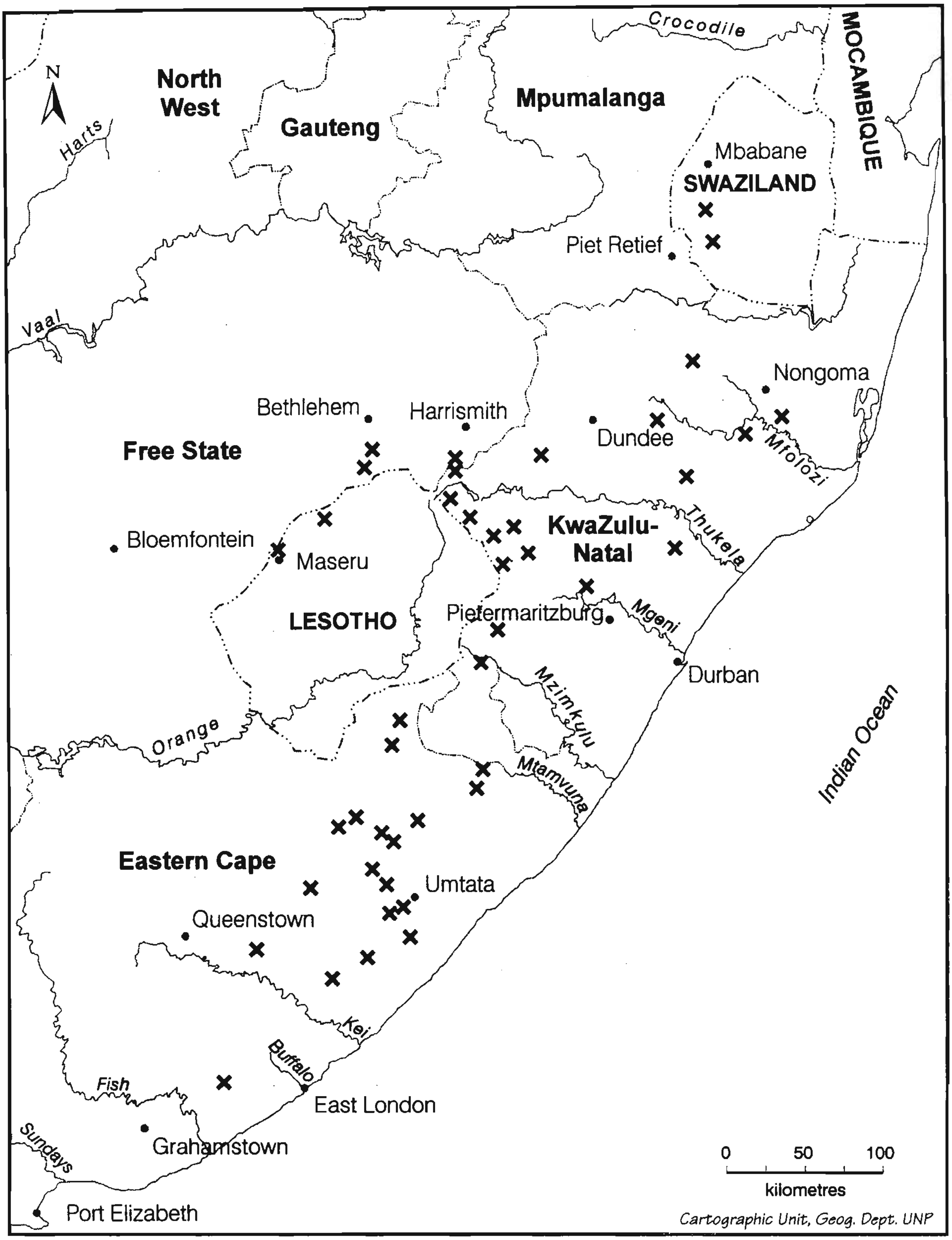


Figure 3.5: Map indicating the locations in eastern southern Africa where piping has either been reported in the literature, or been observed by the author.

Tankard *et al.* (1982) suggest that the following palaeo-environmental conditions prevailed during deposition of the Karoo sequence: as the Dwyka glaciation receded and finally disappeared, the glacial deposits gave way to vast shallow water deposits dominated by upward-coarsening deltaic sequences rich in organic carbon with occasional sand lenses. During the Permo-Triassic period, fluvio-deltaic sedimentation of the Beaufort Group continued into what by then were only a series of individual freshwater lakes of diminishing extent. A further orogenic pulse is seen as the cause also for the clastic sediments characteristic of the Molteno Formation. The Elliot Formation by contrast represents primarily terrestrial sedimentation of alluvial material, whereas the Clarens Formation is interpreted as a low latitude desert environment of dune fields and playa lakes. The Karoo Supergroup thus essentially represents a depositional sequence during a time of progressive aridification. The final phase of the Karoo Supergroup consists of basaltic magma of the Drakensberg Group.

These flood basalts of Jurassic age consist of numerous individual lava flows that were fed by the abundant dyke swarms and sills which have intruded into the underlying lithologies. They have been interpreted as a manifestation of the breakup of Gondwanaland, although vulcanism was initiated at least 20 Ma prior to fragmentation (Scrutton, 1973).

It is significant that, since the fragmentation of Gondwanaland and transgression by the Indian Ocean into the Zululand basin and the Transkei swell during Cretaceous times (Simpson and Dingle, 1973; Cooper, 1990), the south-eastern subcontinent of Africa has been subjected to epeirogenic uplift and seaward tilting in an environment dominated by extensive weathering and erosion (Maud, 1968). Minor accumulations of unlithified alluvial-colluvial sedimentary sequences have occurred in a broadly similar pattern to that of the Masotcheni Formation described by Botha (1992) and Botha *et al.* (1994) for central and northern Natal, although the exact nature of these deposits in Transkei and southern Natal are still unclear.

3.3 Regional Soils

The term 'soil' has many definitions as outlined in Chapter 1. Birkeland (1974) has observed that an engineer (and many geomorphologists) will generally regard soil as all unconsolidated surficial material, whereas a soil scientist will view it primarily as a medium for plant growth. These two views represent the extremes of a spectrum dictated largely by what is useful within a given framework of reference. While not every accumulation of unconsolidated sediment can, nor should, be portrayed as a 'soil', it is necessary within the context of the present study, and in keeping with the approach of researches such as Daniels and Hammer, 1992, to use a broad-based geomorphic interpretation in conjunction with the usual taxonomic reference to soil series because, as will be shown in Chapter Four, the colluvial-alluvial infill within some depressions has a direct bearing on soil pipe development. For ease of reference, the South African binomial soil classification has been used, where possible, together with its international equivalents. This has been undertaken despite the occasional poor match brought about by pedogenesis on originally alluvial-colluvial material that cannot in all cases be classified as a neocutanic B horizon, or where a plinthic horizon has developed as a consequence of secondary chemical action on a pre-existent concentration of molecular iron and manganese oxides.

One of the greatest difficulties in discussing the soils of southern KwaZulu-Natal and Transkei at a general level is the virtual absence of a soils map for the region. Although detailed soil maps are available for some portions of KwaZulu-Natal, the only map available for the complete study area is that produced in 1929, well before the binomial soil classification was introduced for the country. A more recent (but still dated) discussion of the soils is presented by van der Merwe (1962), but again the work is not accompanied by a map of soil distribution.

In broad terms, the soil types vary from lithosols on the Drakensberg basalts, through intrazonal soils of the Drakensberg foothills to the podzolic and duplex soils of the midlands and coastal belt (de Villiers, 1962). Concomitant with this west-east gradation is a general latitudinal zonation, such that soils show both a general shallowing with regard to depth and an increase in sand fraction with increase in latitude. Soils in central Natal tend to be predominantly deep, heavy red loam to sandy loam of low fertility, other than in topographic depressions, where soils tend towards clay loams of moderate to high fertility. Along the Drakensberg foothills soils are light brown to brown or red-brown sandy loams, and are generally deep and fertile. In southern Natal and much of Transkei the soils are shallow, pale brown to grey and red-brown sandy loam. The subsoil tends to be yellowish and display a relative increase in clay content down profile with frequent secondary concretions occurring in the form of plinthic material (van der Merwe, 1962). The latitudinal change alluded to here is, however, mirrored by a general decrease of precipitation, so that care must be taken to guard against any over-simplistic interpretation of a complex multivariate phenomenon (see, for example, the relevant discussion in Buol *et al.,* 1980).

It has been noted by both van der Merwe (1962) and van Wyk (1968) that the podzols of Transkei in particular contain significant quantities of montmorillonite and illite-montmorillonite clays which tend to be active in the presence of water, increasing their propensity for cracking. Soils in the midland regions of KwaZulu-Natal and Transkei grade towards a solonetz and are generally dispersive to a greater or lesser degree (van Wyk, 1968). The occurrence of alluvial-colluvial sedimentary sequences which underlie some of the Natal soils has been addressed by de Villiers (1962) in his extensive treatise on the soils of Natal in which he ascribes these sediments to previous climatic conditions. Such interpretation is supported by the C^{14} dates obtained from paleosols in Transkei (Dardis *et al.*, 1988b, and Dardis, 1989), and by the more recent work of Botha (1992) for Natal. Some uncertainty, however, surrounds the occurrence of plinthic material within the vertical profile of some of the Transkei soils, notably the Longlands (Ultisol) and Wasbank and Valsrivier forms (Inceptisols) and to a lesser extent the Estcourt (Alfisol) soil forms, as these concretions show signs of secondary reworking and stratification. The implication of such reworking is that preweathering and plinth genesis appears to have occurred; the weathered products were then transported and deposited in depressions in a pseudo-pedogenic profile, where the materials have then been subjected to further pedochemical alteration.

3.4 Regional Climate

3.4.1 Mean Temperature Regimes

As would be expected, the mean temperatures closely reflect the altitudinal zonation of the region and range from 11.5°C for Mokhotlong and 13.8°C for Harrismith to 20.0°C for Port St Johns and Durban; a pattern which concurs with the observations of de Villiers (1962). No clear latitudinal variation of temperature can be observed within the region. Mean monthly variation of temperature shows a markedly seasonal pattern with maxima in December-January and minima in June and July. This distribution is in contrast with the maximum recorded temperature for the year, which frequently occurs during the winter months for the midland regions as a consequence of the occurrence of Berg-wind conditions (Preston-Whyte and Tyson, 1988).

3.4.2 Atmospheric Circulation And Wind Phenomena For The Region

Principally the southern KwaZulu-Natal and Transkei region is under the influence of air circulation associated with the fluctuating position of the South Indian Anticyclone in conjunction with the passage of westerly disturbances, as discussed by Preston-Whyte and Tyson (1988). This air movement is responsible for the advection of moisture across the region and, in association with a coastal low, for the adiabatically warmed airflow away from the escarpment in an offshore direction (otherwise known as Berg-winds). These warm, dry winds may blow for several days (Preston-Whyte and Tyson, 1988) and play a significant role in soil moisture depletion and soil desiccation, which is important in the initiation of some forms of subsurface erosion. A mesoscale circulation exists over the region in the absence of a strong synoptic circulation, so that a diurnal airflow of regional and topographically induced winds exists between the

Escarpment and the sea (Preston-Whyte and Tyson, 1988). This airflow is unlikely to have any significant influence on the subsurface erosion, other than in terms of potentially increasing the evapotranspiration rate and hence indirectly contributing to a *slight* decrease in the available moisture.

3.4.3 Precipitation Patterns Over Southern KwaZulu-Natal and Transkei

The mean annual precipitation for South Africa shows a progressive decrease westwards from a maximum of 1250 to 2000 mm pa. along the Drakensberg escarpment to less than 200 mm pa. along the west coast. More pertinent to the present discussion, however, is that the general trend for precipitation for the region *ie.* to the east of the escarpment, again broadly reflects altitudinal and latitudinal zonation, showing a general decrease to the coast, away from the orographic effects of the escarpment and generally lying within the range of 800 to 1250 mm pa. There are, however, individual basins of notably lower precipitation as is seen in Figure 3.6, and from the values in Appendix 1. Specifically, precipitation varies from 575 mm pa. at Mokhotlong on the Lesotho Plateau and 1172 mm pa. for Sani Pass at the base of the escarpment, to 742 mm pa. at Estcourt, 880 mm pa. at Cedara and 1113 mm pa. at Port Shepstone. Latitudinally, values range from 716 mm pa. at Clarens and 986 mm pa. at van Reenen, to 675 mm pa. at Kokstad and 597 mm pa. at Idutywa, to 542 mm pa. at Tsomo.

In considerations involving surficial erosion, rainfall energy is an important contributor to disaggregation processes and therefore to soil erosion as a whole (Morgan, 1986; Hudson, 1981). There is general consensus among researchers (although no unanimity) that the EI_{30} parameter is a good measure of rainfall energy (see, for example, Hudson, 1965; Wischmeier and Smith, 1958; 1978). The EI_{30} parameter may be defined as the product of the kinetic energy of the storm and the greatest average intensity experienced in any 30 minute period, obtained from the storm trace of an autographic rain gauge (Hudson, 1981).

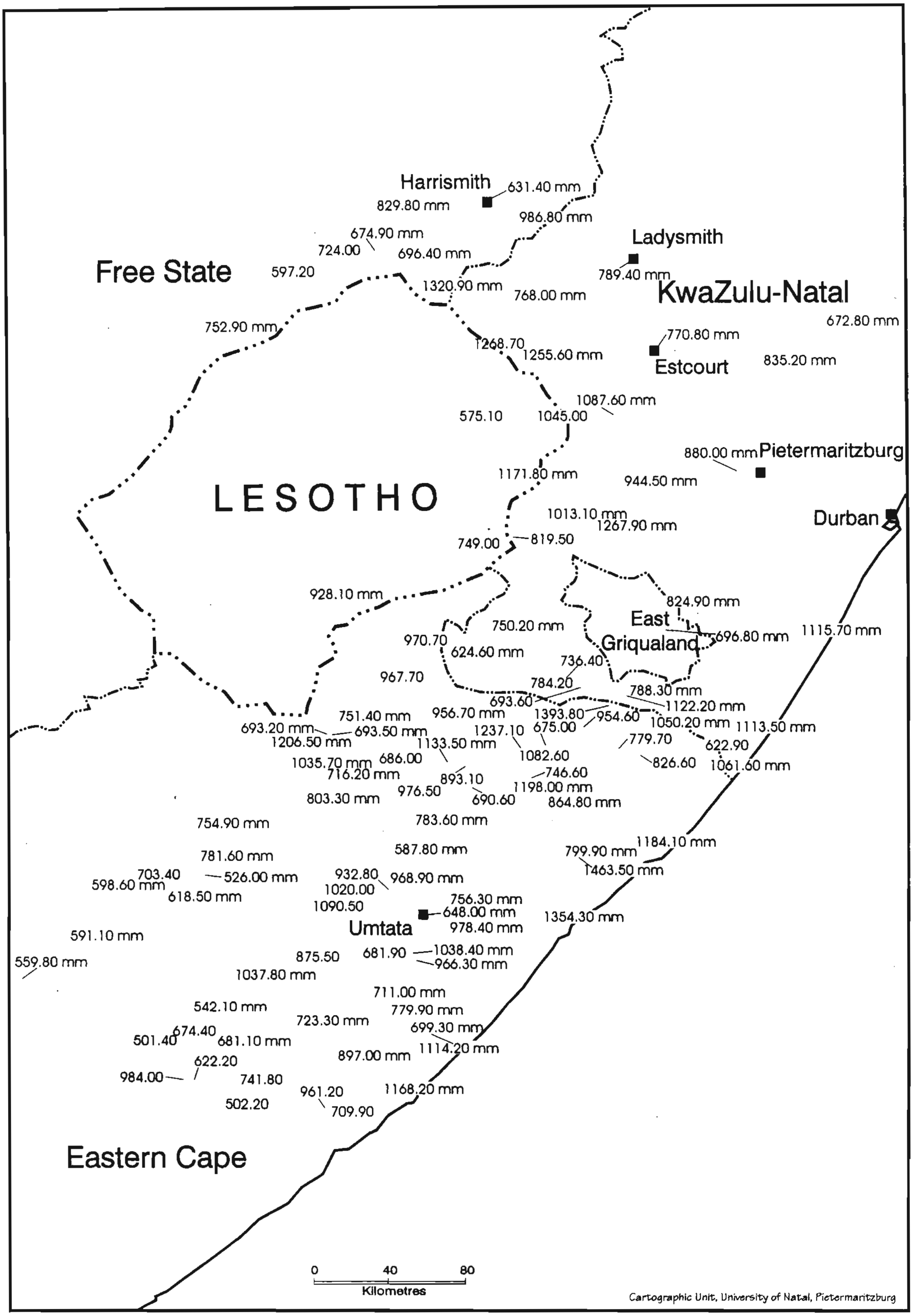


Figure 3.6: The distribution of mean annual precipitation for the region.

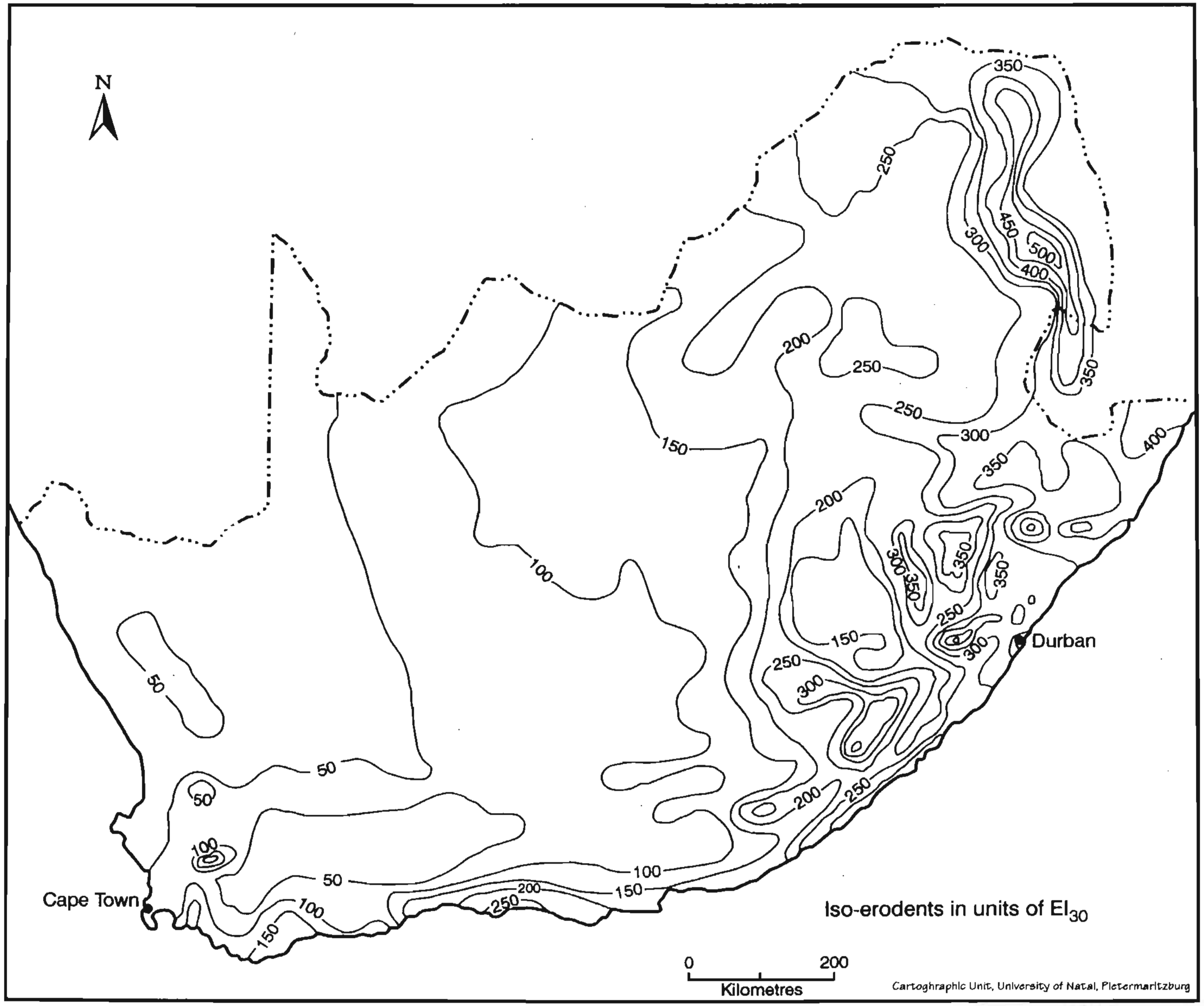


Figure 3.7: Iso-erodent map of southern Africa, showing the distribution of EI_{30} values (after Smithen, 1981)

Where such data are not available, information is obtained by interpolation as indicated in Figure 3.7. These data may be obtained from the Computer Centre for Water Research (CCWR) of the Department of Hydrology, University of Natal, Pietermaritzburg.

While the EI_{30} parameter is decidedly of value within the context of surface erosion, this is not the case with subsurface erosion except possibly in the final stages where partial pipe roof collapse has occurred. It is therefore argued that, although the KwaZulu-Natal-Transkei region has among the highest EI_{30} values in southern Africa (second only to the Mpumalanga region of the escarpment), these values are unlikely to be of great significance within the context of the present discussion as factors such as the infiltration rate and soil permeability are likely to have a more direct bearing on process operation with regard to subsurface erosion phenomena.

3.4.4 Rainfall Seasonality

Several researchers (see *inter alia* Jones, 1981 and Stocking, 1984) have commented on the importance of a seasonal climate to subsurface erosion processes. The seasonal character of the climate mentioned in Section 3.4.1, and specifically of the precipitation, was therefore investigated.

Although harmonic analysis (McGee and Hastenrath, 1966) and directional vectors (McGee, 1977) have been used to classify the climate of the KwaZulu-Natal-Transkei region as seasonal, these methods of analysis are considered inappropriate for the present study. Harmonic analysis has been shown by McGee and Hastenrath (1966) to be useful in objectively describing the spatial distribution of rainfall regimes for South Africa, while the directional vector (or Markham) technique is based on a representation derived from the vector addition of monthly rainfall, weighted in proportion to total mean annual rainfall; if all rainfall were concentrated in a single month, the Seasonality Index would be 100%. The directional vector approach has facilitated a temporal linkage in relation to the time of year during which the rainfall maximum occurs, as illustrated by McGee (1977).

Within the context of subsurface erosion, the seasonal distribution of rainfall during the year is only of potential importance insofar as dry spells are concerned during which desiccation of the soil may occur. Given that the region has been shown to be dominated by summer rainfall (Schumann, 1949; McGee, 1977) it was not necessary to re-analyse the occurrence of rainfall maxima but rather to investigate the seasonal spread of the rainfall. To this end, the Rainfall Distribution Index was calculated for the mean monthly number of rainfall days and for mean monthly rainfall totals as follows:

$$RDI_{D;R} = \frac{\sum_{i=Nov}^{Jan} P_i - \sum_{j=Jun}^{Aug} P_j}{\sum_{i=Nov}^{Jan} P_i + \sum_{j=Jun}^{Aug} P_j} \times 100 \qquad \text{........ Equation 3.4.1}$$

where:

RDI_D and RDI_R are the Rainfall Distribution Indices for mean monthly rainday (D) and mean monthly rainfall (R) totals respectively,

$\sum_{i=Nov}^{Jan} P_i$ is the sum of mean monthly values of *either* rainday (D) *or* rainfall (R) totals for November, December and January, as applicable.

$\sum_{j=Jun}^{Aug} P_j$ is the sum of mean monthly values as for P_i for June, July and August.

The Index therefore measures the relative percentage distribution of *either* summer and winter rainfall (R) *or* raindays (D); the higher the value, the drier on average will be the winters.

The selection of months is based on the definition of summer and winter months as used by McGee (1977). Rainfall statistics of mean monthly rainfall totals for the 109 rainfall stations in the region with a pre-1960 record in excess of 20 years as shown in Figure 3.6, were obtained from the South African Weather Bureau (1965) publication, as data for many of the rainfall stations in Transkei during the period of independence are either unreliable or, more commonly, not available (Stevenson and Associates, 1990). It is noted that, as would be expected, there is a strong correlation between the RDI values for the rainday and rainfall distributions ($r^2 = 0.86$). Despite this correlation, the distributions themselves are significantly different from one another at the 5% level when compared using the Student's t-test.

RDI* values were also computed according to Equation 3.4.2, *viz.,*

$$RDI^{*}_{D;R} = \frac{\sum_{i=Oct}^{Mar} P_i - \sum_{j=Jun}^{Aug} P_j}{T} \times \frac{100}{1} \qquad \text{....... Equation 3.4.2}$$

where: RDI^*_D and RDI^*_R are the Rainfall Distribution Indices for mean monthly rainday (D) and mean monthly rainfall (R) totals respectively, as before

$\sum_{i=Oct}^{Mar} P_i$ is the sum of mean monthly values of *either* rainday (D) *or* Rainfall (R) totals for the months from October to March.

$\sum_{j=Jun}^{Aug} P_j$ is the sum of mean monthly values of *either* raindays (D) *or* Rainfall (R) totals for the months from June to August as before, and

T is the mean annual total for the station (*either* in raindays *or* in total rainfall, as applicable).

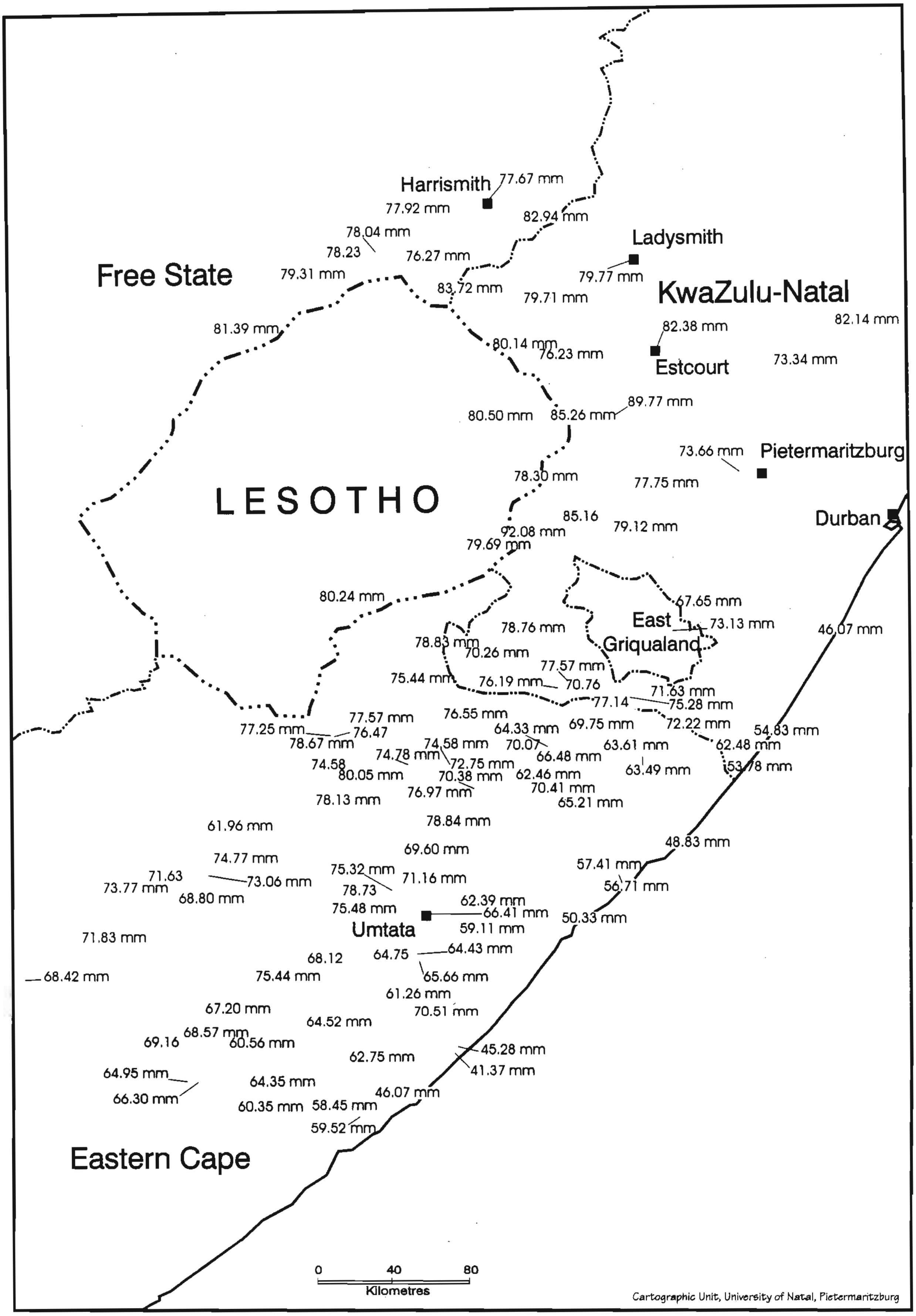


Figure 3.8: The spatial variation of the rainfall index for rainfall data over southern KwaZulu-Natal and Transkei.

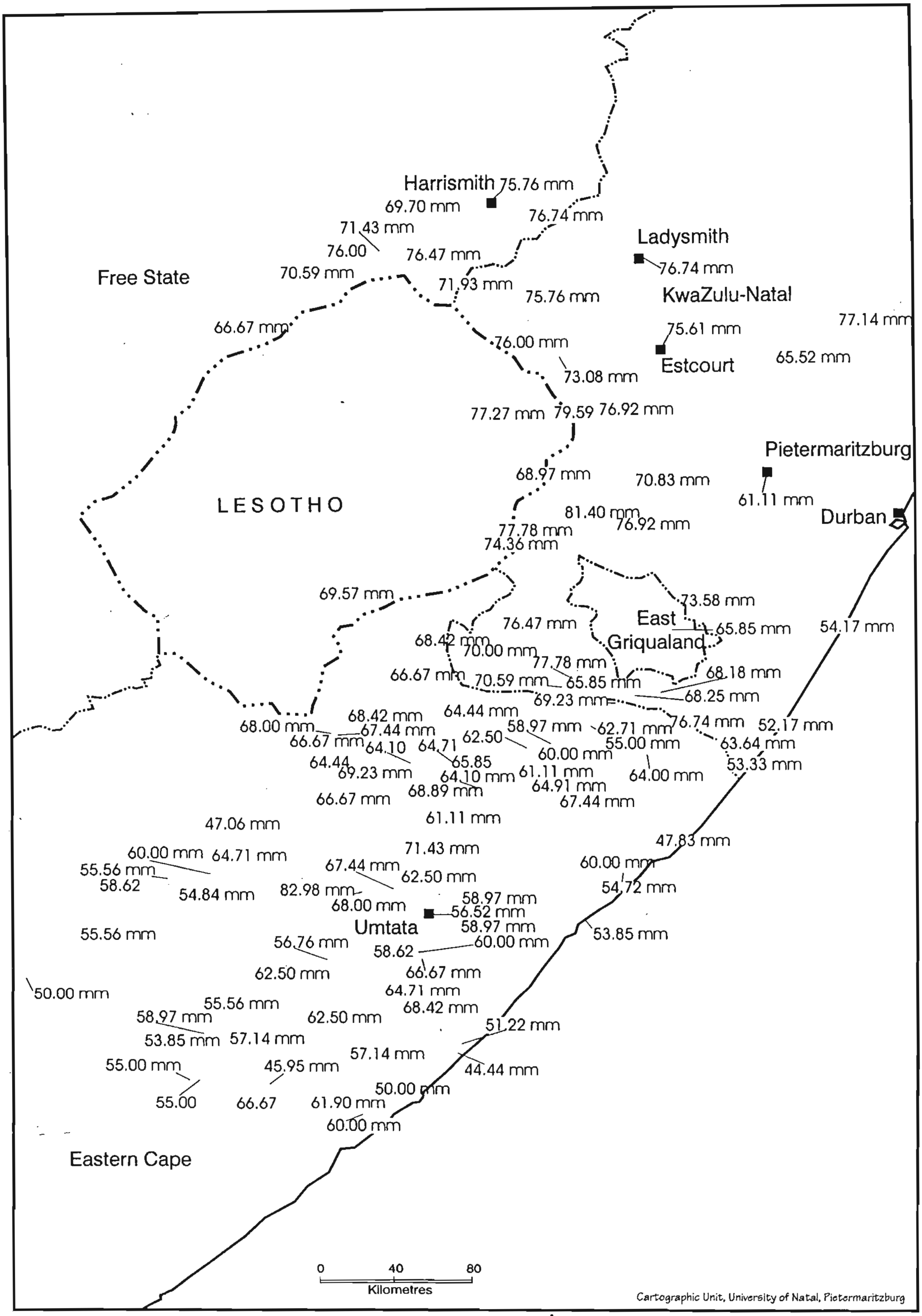


Figure 3.9: Spatial variation of the rainfall index for rainday data over southern KwaZulu-Natal and Transkei.

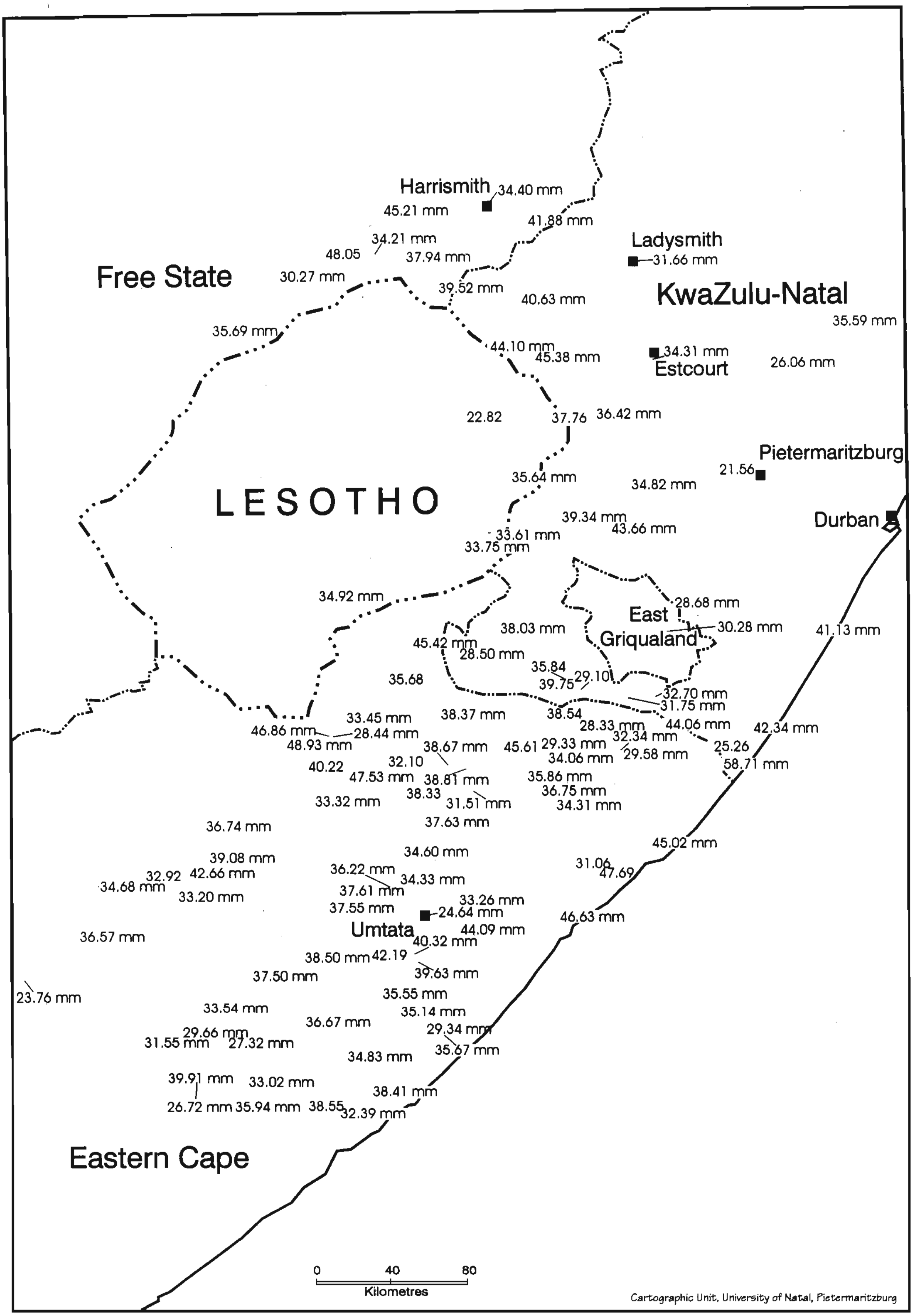


Figure 3.10: Spatial variation of relative rainfall intensity for KwaZulu-Natal and Transkei.

The potential advantage of Equation 3.4.2 is that it allows for a broader spread of rainfall occurrence during the year by also including spring to early summer and late summer to early autumn. Although values for some stations were different, a comparison of the data sets from Equations 3.4.1 and 3.4.2 showed no significant difference at the 5% level on a Student's t-test, and Equation 3.4.1 is therefore retained as the seasons are more clearly defined. The results of the RDI distributions for rainfall and rainday data, as indicated in Figures 3.8 and 3.9 respectively, show a broadly similar pattern to that observed by McGee (1977), namely a decrease in distribution value from the escarpment towards the coast, indicating a broader monthly spread of precipitation at the coast. Although no clear pattern in the distribution of mean annual precipitation (Figure 3.6) is discernible, a general decrease of rainfall amount with increase in latitude may be observed.

3.4.5 Moisture availability

No long-term values on potential moisture availability are available for the region, as even A-pan evaporation values are not consistently available other than for Queenstown, Kokstad, Cedara and Estcourt. Although the ACRU Model 3.00 (*Agricultural Catchments Research Unit Agrohydrological Modelling System,* see Schultze, 1995, and Dent *et al.,* 1988) is capable of estimating soil moisture conditions at a generalised level, it is argued that use of such secondary data would be inappropriate for the present work as it is not possible to link such data back to process genesis with any significant increase in level of confidence beyond that afforded by using the information on relative intensity (defined as the mean annual precipitation divided by the mean annual percentage of days with precipitation) shown in Figure 3.10. It is thus a rough indication of the intensity of the precipitation events when they do occur. This distibution shows broadly similar patterns to those observed previously for the temperature and rainfall distributions, *viz.* a general decrease in moisture availability with increase in latitude and a decrease in moisture from the escarpment towards the coast with a small increase along the coast itself.

A combination of practicality related to the size of the area under consideration, cost (including the real risk of vandalism to equipment) and weather variability has necessitated discontinuing attempts to obtain suitable soil moisture data directly by means of data loggers. This in no way negates the importance of soil moisture as a parameter in the development of subsurface erosion forms.

3.5 Vegetation Patterns

Not surprisingly the vegetation patterns broadly follow the climatic and particularly the moisture regimes, as also observed by Acocks (1953; 1975). Broadly, biomes vary from coastal tropical forest along the coast and inland along the riverine gorges, to temperate transitional forest and scrub to grassveld (Figure 3.11). White (1983) and Meadows (1985) identify a similar pattern with slightly different terminology, ranging from miscellaneous coastal vegetation with evergreen and semi-evergreen bushland in the major river valleys and areas adjacent to these, to undifferentiated afromontane and finally altimontane vegetation along the escarpment, grading to transitional Karoo and Highveld grassland in the south.

Unfortunately, relatively little is known about the vegetation pattern which existed in South Africa during the Pleistocene and Holocene epochs and the more recent past which, as Granger (1984) points out, casts doubt over any attempt to determine acceptable values for contemporary soil loss tolerance. When considering the role of vegetation within the context of subsurface erosion specifically, the situation is still more complex. As suggested in the review presented in Chapter two, although vegetation has a stabilising influence in terms of surface erosion, in the context of subsurface erosion the role may be both positive *and* negative. Vegetation binds the soil and hence adds strength and prevents disaggregation and thus inhibiting transportation. It however also enhances infiltration both by increasing the surface roughness and by providing potential conduits into the soil in the form of root channels, as well as ultimately increasing the organic matter content of the soil and hence increasing the permeability.

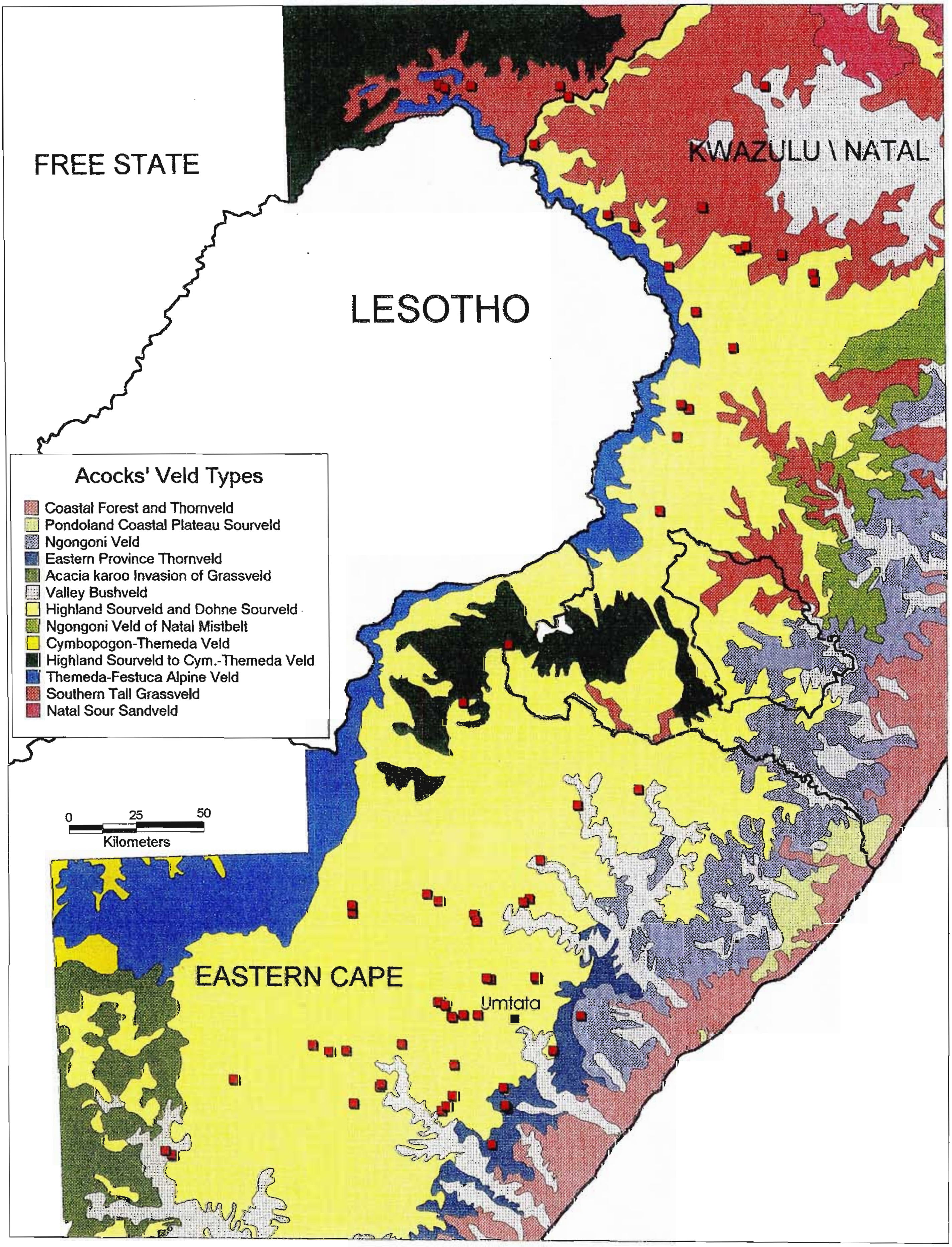


Figure 3.11: Map of Acocks' veld types for KwaZulu-Natal and Transkei, showing the location of the pipe systems analysed.

As is evident from Figure 3.11, the grassveld (and particularly *Themeda* grassveld) is of importance in areas where soil piping has been observed. It is the contention of Tainton (1972) and McKenzie (1982) that several of these climax grasslands are maintained by fire and by selective grazing, leading to veld deterioration and ultimately aiding the erosion processes.

There is little direct evidence which has been found in support of the above contention. Evidence was found to suggest that the Transkei region (specifically in the Tsolo district) has been highly dynamic with regard to sediment mobility during at least the past 200 years or so. This evidence will be discussed in the next chapter.

Chapter 4

4. Subsurface Erosion in Southern KwaZulu - Natal and Transkei

4.1 An Overview

Subsurface erosion, specifically piping, was first reported on duplex soils of the Escourt form (Alfisol - orthic natrustalf) near Mooi River by Henkel *et al.* (1938), who ascribed the erosion to the combined effect of soil shrinkage and the marked difference in permeability between the A and B horizons. The work of Downing (1968) and Beckedahl (1977) concurs with these observations, although climatic seasonality and soil dispersivity were cited as additional important factors triggering the clay activity and resulting in vertical cracks within the soil profile, facilitating the removal of material from the profile itself. Subsurface erosion has been researched in eastern southern Africa on an ongoing basis since the research of Downing (1968), as is evident in the work of, for example, Watson and de Villiers (1968); Beckedahl and Dardis (1988); Dardis and Beckedahl (1988) and Beckedahl (1993a;b). Nonetheless, much of the work is qualitative and highly site-specific in nature. Of the work specifically on piping, it is only the work of Garland and Humphrey, (1992) which reports on values for piping discharge. The work gives very little information on either the morphology of the overall pipe system at Kamberg or on the potential effects (if any) which the retention of the pipe discharge for measurement purposes had on the surrounding pore water pressure.

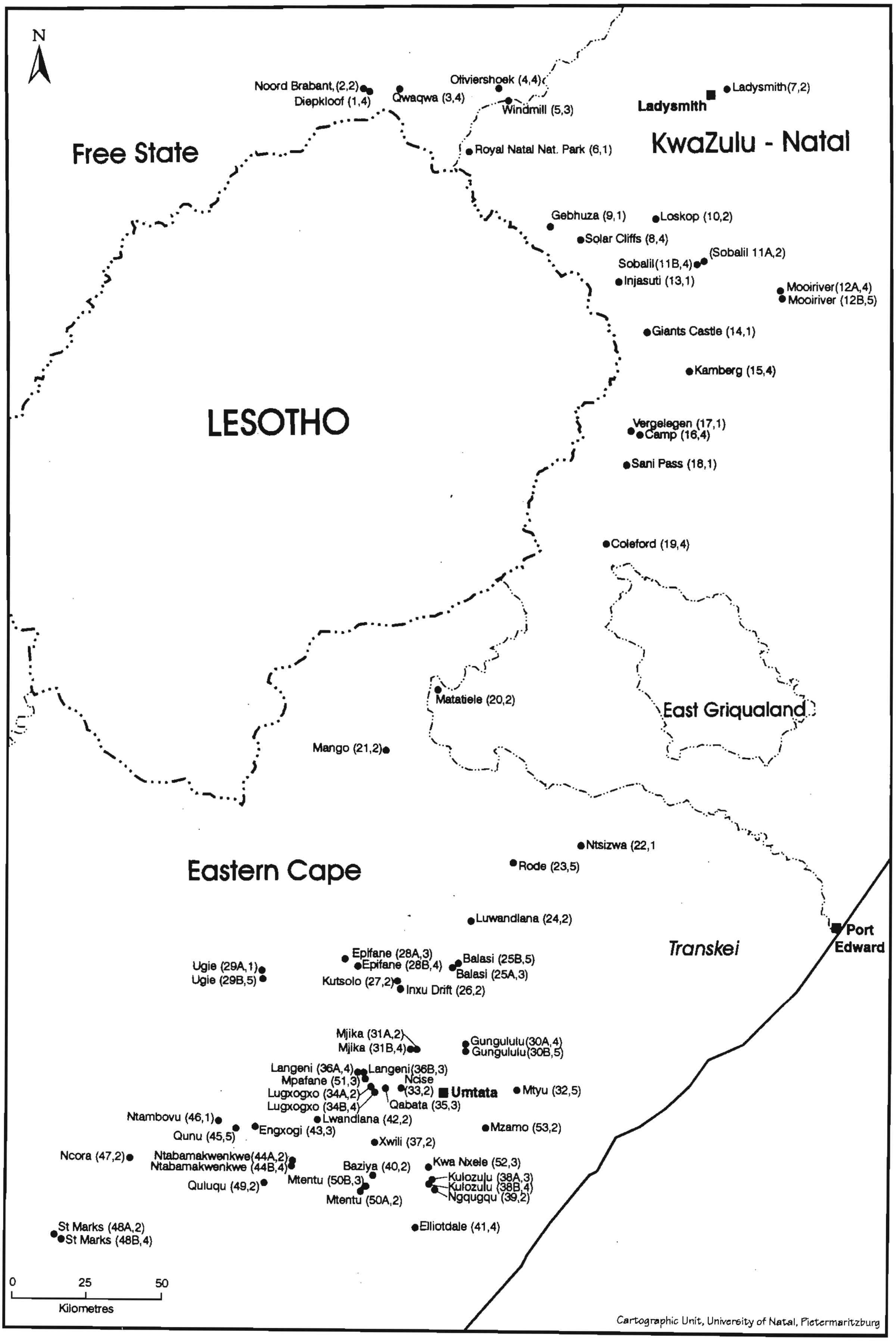


Figure 4.1: General location map of pipes.

Table 4.1: Location and type of piping observed in southern KwaZulu/Natal and Transkei

SITE REFERENCE NUMBER (FIG4.1)	LOCATION	POSITION	PIPING TYPE
1	DIEPKLOOF, GGHNP	VALLEY BOTTOM	IV
2	NOORD BRABANT, GGHNP	M-VALLEY SIDE	II
3	QWA QWA NATIONAL PARK	VALLEY BOTTOM	IV
4	DAM, OLIVIERSHOEK PASS	M-VALLEY SIDE	IV
5	WINDMILL, OLIVIERSHOEK	ROAD CUTTING	III
6	ROYAL NATAL NATIONAL PARK	M-VALLEY SIDE	I
7	LADYSMITH	VALLEY BOTTOM	II
8	SOLAR CLIFFS, CATHEDRAL PEAK RESERVE	L -VALLEY SIDE	IV
9	GEBHUZA, CATHEDRAL PEAK RESERVE	L-VALLEY SIDE	I
10	LOSKOP, ESTCOURT DISTR.	VALLEY BOTTOM	II
11	SOBALIL, ESTCOURT DISTR.	VALLEY BOTTOM	IV; II
12	MOOIRIVER, N3 MOTORWAY	L-VALLEY SIDE	IV; V
13	INJASUTI RESERVE	M-VALLEY SIDE	I
14	GIANTS CASTLE	M-VALLEY SIDE	1
15	KAMBERG RESERVE	L-VALLEY SIDE	IV
16	CAMP, VERGELEGEN RES.	L-VALLEY SIDE	IV
17	VERGELEGEN RESERVE	M- VALLEY SIDE	I
18	SANI PASS	M-VALLEY SIDE	I
19	COLEFORD DISTRICT	M-VALLEY SIDE	V
20	MATATIELE DISTRICT	VALLEY BOTTOM	II
21	MANGO, MATATIELE DISTRICT	VALLEY BOTTOM	II
22	NTSIZWA, Mt AYLIFF DISTRICT	L-VALLEY SIDE	I
23	RODE DISTRICT, MT FRERE	M-VALLEY SIDE	V
24	LUWANDLANA, MT FRERE	L-VALLEY SIDE	II
25	BALASI, QUMBU DISTRICT	M-VALLEY SIDE (CONT. EMBANK.)	V; III
26	INXU DRIFT, TSOLO DISTRICT	VALLEY BOTTOM	II
27	KUTSOLO, TSOLO DISTRICT	VALLEY BOTTOM	II

/CONTINUED: 28 EPIFANE

SITE REFERENCE NUMBER (FIG 4.1)	LOCATION	POSITION	PIPING TYPE
28	EPIFANE, MACLEAR DISTRICT	ROAD EMBANKM. M-VALLEY SIDE	IV; III
29	UGIE DISTRICT	M-VALLEY SIDE	I; V
30	GUNGULULU, TSOLO DISTR.	M-VALLEY SIDE	IV; V
31	MJIKA, UMTATA DISTRICT	VALLEY BOTTOM	IV; II
32	MTYU, LIBODE DISTRICT	M-VALLEY SIDE	V
33	NCISE, UMTATA DISTRICT	VALLEY BOTTOM	II
34	LUGXOGXO, UMTATA DISTR.	M-VALLEY SIDE	IV; II
35	QABATA, UMTATA DISTRICT	ROAD EMBANKM. L-VALLEY SIDE/	III
36	LANGENI FORESTS	ROAD EMBANKM. L-VALLEY SIDE/	IV; III
37	XWILI, UMTATA DISTRICT	VALLEY BOTTOM	II
38	KULOZULU, MQANDULI DIST.	ROAD CULVERT VALLEY HEAD	III; IV
39	NGQUGQU, MQANDULI DIST.	VALLEY BOTTOM	II
40	BAZIYA, ELLIOTDALE DISTR.	VALLEY BOTTOM	II
41	ELLIOTDALE	L-VALLEY SIDE	IV
42	LWANDLANA, UMTATA DIST.	VALLEY BOTTOM	II
43	ENGXOGI, ENGCOBO DISTR.	CONT. EMBANKM. M-VALLEY SIDE	III
44	NTABAMAKWENKWE, CLARKEBURY DISTRICT	L-VALLEY SIDE	IV; II
45	QUNU, ENGCOBO DISTRICT	M-VALLEY SIDE	V
46	NTAMBOVU, ENGCOBO DIST.	M-VALLEY SIDE	I
47	NCORA DISTRICT	VALLEY BOTTOM	II
48	St MARKS DISTRICT	VALLEY BOTTOM	II; IV
49	QULUQU, QUKAMA DISTRICT	VALLEY BOTTOM	II
50	MTENTU DIST, MBASHE RIVER	ROAD EMBANKM. M-VALLEY SIDE	II; III
51	MPAFANE, UMTATA DISTRICT	ROAD CULVERT L-VALLEY SIDE	III; IV
52	KWA NXELE, MQANDULI DIST.	CONT. EMBANKM. M-VALLEY SIDE	III
53	MZAMO, UMTATA DISTRICT	L-VALLEY SIDE	II

The pipe system of Garland and Humphrey (1992) at Karnberg is anomalous when compared with other subsurface erosion reported for southern Africa (see for example Stocking, 1976; Beckedahl *et al.*, 1988; Nordström, 1988) in that the soil within which the system has developed is non-dispersive.

In an attempt to gain a greater insight into the role and significance of subsurface erosion phenomena in eastern southern Africa, 66 subsurface erosion systems were analysed at 53 sites. These were studied in an area stretching from the Golden Gate Highlands and Qwa-Qwa National Parks just beyond the Natal and Orange Free State provincial border through to Tsomo in southern Transkei, and from the base of the Drakensberg escarpment eastwards into the midlands region of KwaZulu-Natal and Transkei, as indicated in Figure 4.1 and summarised in Table 4.1. The 53 sites are thus spread across an area of approximately 40 000 km^2 and were chosen primarily on the basis of accessibility, in that they are within a three hour walking distance of the nearest vehicle track. No claim is therefore made that all subsurface systems within the designated area have been identified here. A further criterion used was to concentrate on already degraded areas, or areas where a change in vegetation pattern suggested the possible existence of a subsurface system. Although the approach used for site selection was expedient, it has the disadvantage that systems in their early stages of development are under-represented within the data set.

In isolated cases enlarged aerial photography proved useful in selecting degraded areas for closer scrutiny, but photographic imagery was generally not found to be suitable for the identification and analysis of subsurface systems, owing primarily to problems of scale - even 'large' systems with pipe segments in excess of 200m are only a few millimetres in length on an enlarged aerial photograph. Once identified, systems were traced by completing a detailed compass traverse through the system where possible, or else by following the directional trend.

More sophisticated techniques such as a `stethoscope-type' system used by Jones (1981), shallow ground-penetrating radar (GPR), (see Jol and Smith, 1993) and resistivity surveys (Ewers, 1972) were investigated; these proved to be inappropriate either due to prohibitive cost (for example the GPR) or because the method is not suited to the ephemeral conditions of irregular discharge (for example Jones' 1981 system), or is too time-consuming for anything other than a very detailed, highly site-specific analysis.

Table 4.2: Dimensional details of soil pipe phenomena in Transkei and southern KwaZulu/Natal.

SITE NO.	SITE LOCATION	PIPE DIMEMSIONS (m)			NO OF PIPES	TYPE OF PIPE	MEAN ROOF THICK-NESS (m)	ESTIMATED VOL. OF SOIL LOST BY PIPING (m^3)		SLOPE UNIT AFFECTED *
		Length	Mean Height	Mean Width				PER PIPE	PER SITE	
1	DIEPKLOOF, GGHNP	30	1.1	1.3	1	IV	0.5	34.32	34.32	2
2	NOORD BRABANT, GGHNP	4	0.3	0.2	2	II	0.6	0.19	0.38	6
3	QWA QWA NATIONAL PARK	125	1.2	0.7	2	IV	0.4	84.0	168.0	6
4	DAM, OLIVIERSHOEK PASS	97	0.8	0.5	2	IV	0.3	31.04	62.08	6
5	WINDMILL, OLIVIERSHOEK	2	0.3	0.1	2	III	0.4	0.05	0.1	CUTTING 5
6	ROYAL NATAL NAT. PARK	14	~ 0.4	~ 0.3	3	I	0.7	1.34	4.03	5
7	LADYSMITH	4	0.4	0.2	2	II	1.1	0.26	0.51	7
8	SOLAR CLIFFS, CATHEDRAL PEAK RESERVE	52	1.2	0.6	1	IV	0.3	29.95	29.95	6
9	GEBHUZA, CATHEDRAL PEAK RESERVE	18	~ 0.3	~ 0.2	1	I	0.5	0.86	0.86	5
10	LOSKOP, ESTCOURT DIST.	3	0.4	0.2	3	II	0.5	0.19	0.58	7
11A	SOBALIL, ESTCOURT DIST.	2	0.3	0.1	3	II	0.6	0.05	0.14	7
11B	SOBALIL, ESTCOURT DIST.	87	0.6	0.4	1	IV	0.4	16.7	16.7	6
12A	MOOIRIVER, N3	45	0.3	0.2	1	IV	0.4	2.16	2.16	2
12B	MOOIRIVER, N3	?	?	?	1	V	?			5
13	iNJASUTI RESERVE	24	~ 0.3	~ 0.2	2	I	0.6	1.15	2.3	5
14	GIANTS CASTLE	16	~ 0.3	~ 0.3	1	I	0.5	1.15	1.15	5
15	KAMBERG RESERVE	37	0.3	0.2	1	IV	0.9	1.78	1.78	6
16	CAMP, VERGELEGEN RES.	136	0.3	0.2	2	IV	0.3	6.53	13.06	6
17	VERGELEGEN RESERVE	31	~ 0.3	~ 0.3	1	I	0.5	2.23	2.23	5
18	SANI PASS	67	~ 0.3	~ 0.3	1	I	0.6	4.82	4.82	5
19	COLEFORD DISTRICT	54	0.3	0.3	1	IV	0.5	3.89	3.89	6
20	MATATIELE DISTRICT	3	0.5	0.3	2	II	1.1	0.36	0.72	7
21	MANGO, MATATIELE DIST.	4	0.5	0.2	4	II	2.1	0.32	1.28	7
22	NTSIZWA, Mt AYLIFF DIST.	24	~ 0.3	~ 0.2	3	I	0.4	1.15	1.15	5
23	RODE DISTRICT, MT FRERE	?	?	?	1	V	?			5
24	LUWANDLANA, MT FRERE	2	0.4	0.2	2	II	0.6	0.13	0.26	7
25A	BALASI, QUMBU DISTRICT	4	0.3	0.2	3	III	0.4	1.25	3.74	CONTOUR 5
25B	BALASI, QUMBU DISTRICT	?	?	?	1	V	?			5
26	INXU DRIFT, TSOLO DIST.	4	0.7	1.2	4	II	2.5	2.69	41.47	

SITE NO.	SITE LOCATION	PIPE DIMENSIONS (m)			NO OF PIPES	TYPE OF PIPE	MEAN ROOF THICK-NESS (m)	ESTIMATED VOL. OF SOIL LOST BY PIPING (m^3)		SLOPE UNIT AFFECTED *
		Length	Mean Height	Mean Width				PER PIPE	PER SITE	
27	KUTSOLO, TSOLO DIST.	5	0.4	0.2	5	II	1.1	0.32	1.6	7
28A	EPIFANE, MACLEAR DIST.	2	0.3	0.1	1	III	0.5	0.05	0.05	CUTTING 5
28B	EPIFANE, MACLEAR DIST.	34	0.4	0.3	1	IV	0.4	3.26	3.26	6
29A	UGIE DISTRICT	21	~0.3	~0.3	1	I	0.4	1.51	1.51	5
29B	UGIE DISTRICT	?	?	?	1	V	?			4
30A	GUNGULULU, TSOLO DIST.	68	0.5	0.3	1	IV	0.4	8.16	8.16	6
30B	GUNGULULU, TSOLO DIST.	?	?	?	2	V	?			4
31A	MJIKA, UMTATA DISTRICT	2	0.3	0.2	4	II	0.7	0.1	0.38	7
31B	MJIKA, UMTATA DISTRICT	56	0.4	0.3	1	IV	0.4	5.38	5.38	6
32	MTYU, LIBODE DISTRICT	?	?	?	1	V	?			5
33	NCISE, UMTATA DISTRICT	3	0.8	0.5	6	II	1.4	0.96	5.76	7
34A	LUGXOGXO, UMTATA DIST.	2	0.4	0.2	4	II	0.5	0.13	0.51	6
34B	LUGXOGXO, UMTATA DIST.	53	0.4	0.3	14	IV	0.4	5.09	71.23	6
35	QABATA, UMTATA DIST.	6	0.6	0.5	4	III	1.3	1.44	5.76	CUTTING 6
36A	LANGENI FORESTS	3	0.4	0.2	3	III	0.6	0.19	0.58	CUTTING 6
36B	LANGENI FORESTS	39	0.5	0.2	1	IV	0.5	3.12	3.12	6
37	XWILI, UMTATA DISTRICT	2	0.3	0.1	2	II	0.6	0.05	0.1	7
38A	KULOZULU, MQANDULI	24	0.3	0.2	1	III	0.3	1.15	1.15	RD DRAIN2
38B	KULOZULU, MQANDULI	26	0.4	0.3	1	IV	0.3	2.5	2.5	2
39	NGQUGQU, MQANDULI	2	0.3	0.2	4	II	0.5	0.1	0.38	7
40	BITYI, ELLIOTDALE DIST.	2	0.4	0.2	3	II	0.6	0.13	0.38	7
41	ELLIOTDALE	58	0.4	0.3	1	IV	0.4	5.57	5.57	6
42	LWANDLANA, ENGCOBO D.	4	0.5	0.4	5	II	0.6	0.64	3.2	7
43	ENGXOGI ENGCOBO DIST.	2	0.3	0.2	2	III	0.4	0.1	0.19	CONTOUR 6
44A	NTABAMAKWENKWE, CLARKEBURY DISTRICT	3	0.3	0.2	2	II	0.7	0.14	0.29	7
44B	NTABAMAKWENKWE, CLARKEBURY DISTRICT	35	0.4	0.3	1	IV	0.4	3.36	3.36	6
45	QUNU, ENGCOBO DISTRICT	?	?	?	1	V	?			4
46	NTAMBOVU, ENGCOBO	17	~0.3	~0.2	1	I	0.6	0.82	0.82	5
47	NCORA DISTRICT	2	0.3	0.2	2	II	0.5	0.12	0.36	7
48A	St MARKS DISTRICT	2	0.3	0.2	2	II	0.6	0.10	0.19	7

SITE NO.	SITE LOCATION	PIPE DIMEMSIONS (m)			NO OF PIPES	TYPE OF PIPE	ROOF THICK-NESS (m)	ESTIMATED VOL. OF SOIL LOST BY PIPING (m^3)		SLOPE UNIT AFFECTED *
		Length	Height	Width				PER PIPE	PER SITE	
48B	St MARKS DISTRICT	24	0.3	0.2	1	IV	0.4	1.44	1.44	6
49	QULUQU, QOKAMA DIST.	2	0.4	0.3	3	II	0.6	0.19	0.58	7
50A	MTENTU DISTRICT, MBASHE RIVER	2	0.3	0.2	3	II	0.7	0.1	0.19	7
50B	MTENTU DISTRICT, MBASHE RIVER	2	0.3	0.1	2	III	0.9	0.05	0.1	CUTTING 6
51	MPAFANE, UMTATA DIST.	22	0.5	0.2	1	III	0.4	1.76	1.76	RD DRAIN 6
52	KWA NXELE, MQANDULI	2	0.3	0.1	1	III	0.9	0.05	0.05	CUTTING 6
53	MZAMO, UMTATA DISTRICT	2	0.3	0.1	3	II	1.2	0.05	0.14	7

* after the work of Dalrymple, Blong and Conacher (1968) and Jones (1981).

The time constraint is particularly pertinent in the use of resistivity surveys and, even if the time implication is accepted, serious doubt exists as to whether the survey would identify small pipes with a diameter less than 0.4m, especially where these were in excess of 1.5m below ground.

4.2 Pipe Morphology

The morphological parameters of length, height, width and roof thickness were measured in each of the 66 systems. Measurements were taken at the in- and outlet of pipe sections and at 10m intervals. Mean values were then calculated. Only pipe sections longer than 1.5m were considered in the analysis so as to distinguish between a soil pipe and what is generally considered a 'soil arch' (Bryan and Yair, 1982). Further, the position of pipes within the landscape was noted. Where roof collapse has occurred over a distance of more than 5m the next roofed pipe section, although still classified as part of the same overall system, was deemed to be a new pipe. On this basis a total of 148 soil pipes were monitored in the course of the present study, as shown by Table 4.2.

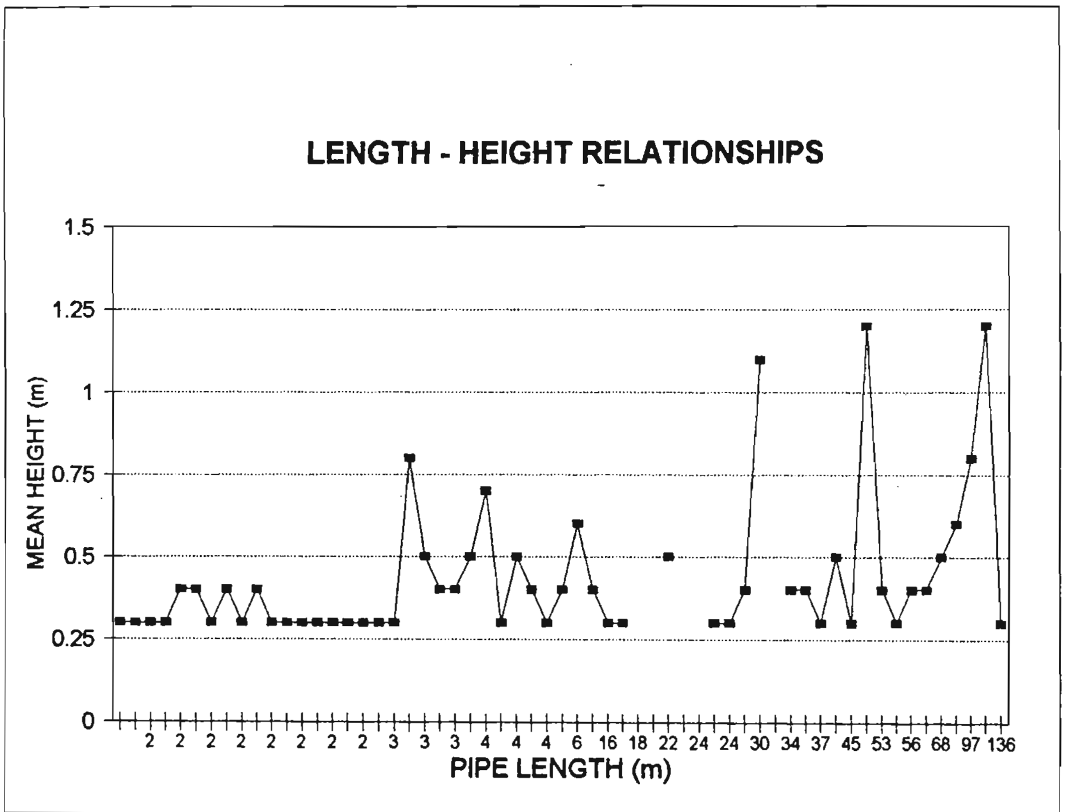


Figure 4.2(a): Mean height plotted against ranked pipe length.

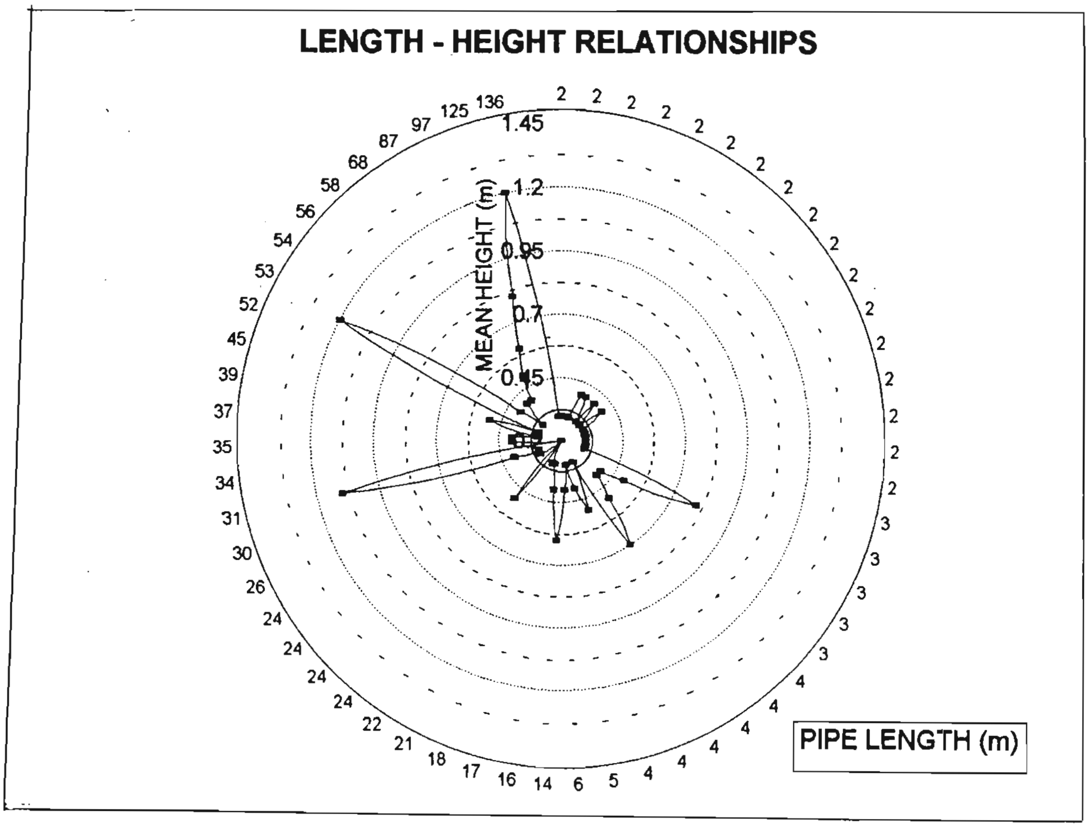


Figure 4.2(b): Circular plot of the same data as in Figure 4.2(a).

In order to investigate any morphological relationships which may exist, the correlation between pipe length and mean pipe height was calculated and found to be r = 0.4, suggesting a weak relationship of increasing height with increasing length. This pattern is also evident when the data are represented graphically as in Figure 4.2(a) in which mean height are plotted against ranked values of pipe length. Figure 4.2(b) represents the same data, but on a circular plot in which the ranked pipe length for systems are plotted along the circumference of a circle and the mean height is represented as proportional to the radius of the circle. As is evident from Figure 4.2(b), the greater values of mean pipe length are concentrated in the fourth quadrant of the circle, whereas the smallest mean height values predominate in the first quadrant and corresponds to the shortest pipe lengths.

When the data for pipe width are analysed relative to ranked pipe length, a correlation of only r = 0.25 is observed, suggesting a very weak relationship. This relationship is seen graphically Figure 4.3, in which large mean width values are observed in the second and third quadrants or intermediate values of pipe length. The correlation of mean width *vs.* mean height shows a high value of r = 0.8. In the light of the other two correlations cited, this value is important. Although the relationship between height and width is as would be expected with a pipe approximating to a roughly circular cross-section, the fact that the correlations of height *vs* length and width *vs* length differ markedly from one another suggests that the controls on cross-sectional morphology are complex. This is also evident from the graphical representation of height *vs* width in Figure 4.4 which shows a large degree of variance. In a significant number of cases field observations of pipe cross-sections were not found to approximate to a circular form, but rather to increase in width towards the base of the pipe, thus approximating a roughly triangular shape as indicated in Figure 4.5. The reasons for this will be discussed in Chapter 5.

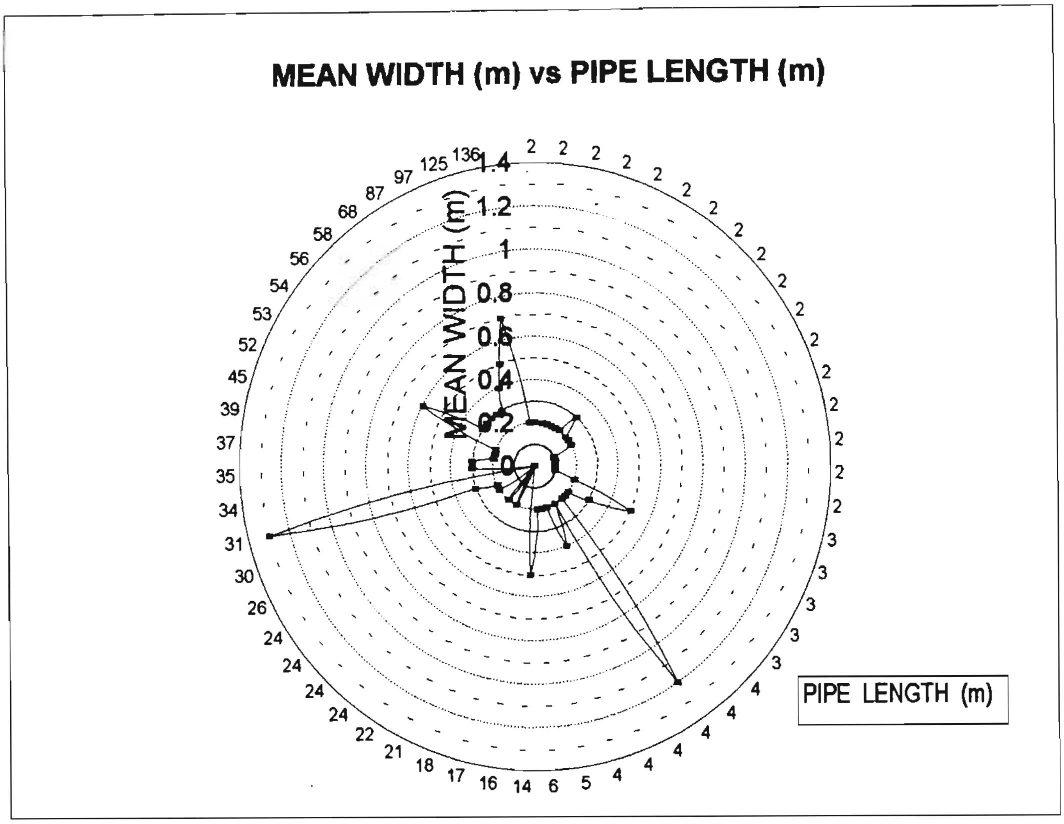


Figure 4.3: Circular representation of mean width *vs* pipe length.

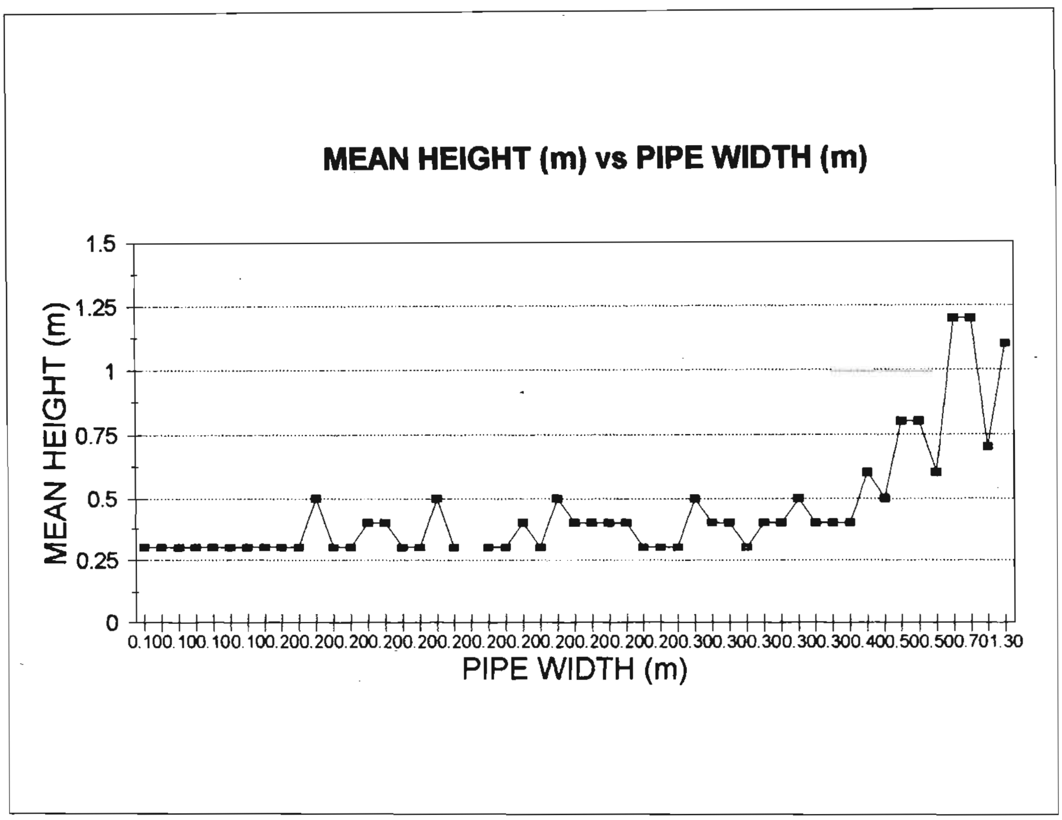


Figure 4.4: Plot of height *vs* pipe width.

Figure 4.5: Photograph of the interior of one of the soil pipes at Qabata, Transkei, showing the triangular cross-sectional shape.

4.3 Classification of Observed Subsurface Erosion

On the strength of the interdependencies between pipe length, mean width and mean height as well as on the strength of field and laboratory observations, the 66 subsurface erosion systems analysed were grouped into the following five categories:

Type 1: Irregular pipes found in the proximity of scree slopes in non-dispersive soils;

Type 2: Gully sidewall pipes;

Type 3: Anthropogenically - related soil pipe systems;

Type 4: Conventional soil pipes similar to those most frequently cited in the literature. These systems are commonly associated with dispersive soils and/or soils containing smectitic clays.

Type 5: Systems identifiable as zones of subsurface water movement and associated sediment loss. These may be micro-pipes and are not identifiable as soil pipes but rather as seepage zones in the field. It is the seepage which frequently draws attention to a specific site in the first instance in contrast to partial roof collapse in each of the other four systems.

Morphologically variations in pipe length were the most noticeable among the data set of 148 pipes, as indicated in Table 4.3:

Table 4.3: Descriptive statistics of the morphological parameters for 148 soil pipes.

MORPHOLOGY \ STATISTIC	STANDARD DEVIATION	VARIANCE	SKEWNESS	MAXIMUM	MINIMUM
SYSTEM LENGTH (m)	30.9	9.56	1.87	136	2
MEAN PIPE HEIGHT (m)	0.24	0.06	1.55	2.2	0.3
MEAN PIPE WIDTH (m)	0.24	0.06	2.68	1.3	0.1
MEAN ROOF THICKNESS (m)	0.44	0.19	2.33	2.5	0.2

In order to investigate the validity of the proposed classification, a graph of pipe length *vs.* type was plotted (Figure 4.6). This graph shows that the Type 1 systems are comparable to one another; the Type 2 systems form a distinct group and, although group 4 shows a large degree of scatter, the values are clearly greater than for the other groups. Type 3 is anomalous in the high degree of variance evident within that grouping. The apparent distinction between the four types is also evident from Table 4.4, showing mean morphological values according to type of subsurface system.

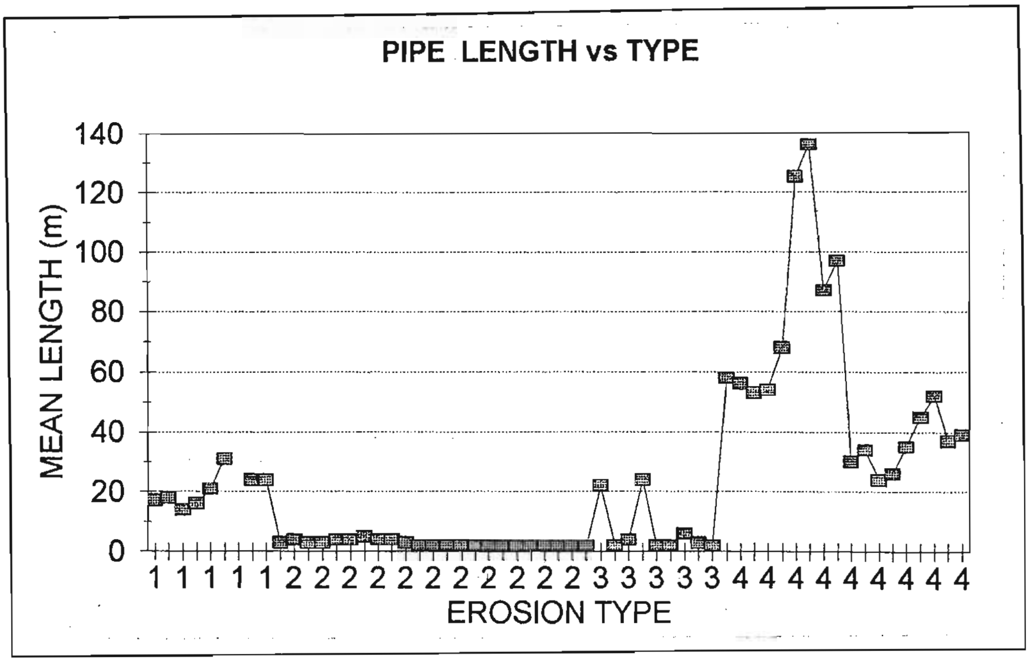


Figure 4.6: Plot of pipe length *vs* type of subsurface erosion system.

Table 4.4: Mean morphological values according to type of subsurface erosion system.

PARAMETER / TYPE	MEAN LENGTH (m)	MEAN WIDTH (m)	MEAN HEIGHT (m)	MEAN ROOF THICKNESS (m)	NO. PIPES PER TYPE
TYPE 1	25.8	0.28	0.35	0.5	9
TYPE 2	2.7	0.31	0.42	0.9	22
TYPE 3	9.1	0.33	0.34	0.6	10
TYPE 4	58.7	0.38	0.48	0.4	18

Type 5 is not reflected in Figure 4.6 nor in Table 4.4 as there are insufficient reliable data - the systems being too small to analyse from within the specific pipe.

A number of tracing techniques (specifically the use of dyes; radioactive tracer substances; chemical salts; and suspended matter - polypropylene particles or plant spores) were investigated in the hope of being able to trace the individual seepage systems reliably, but this was not successful. The difficulties encountered centre around meeting the criteria given by Drew and Smith (1969), *viz.* that with these systems specifically, the tracers should be unaffected by the water filtering through macro pores in the ground; should not be offensive nor environmentally objectionable, and particularly the technique should be relatively inexpensive and should not require continuous monitoring. The Type 5 category of subsurface erosion is thus a qualitative rather than quantitative grouping in which the values of mean width and mean height are best approximations and are not obtained with the same rigour as for the remaining data set.

In order to understand the properties of the individual types of subsurface erosion, the individual data sets were subjected to further statistical analysis.

4.4 Analysis of Variance

Further investigation of the statistical justification for the classification of subsurface erosion into five morphological types was undertaken using Analysis of Variance, and Student's t-tests were applied to the data set of the 148 subsurface systems. The following three parameters were used as diagnostic criteria:

- mean roof thickness
- pipe length, and
- estimated volumetric soil loss.

These criteria were selected for the following reasons:

i) Mean roof thickness is a reflection of the depth of the pipe system which, as may be seen from Table 4.3, varies greatly and may well be a reflection of differences in genesis of the system.

ii) Pipe length is interpreted as a good indicator of the overall linear extent of the system as suggested by the data in Table 4.4, and is again a potential indicator of the origin of the system.

iii) The estimated volume of soil lost per pipe multiplied by sa factor of 0.8 to provide a conservative estimate by allowing for internal pipe irregularities, representing the product of mean height, mean width and length of each pipe, is a crude measure of the actual size of the individual pipe. Volumetric soil loss has been used in preference to either mean height or mean width because of the relatively poor trends evident in the preliminary analyses discussed in conjunction with Figures 4.3 and 4.4, despite the recognition that volumetric soil loss is a very rough measure in that it does not take cognisance of the irregular cross-sectional form of the soil pipes.

As has already been emphasized, the Type 5 class has been derived from deduction based on morphology and is therefore largely excluded from the present analysis. An Analysis of Variance test was conducted for values of mean roof thickness, pipe length and volumetric soil loss, subdivided according to type of subsurface erosion. Subsequently a *'matrix of difference'* was compiled, based on the results of Student's t-tests for the difference between subsurface erosion types calculated at the 5% level - the most widely used level of confidence testing in the earth sciences (Davis, 1973). This methodology was used as Chi-squared testing was inappropriate given the unequal populations of the four different types of pipe systems being considered as well as the complexity of interactions that exist within soil geomorphic and soil erosion-landscape geomorphology systems (Knuepfer and McFadden, 1990). The one-to-one method of analysis was also deemed preferable to, for example, Principal Components or Factor Analysis as, according to Davis (1973), it is not always possible to ascribe reliable meaning to variables determined by these techniques with confidence when small samples are used. Such consideration is of particular importance in the present study, given the small populations of most of the subsurface erosion Type-classes observed.

Table 4.5: Student's *t* values of statistical difference in type of soil pipe based on pipe roof thickness at the 5% level. Critical *t* values are indicated in brackets.

TYPE	TYPE 1	TYPE 2	TYPE 3	TYPE 4
TYPE 1				
TYPE 2	-3.15 (2.01)			
TYPE 3	1.74 (2.01)	1.62 (2.01)		
TYPE 4	2.13 (2.08)	3.[illegible] (2.07)	1.87 (2.26)	

Table 4.6: Interpretation of Student's *t* values of statistical difference in type of soil pipe based on pipe roof thickness as shown in Table 4.5.

TYPE	TYPE 1	TYPE 2	TYPE 3	TYPE 4
TYPE 1				
TYPE 2	YES			
TYPE 3	NO	NO		
TYPE 4	YES	YES	NO	

4.4.1 Pipe Roof Thickness

An Analysis of Variance for mean pipe roof thickness gives an *F* value of 15.13, whereas the $F_{critical}$ value for 'between groups' is 2.71. These values may be interpreted as indicating that the four types of subsurface erosion, based on 59 systems, can be distinguished on the basis of pipe roof thickness. Testing the respective types of subsurface erosion against one another for significant difference yields the data for Table 4.5. Values for '*t*' are indicated relative to the respective critical values for a two-tailed *t*-test at the 5% level, as indicated in brackets. The interpretation of these values is given in Table 4.6. These results indicate that although Type 1, 2 and 4 are different from one another, the pipe systems in Type 3 (anthropogenically-induced erosion systems) may not be distinguished from the other type-systems using the criterion of pipe roof thickness.

4.4.2 Pipe Length

On conducting an Analysis of Variance for pipe length according to the four types, an *F* - value of 23.09 is obtained relative to an $F_{critical}$ value of 2.71. The 'between group' variance is thus greater than the variance which exists within groups, indicating that the groups (or types) differ from one another. When the values of pipe length are compared for the four types of systems, Table 4.7(a) is obtained. The values may be interpreted as supporting the hypothesis that, with the exception of Type 3, the systems in each Type are significantly different from one another, as indicated by Table 4.7(b). It is evident that Type 3 is itself distinct from the other types of subsurface erosion with the exception of Type 2. Some degree of commonality may therefore exist between anthropogenically-related pipe erosion and gully sidewall piping. This commonality will be discussed further in Chapter 5.

Table 4.7(a): Student's *t* values of statistical difference in type of soil pipe based on pipe length at the 5% level. Critical *t* values are indicated in brackets.

TYPE	TYPE 1	TYPE 2	TYPE 3	TYPE 4
TYPE 1				
TYPE 2	4.23 (3.36)			
TYPE 3	2.63 (2.16)	2.63 (3.01)		
TYPE 4	-3.49 (2.79)	-7.26 (2.90)	-5.92 (2.82)	

Table 4.7(b): Interpretation of Student's *t* values of statistical difference in type of soil pipe based on pipe length as shown in Table 4.7(a).

TYPE	TYPE 1	TYPE 2	TYPE 3	TYPE 4
TYPE 1				
TYPE 2	YES			
TYPE 3	YES	NO		
TYPE 4	YES	YES	YES	

Table 4.8(a): Student's *t* values of statistical difference in type of soil pipe based on estimated volumetric soil loss at the 5% level. Critical *t* values are indicated in brackets.

TYPE	TYPE 1	TYPE 2	TYPE 3	TYPE 4
TYPE 1				
TYPE 2	3.07 (2.26)			
TYPE 3	2.61 (2.26)	0.19 (2.05)		
TYPE 4	-2.21 (2.12)	-2.37 (2.12)	-2.71 (2.11)	

Table 4.8(b): Interpretation of Student's *t* values of statistical difference in type of soil pipe based on estimated volumetric soil loss as shown in Table 4.8(a).

TYPE	TYPE 1	TYPE 2	TYPE 3	TYPE 4
TYPE 1				
TYPE 2	YES			
TYPE 3	YES	NO		
TYPE 4	YES	YES	YES	

4.4.3 Volumetric Soil Loss per Pipe

Analysis of Variance again gives a larger F than $F_{critical}$ value (6.92 and 2.71 respectively). As before, this is seen as indicating that the types of subsurface erosion identified are distinct. The '*matrix of difference*' shown in Table 4.8(a) may be interpreted in a similar manner to Table 4.7(a), such that Tables 4.7(b) and 4.8(b) are identical and must therefore be interpreted as indicating the same result. Although it is possible to subdivide the Type 3 subsurface erosion into two subcategories (namely systems associated with road embankments and those subsurface systems associated with the artificial concentration of water on the surface of the soil) such a subdivision results in only two systems falling within one of the subcategories. As a consequence, the statistical reliability of such a subdivision is highly questionable and the line of analysis has therefore not been pursued. Subdivision of Type 3 such as that proposed may, however, elucidate further the potential erosion risk associated with human influence on the soil system and is therefore worthy of future research, provided that data from more systems become available to increase the statistical reliability of the results obtained.

4.4.4 Spatial Considerations and Subsurface Erosion within the Landscape

In an effort to establish causal relationships between landscape forming processes and subsurface erosion, the recommendation to identify the slope unit on which the erosion occurs (see Jones, 1981;1990), was adopted. Within the present work, the individual slope unit is defined as a slope segment of quasi-uniform meso-scale slope angle and having similar conditions of lithology, microclimate and process operation. The work follows the principles and nomenclature of the Nine Unit Landscape Model (NULM) of Dalrymple, Blong and Conacher (1968) and Conacher and Dalrymple (1977). The relationship between slope unit and each subsurface system is summarised in Table 4.4 and Figure 4.7. From this work, it is evident that certain types of system are restricted to specific slope units within the NULM. In general, the observations concur with the findings of Jones (1981) in that piping occurs preferentially on units 2,5,6 and 7.

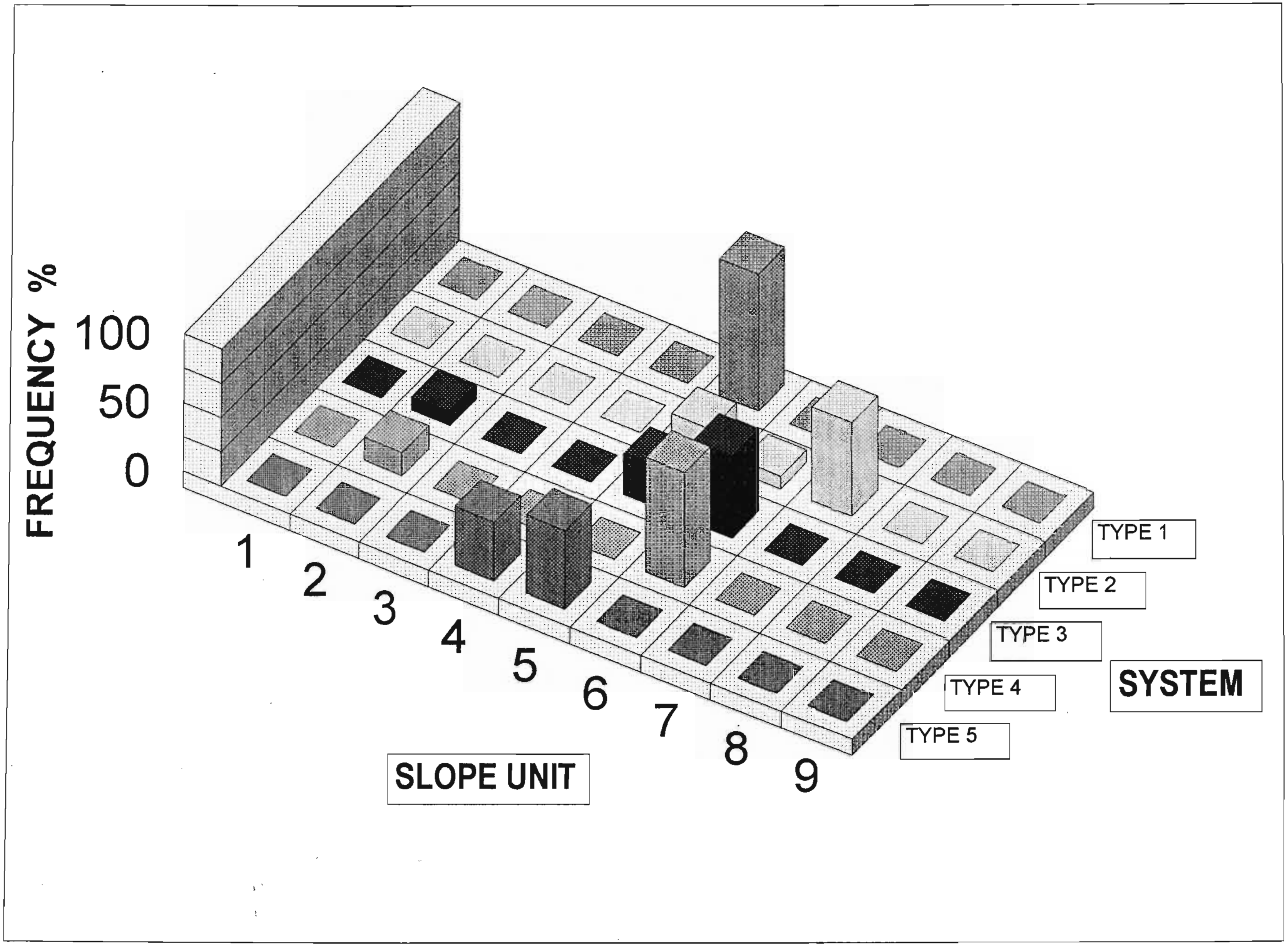


Figure 4.7: The relationship between the type of subsurface erosion system and the slope unit, based on the nomenclature of the Nine Unit Landscape Model of Blong and Conacher (1977)

Of significance is that Type 1 systems are only observed on unit 5 whereas Type 5 systems are restricted to units 4 and 5. It is argued that this correlation is a reflection of the morphogenetic processes characteristic of the respective landscape units; these processes are then interpreted as contributing directly to the particular subsurface system(s). For types 2, 3 and 4, the same principle still holds, but the situation is more complex. These interdependancies with slope process will be discussed further in Chapter 6.

An attempt was initially made to relate the type of subsurface erosion system to slope unit angle, but was abandoned when it became clear that the degree of variance is such that no pattern would emerge. The lack of correlation between slope angle and type of subsurface erosion may be explained by the high variability of submeso-scale relief and by the fact that several of the subsurface systems are of relatively limited extent. It is further argued that slope angle is only one of the determinants of prevailing morphogenetic process. Analysis of slope angle in isolation ignores variation in factors such as aspect, vegetation, time, substrate material and permeability; by contrast, use of the NULM is a more process-based approach, albeit less directly quantitative.

The aforegoing discussion has shown that morphological criteria may be used successfully to classify subsurface erosion forms into five types with an acceptable level of statistical confidence. In order to understand their characteristics and genesis, each of the five types will be discussed in detail by making use of representative case studies. This is the focus of the next Chapter.

Chapter 5

5. Case Studies of the Subsurface Erosion Systems

The data analysis presented in Chapter 4 has validated the initial subdivision of the 66 systems of subsurface erosion presented in Table 4.1 into five types, based primarily on morphological criteria. The distribution of systems within each type is shown in Table 5.1. The characteristics of the respective types of subsurface erosion were investigated by selecting representative case studies.

Table 5.1: Distribution of subsurface erosion by type for the present study.

TYPE / NATURE	1 SCREE SLOPE PIPING	2 GULLY SIDEWALL SYSTEMS	3 HUMAN INDUCED SYSTEMS	4 SYSTEMS IN DISPERSIVE SOILS	5 SEEPAGE SYSTEMS	TOTAL
NO OF SYSTEMS	9	22	10	18	7	66
INDIVIDUAL PIPES	14	71	20	35	8	148
PIPES PER SYSTEM	1.6	3.2	2.0	1.9	1.1	***

For each of the representative sites shown in Figure 5.1, geotechnical, soil-physical, soil-chemical and soil-hydrological parameters were determined. Theoretical values for soil erodibility based on the K-value of Wischmeier *et al.* (1971), were calculated using the nomograph as outlined in the Appendix. This approach was used despite the call for caution by Bergesma and Valenzuela (1981), who found that where the nomograph is used outside of the United States the potential for inaccuracies to occur increases, probably due to the poorer availability of data. The nomograph was used as it was not possible to determine the K-values empirically in the absence of sufficient standardised runoff plots within the study area. The K-value represents an

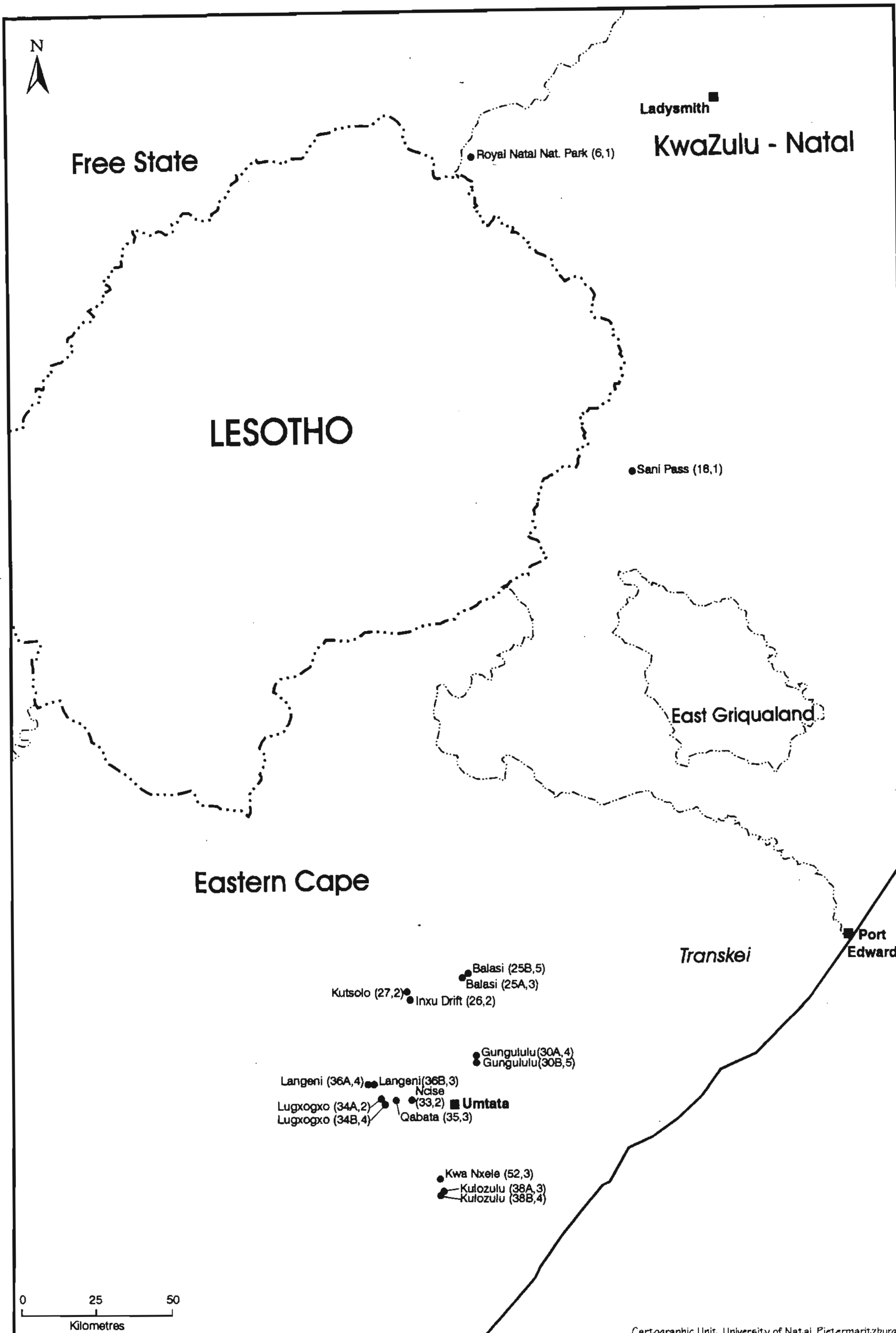


Figure 5.1: Location of representative field sites for the different types of subsurface erosion

approximate index of the susceptibility of a soil to wash-erosion, as it provides a measure of commonality and thereby facilitates a comparison of the different soils. It is emphasized, however, that the K-values are of limited direct applicability and should only be used in a comparative sense in this study as the parameter itself is not designed for conditions of subsurface flow and should thus not be transposed into a different context until it has been suitably validated.

5.1 Type I: Scree-slope Piping

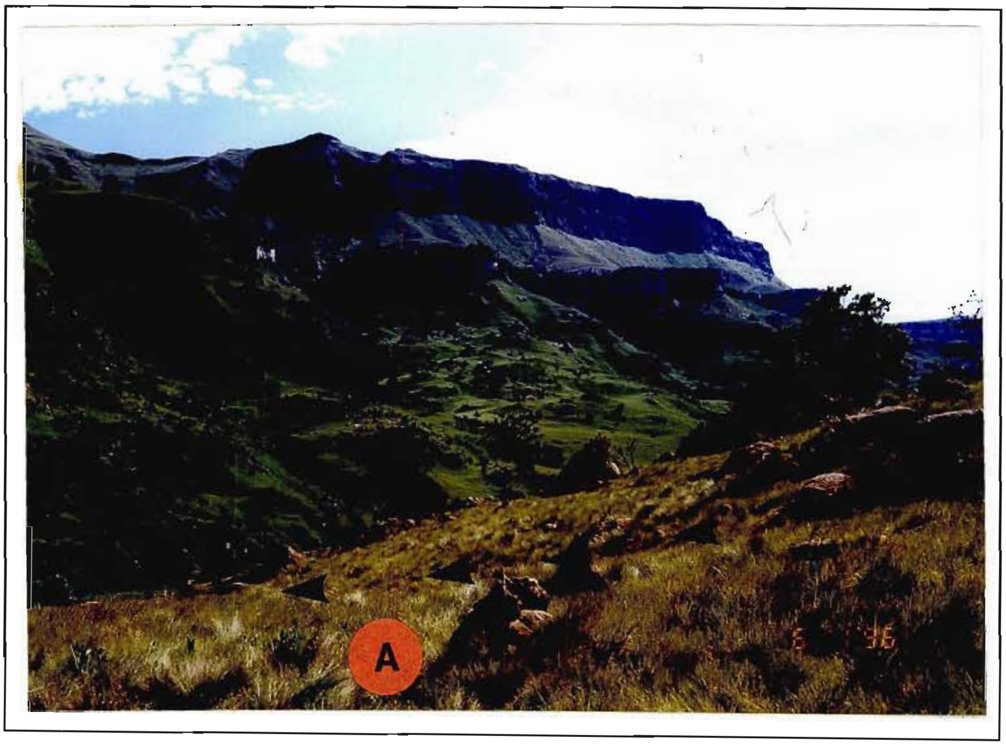


Figure 5.1.1: The position of the Sani Pass Pipe (indicated by broken lineat A) on the transportational midslope.

These systems are invariably associated with slope unit 5 - the transportational midslope of Conacher and Dalrymple's (1977) Nine Unit Landscape Model (Figure 5.1.1). The piping is highly irregular (as illustrated by Figure 5.1.2) and occurs where a soil has developed on a semi-stable to stable, coarse scree deposit. As far as could be ascertained without the use of tracer substances, it is evident from Figure 5.1.2 that the systems are generally linear in extent.

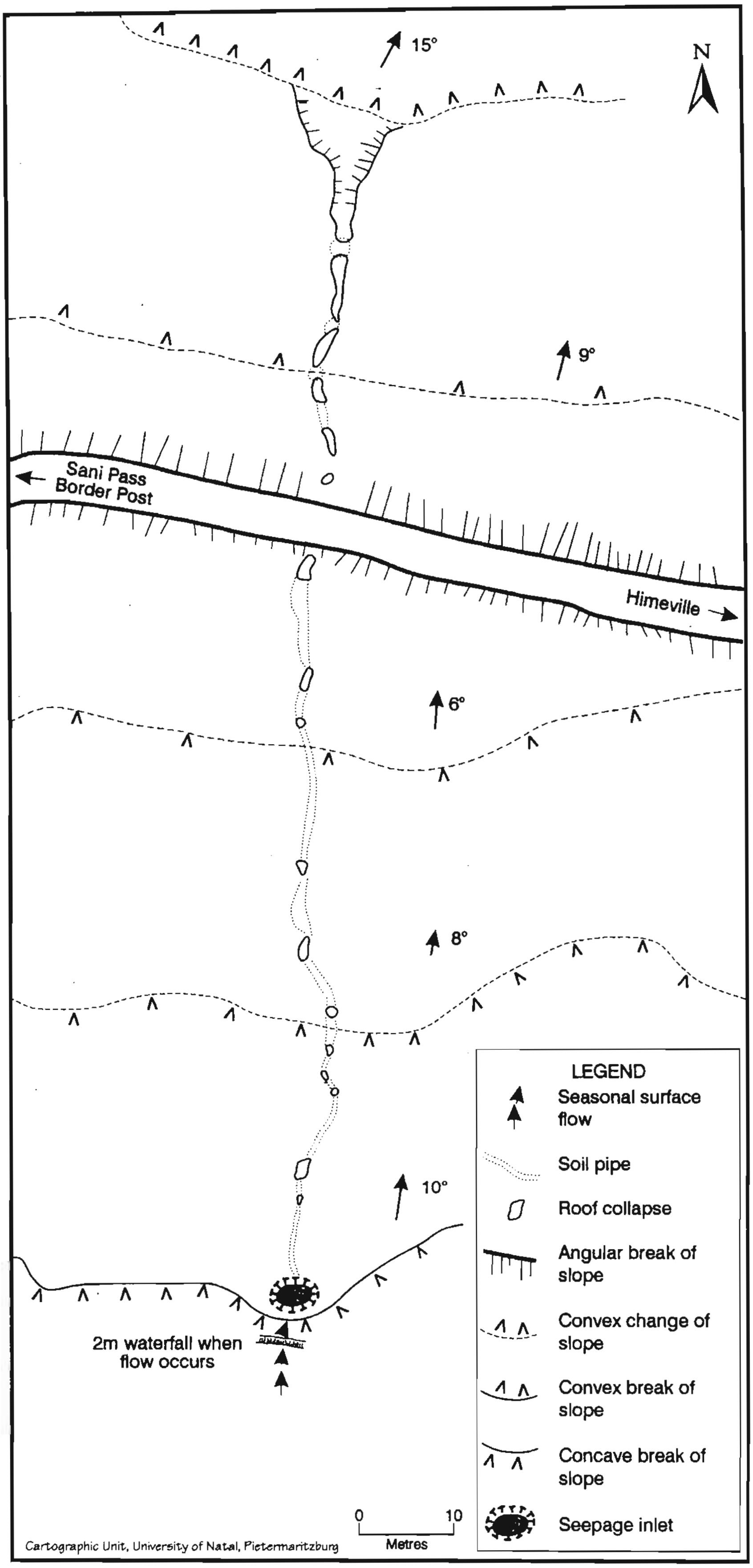


Figure 5.1.2: Detailed map of the Sani Pass pipe system.

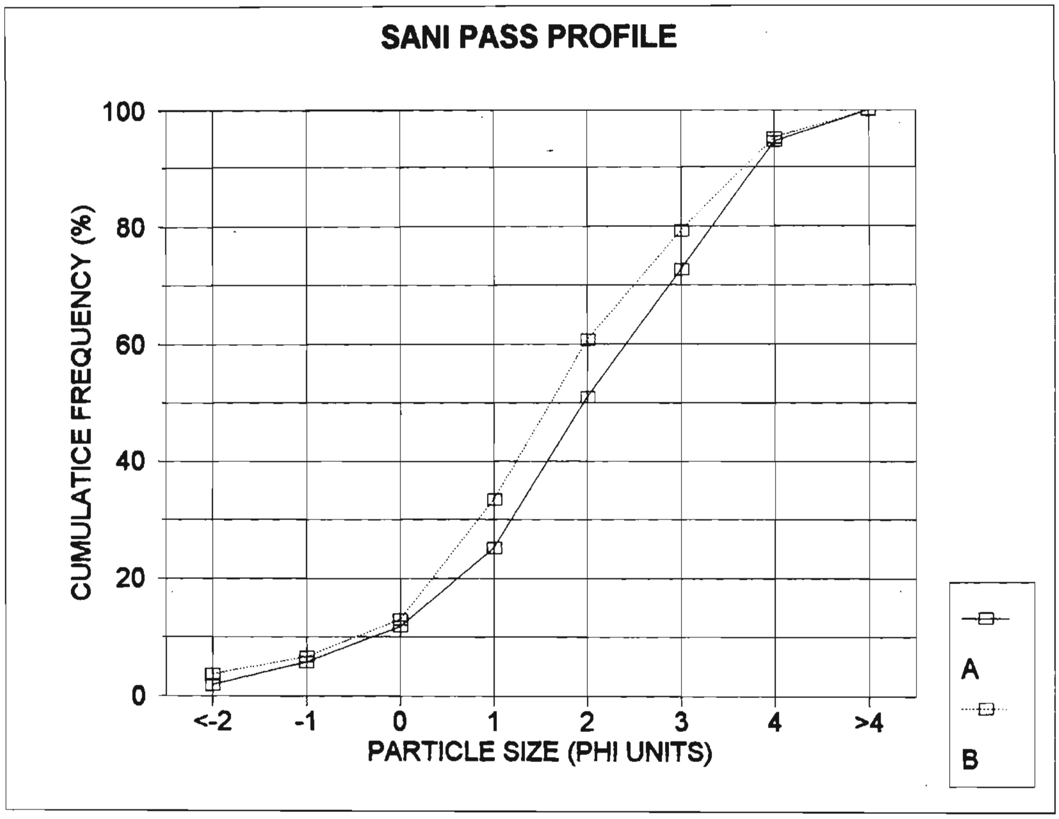


Figure 5.1.3(a): Cumulative grain size distribution for the Sani Pass site.

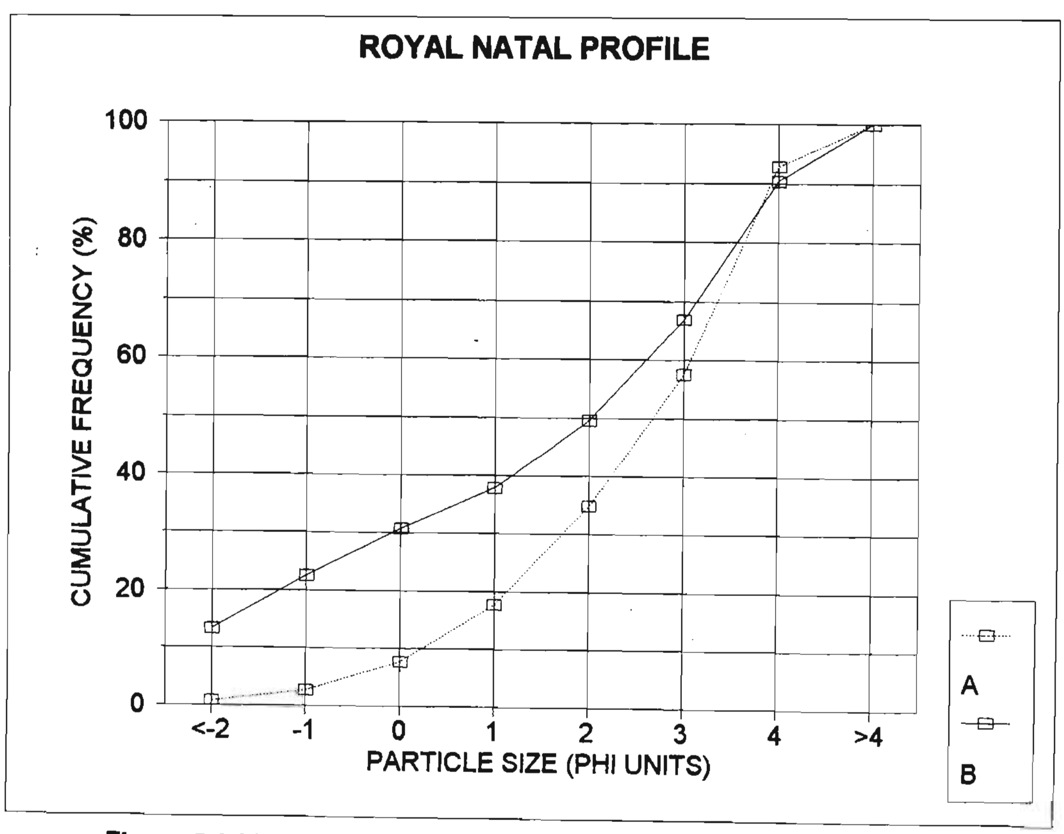


Figure 5.1.3(b): Cumulative grain size distribution for the Royal Natal site.

It is clear, however, that macro-pore flow does augment pipe discharge as, during one of the rare flow events witnessed, surface water filtered into the intake of the Sani Pass system at a rate of approximately 600l.hr^{-1}, but discharged from the pipe outlet at some 1000 l.hr^{-1}.

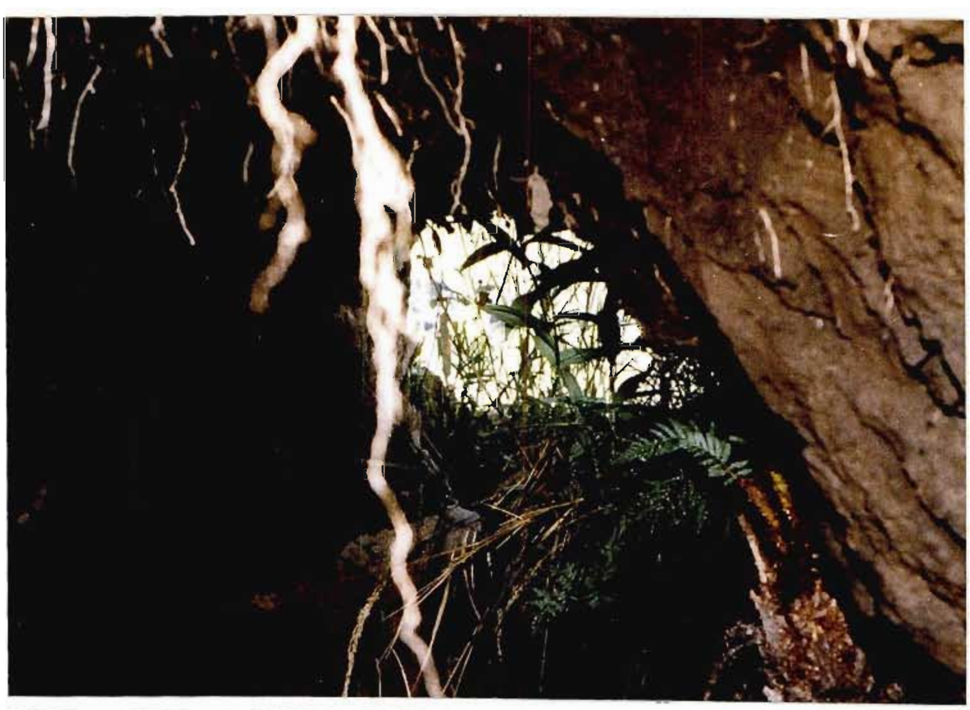
The soils within which the Type1 systems develop are less structured than those of the other subsurface systems, and have the highest percentage of sand of the 5 subsurface erosion types in a hydrometer-based textural analysis. They, however, also have the highest mean phi values (*ie.* smallest mean size fraction) in a dry sieve analysis used to ascertain the size of aggregates, as illustrated by Figures 5.1.3(a) and (b) for the Sani and Royal Natal sites respectively.

As the aim of the present study was to understand the morphodynamics of the soils under *field conditions* so as to gain a better understanding of the different systems of subsurface erosion, texture was determined both by the hydrometer method after dispersion in water and by sieving an air-dry sample for 20 minutes at 75 Hz *without* the artificial destruction of aggregates in a mortar and pestle. Sieves were selected at intervals of one phi (ϕ) unit from -2ϕ (4 mm) down to 4ϕ (63μm). The results were plotted on a cumulative frequency curve (Figures 5.1.3(a) and (b)), from which the mean and median values were calculated. As the mean should strictly be calculated as one third of the sum of the seventy fifth, fiftieth and twenty fifth percentiles, and in excess of 25% of the sample was on occasion retained on the -2ϕ sieve, it was not always possible to calculate the mean grain size accurately. (This problem is especially relevant to the Type 2 systems).

The soils have moderately high liquid limits, but these are compensated for in terms of stability by low values for both the plasticity index and the linear shrinkage. The plasticity index is defined as a measure of the plastic behaviour of a soil, and is obtained by subtracting the plastic limit (or smallest water content at which a soil is plastic), from the moisture content characterising the liquid limit.

Figure 5.1.4(a): View into the Sani scree pipe. Note the abundance of rock debris on the floor of the pipe, and the moss covered pipe-roof.

Figure 5.1.4(b): A view from some 4m into the Sani pipe. Note the root matting in the A-horizon pipe roof.



The linear shrinkage is that moisture content (as a percentage by weight), at which the soil volume undergoes no further change upon drying (Goudie, 1981).

Table 5.1.1: The physical properties of soils displaying scree-slope piping.

PARAMETER \ SITE AND SOIL HORIZON	SANI PASS		ROYAL NATAL	
	A	B	A	B
THICKNESS (cm)	45	100	40	70
COLOUR	7.5YR3/2 DARK BROWN	10YR6/6 BROWNISH YELLOW	10YR3/2 VERY DARK GRAYISH BROWN	7.5YR4/4 DARK BROWN
SOIL FORM	CLOVELLY (*INCEPTISOL*)		HUTTON (*OXISOL*)	
TEXTURE				
SAND %	66.2	70.6	66.1	51.5
SILT %	22.5	12.2	23.6	24.8
CLAY %	11.3	17.2	10.3	23.8
MEAN (Φ)	1.9	1.6	2.5	1.8
MEDIAN (Φ)	2.0	1.6	2.6	2.0
DESCRIPTION	SANDY LOAM	SANDY LOAM	SANDY LOAM	SANDY CLAY LOAM
STRUCTURE	CRUMB	PLATY	CRUMB	PLATY
GEOTECHNICAL				
LIQUID LIMIT %	25.0	18.0	25.0	25.0
PLASTICITY INDEX %	6.0	4.0	8.0	8.0
LINEAR SHRINKAGE %	3.0	2.0	4.0	4.0
HAND SHEAR VANE (kPa)	50.0	78.0	46.0	62.0
BULK DENSITY ($g.m^{-3}$)	1.5	1.4	1.5	1.4
ERODIBILITY (K VALUE)	0.26	0.17	0.2	0.21

The soils have a low *in situ* strength as indicated by the Farnell hand shear vane values in Table 5.1.1. The pipe roof consists of almost exclusively the A horizon and gains its strength from the abundant roots and mosses which it contains (Figure 5.1.4(a) and (b)). Although a laboratory shear box apparatus is conventionally used in geotechnical strength analysis, Goudie (1981) has noted that a good correlation exists between values so obtained and the hand shear vane, provided that the operating range of the latter instrument is not exceeded. Given the great versatility of the hand shear vane when compared with the cumbersome logistics of undisturbed field sampling and subsequent shear box analysis, the former method was adopted for the present study.

Bulk density was determined by using a 50 mm x 50 mm sharp-end plunger and driving this a pre-set 100 mm into the clean soil profile. The density (corrected for field moisture content) is then determined from this 250 cm^3 bulk sample. It is significant that the bulk density decreases down profile to the scree material and, although it was not possible to obtain a reliable sample of the interstitial material within the scree, it

Table 5.1.2: Soil hydrological and associated conditions for scree-slope pipes.

SITE AND SOIL HORIZON / PARAMETER	SANI PASS		ROYAL NATAL	
	A	B	A	B
THICKNESS (cm)	45	100	40	70
TEXTURE				
SAND %	66.2	70.6	66.1	51.5
SILT %	22.5	12.2	23.6	24.8
CLAY %	11.3	17.2	10.3	23.8
DESCRIPTION	SANDY LOAM	SANDY LOAM	SANDY LOAM	SANDY CLAY LOAM
STRUCTURE	CRUMB	PLATY	CRUMB	PLATY
PRECIPITATION TOTAL (mm pa)	1171.8		1320.9	
RDI% #	78.3		83.7	
DISTRIBUTION OVER YEAR % #	32.4		33.4	
RELATIVE INTENSITY #	35.6		39.5	
SOIL HYDROLOGY				
FIELD MOISTURE %	14.7	15.2	21.2	28.3
FIELD CAPACITY %	43.9	33.4	52.1	37.6
SATURATION POTENTIAL %	51.4	30.5	50.6	47.5
INFILTRATION RATE ($ml.hr^{-1}$)	9.3	14.4	8.4	12.5
SATURATED INFILTRATION RATE ($ml.hr^{-1}$)	2.6	4.7	1.9	3.4
BULK DENSITY ($g.m^3$)	1.48	1.40	1.50	1.40
ERODIBILITY (K VALUE)	0.26	0.17	0.20	0.21

as defined in Chapter 3

appears that the trend continues. The bulk density for the scree material together with its matrix shows a sharp increase in density where the state of weathering facilitates such measurement, but the low bulk density of the matrix infill is significant.

As shown in Table 5.1.2, the soil has a significantly higher field moisture content than soils of the other types of subsurface system (soil moisture was determined using a Speedy Soil Moisture Meter, and is given in percent by weight of dry soil). Considering the sandy nature of the soil, this field moisture condition may account for the surprisingly low field infiltration rates observed. The high field moisture content is ascribed primarily to the combined effect of precipitation and soil character. The high precipitation levels are reflected by the mean precipitation value for the Type 1 system being in excess of 1100 mm pa.. Such precipitation is strongly seasonal in charater with RDI values above 75% and, together with good rainfall distribution values greater than 30%, result in comparatively high rainfall intensity indeces. The soils have a high saturation potential; an indirect indicator of the water holding capability of the soil. The sandy loam texture does, however, account for the moderately high saturated infiltration rate of these soils as given in Table 5.1.2.

Figure 5.1.5: The doline-like depression resulting from roof collapse of scree-slope pipes.

The soils are non-dispersive and non-sodic (Table 5.1.3), and are acid. Pipe discharge has a pH of 6.01. The low values for electrical conductivity (EC) suggest that very little leaching is occurring at present. The pipe discharge has a low sediment content and is clear, lending further support to the interpretation that dispersion is absent.

Where roof collapse has occurred, the exposed sidewalls are rapidly revegetated, resulting in small doline-like depressions some 1 to 1.5 m deep remaining as the only evidence that collapse occurred (Figure 5.1.5). This is in sharp contrast with the other types of subsurface erosion, where collapse has initiated clearly evident gully development. The K-values determined are moderate within the context of the range of values identified by El-Swaify *et al.* (1982), namely 0.01 up to 0.69. The values obtained for the Type 1 systems are a direct result of the sandy textured soils, their low

Table 5.1.3: The charateristic soil chemistry of soils prone to scree slope piping.

PARAMETER \ SITE AND SOIL HORIZON	SANI		ROYAL NATAL	
	A	B	A	B
THICKNESS (cm)	45	100	40	70
TEXTURE				
SAND %	66.3	70.6	66.1	51.5
SILT %	22.5	12.2	23.6	24.8
CLAY %	11.3	17.2	10.3	23.8
DESCRIPTION	SANDY LOAM	SANDY LOAM	SANDY LOAM	SANDY CLAY LOAM
ORGANIC CARBON	2.87	0.38	2.44	1.14
SOIL CHEMISTRY				
DISPERSION RATIO %	6.01	3.5	9.1	8.5
CEC ($cmol.kg^{-1}$)	25.1	18.0	22.5	42.8
EC ($mS.m^{-1}$)	21.3	44.4	14.5	10.5
ESP	0.00	0.24	0.02	0.05
SAR	0.5	3.5	0.3	1.6
pH	5.0	4.7	5.4	5.3
ERODIBILITY (K VALUE)	0.26	0.17	0.2	0.21

bulk density and the relatively low values of organic carbon which they contain as also the low degree of aggregation present. As a consequence, the individual soil particles are washed out of the profile with relative ease.

The process of subsurface erosion for Type 1 systems may be understood in the light of dynamic cone penetrometer (DCP) traces, following the work of Sanglerat (1972) and Beckedahl and Bird (1995). These penetration traces are illustrated in Figure 5.1.6. The rate of penetration of a DCP into a soil is a function of the shear strength of the soil, which is in turn *inter alia* dependant on the bulk density and moisture content of the soil. Figure 5.1.6(a) shows the penetration trace into the scree material; the greater penetration in the B horizon reflecting the decrease in its bulk density. Similarly the low penetration rate of the weathered scree material is an indication of the greater bulk density and shear strength of that material.

Figure 5.1.6(b) reflects the situation where the penetrometer passes through interstitial material between boulders before encountering the weathered scree material. The high penetration rate is further evidence of the field observation that the infill material has a low bulk density and a low cohesive strength. The above findings are interpreted to indicate that the scree material was originally a poorly sorted boulder deposit (possibly related to palaeo-slope failure) and that the interstitial material is derived primarily by infill of colluvial fines under gravity and minor slope wash events, ultimately accumulating to a sufficient extent for pedogenesis to occur. The presence of the coarse scree material has, however, prevented the interstitial infill material from becoming compacted by the overlying soil horizons.

Where infiltration of slope wash occurs, the scree deposit will offer least resistance to flow and therefore represents a natural route for downslope drainage relative to adjacent areas. The material below the scree deposit is less permeable than the infill, creating conditions conducive to a perched water table. This in turn will result in an increased pore water pressure within the scree deposit and, given the low shear

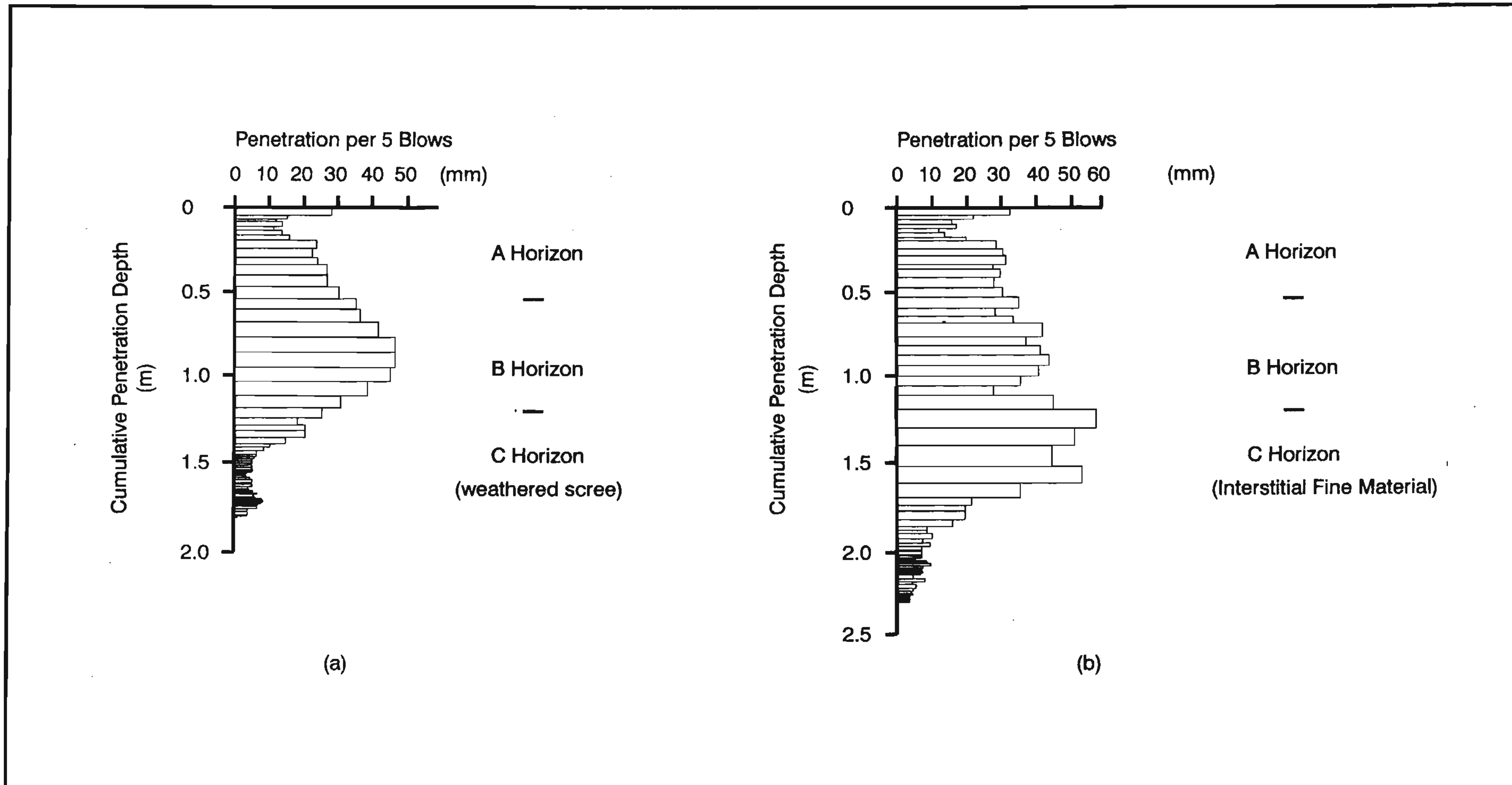


Figure 5.1.6: Dynamic cone penetrometer traces showing penetration into (a) scree material and (b) through the instertitial fines

strength of the infill material, has the potential to entrain the fines and so to move them downslope through the macro-pores of the scree deposit, hence initiating subsurface flow. Once developed to the point where turbulent flow exists, the system will tend to become a self-accelerating processes of fluvial transport and erosion. Roof collapse, when it occurs, takes place primarily into the voids within the scree material and is consequently of limited extent, in turn accounting for the 'doline-like' morphology of the surface subsidence compared with the incipient gully development related to collapse of the other types of subsurface erosion. The more sustained gully-like morphology at the outlet of the Sani Pass pipe shown in Figure 5.1.2 may be explained by the outlet being in close proximity to the outcrop of a sandstone lens at the southern-most break of slope. The already mentioned increase in observed discharge of the system with distance downslope suggests that during peak discharge the subsurface water level would have risen to the base of the B horizon, undercutting it as is evident in the field (see Figure 5.1.7). Roof collapse under these conditions would tend to be linear rather than circular in planimetric morphology.

Figure 5.1.7: The broadened outlet of the Sani Pass pipe system. Note the removal of the B-horizon (A), resulting in roof instability.

5.2 Type 2: Gully Sidewall Systems

The dominant characteristics of these erosion systems are that they have the shortest mean length of all five types, the greatest mean roof thickness (Table 4.4) and the greatest number of pipes per system (Table 5.1). They are found in association with a range of slope units within the context of the Nine Unit Landscape Model because, as will be shown, the genesis of these systems is directly dependent on the gully and associated incision, rather than on slope processes *per se*. They are frequently observed where a gully has developed on a duplex soil, (defined by the Soil Classification Working Group (1991) as a soil with relatively permeable horizons overlying a slowly permeable subsoil horizon). The representative field sites for this type of system are Ncise, Kutsolo and Inxu Drift; the latter two sites being within two kilometres of one another.

The Ncise site, shown in detail in Figures 5.2.1(a); (b) and 5.2.2, is associated with a gully incised into a complex pedogenic sequence developed on a range of alluvial-colluvial sediments with a total thickness of 4.5 m (Figure 5.2.3(a) and (b)). Overall the material approximates to a sandy loam but contains a well structured, well aggregated palaeosol (A in Figure 5.2.3(a)) with a higher clay content (Table 5.2.1). The base of the profile contains some matrix supported gravels but also has an increased clay content, at least in part due to illuviation (B, Figure 5.2.3(b) and Figure 5.2.4). In its dry state the soil has a high shear strength, particularly in the A, palaeo A and C horizons. There is no meaningful distinction between the soil horizons on the basis of the Atterberg Limits shown in Table 5.2.1.

Although the Inxu Drift site (Figures 5.2.5 and 5.2.6) has been described in detail with regard to its morphology by Dardis and Beckedahl (1988), the nature of the material within which the system occurs has not been previously discussed. The Inxu Drift and Kutsolo sites will be discussed together, although differences will be highlighted.

Figure5.2.1(a): General overview of the Ncise gully system.

Figure5.2.1(b): View of the near-gully region, showing the depressions caused by sidewall pipe collapse.

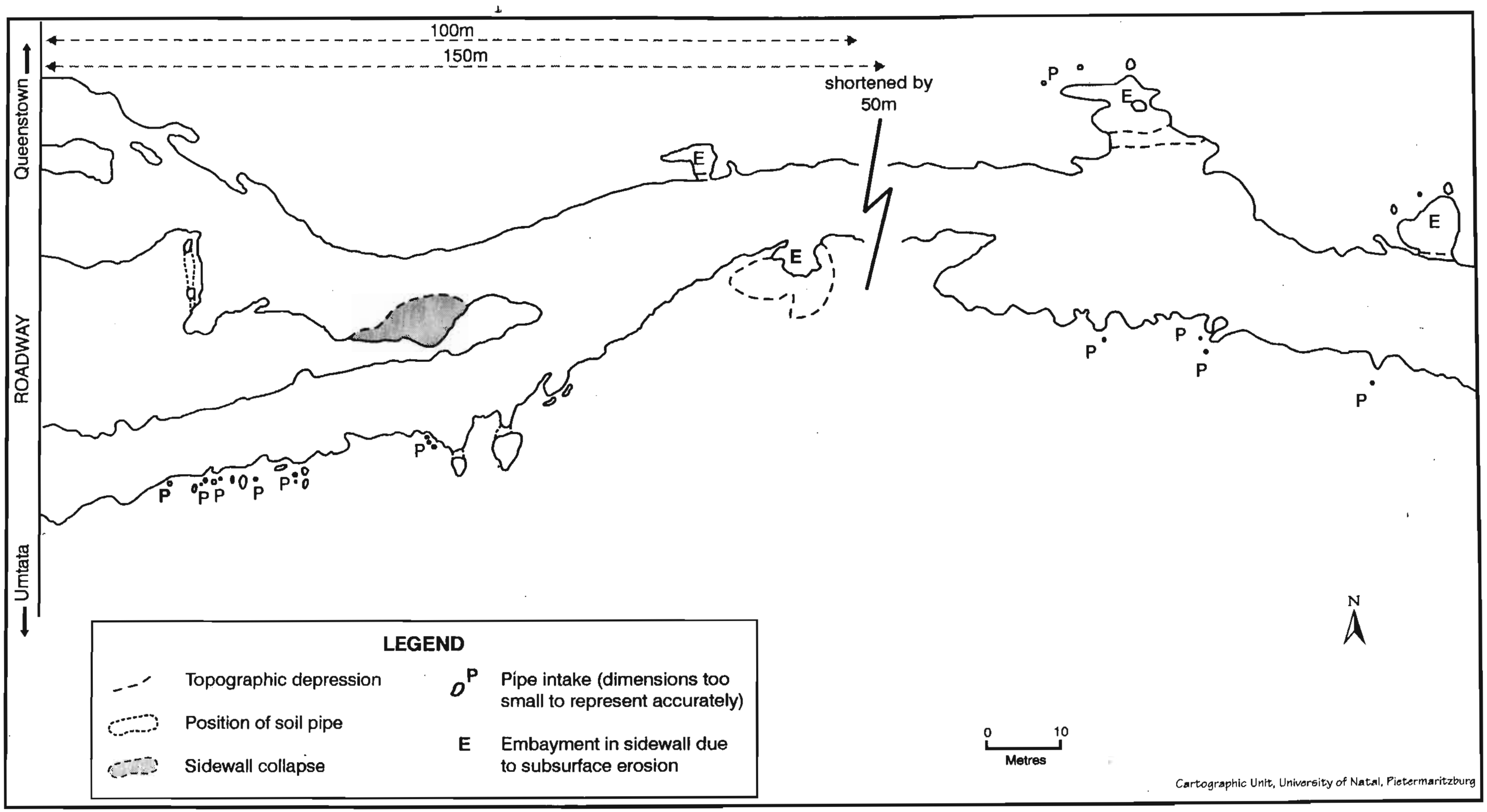


Figure 5.2.2.: Map showing a portion of the Ncise gully system and the associated sidewall pipes.

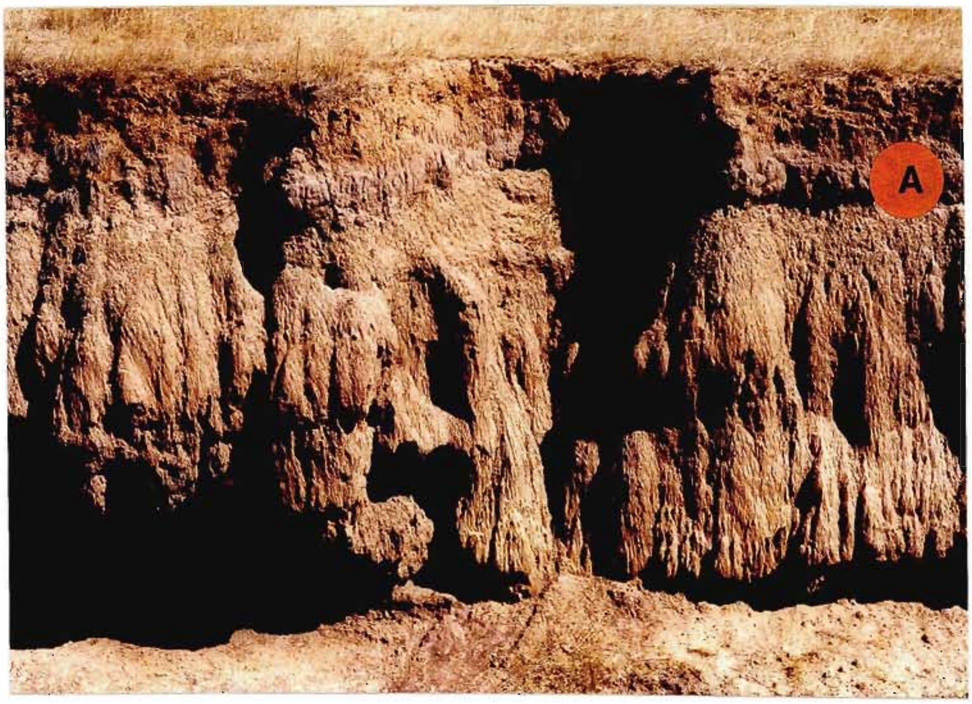


Figure 5.2.3(a): The soil profile exposed in the gully sidewall at Ncise. Note the well structured (and well aggregated palaeosol indicated by **A**.

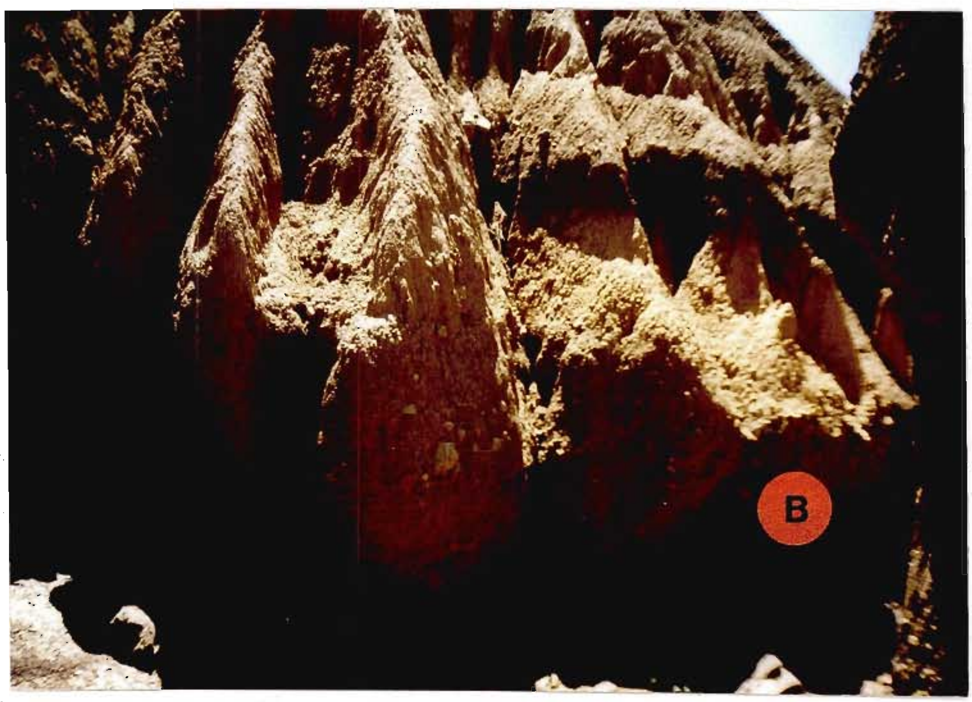


Figure 5.2.3(b): A close-up view of the matrix supported gravel **B** within the alluvial-colluvial sequence forming the soil at Ncise.

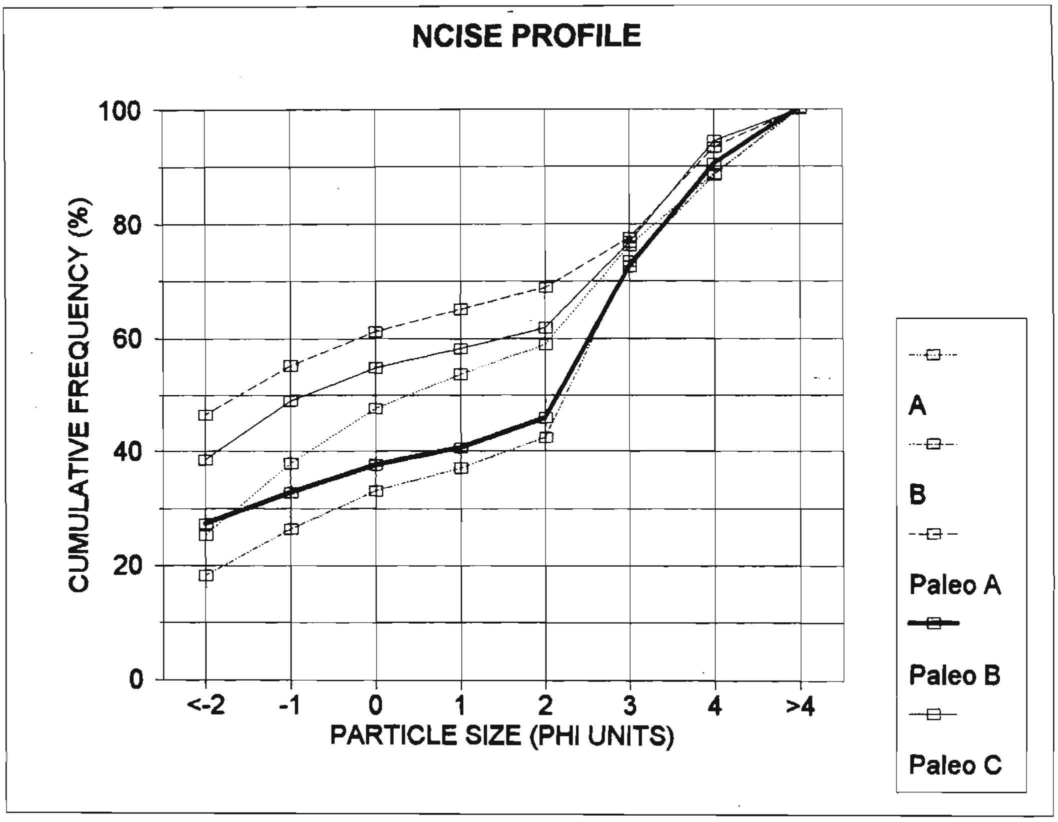


Figure 5.2.4: Cumulative frequency distribution of grain size for soils associated with the Ncise gully system.

As was the case with Ncise, both the Kutsolo and Inxu Drift systems have developed in well structured soils with a high degree of aggregation, and have again developed adjacent to a deep gully system incised into alluvial-colluvial material in excess of 6 m in thickness (Figure 5.2.7(a) and (b)). The B horizon at Kutsolo is the only horizon in which pedogenic carbonate was found.

Texturally all three Type 2 sites are broadly similar although Kutsolo and Inxu Drift are coarser-textured on the dry sieve analysis, primarily due to a greater degree of aggregation. As previously stated, texture was determined both by the hydrometer method after dispersion in water and by sieving an air-dry sample.

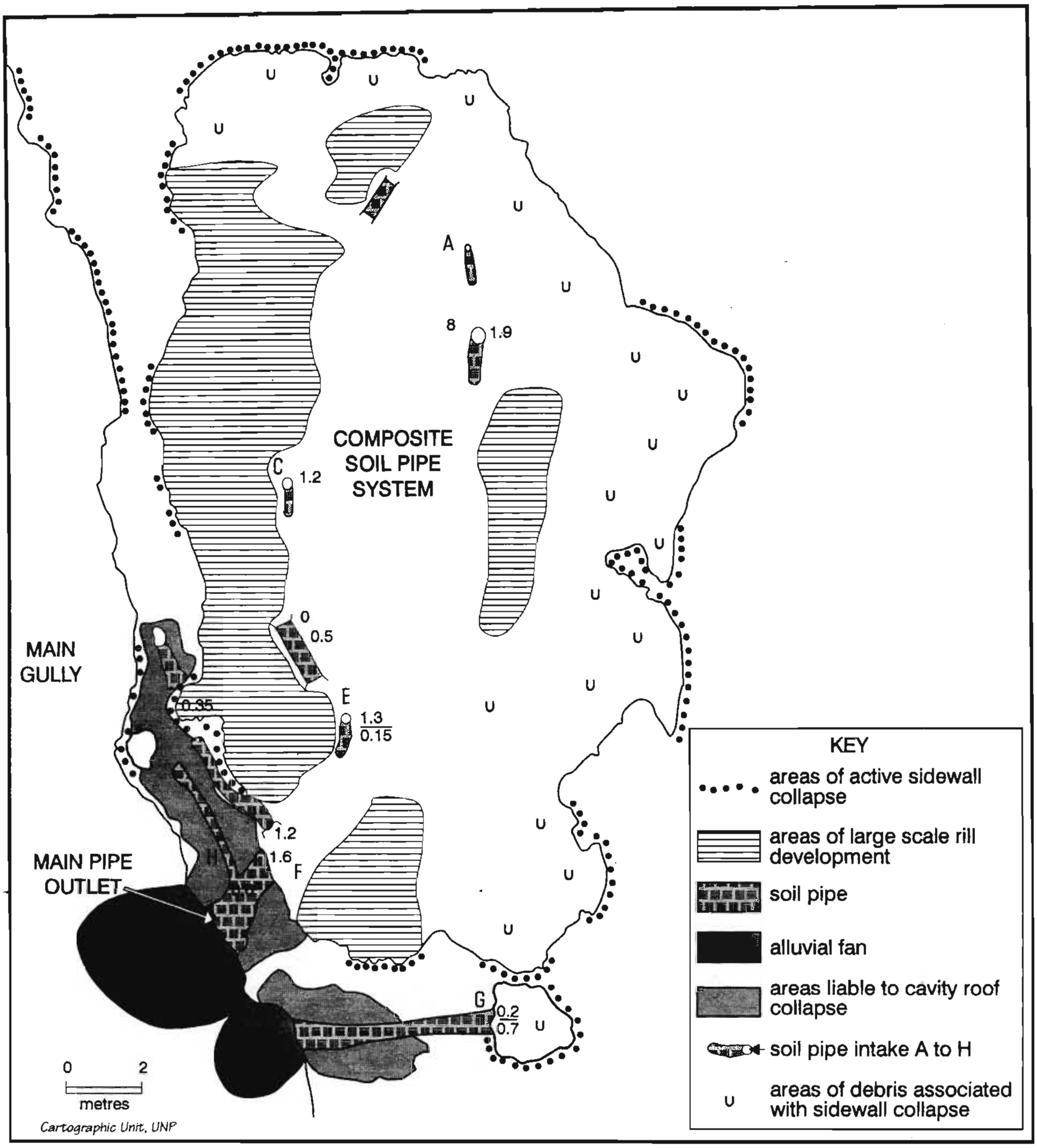


Figure 5.2.5: A map of the Inxu Drift (from Dardis and Beckedahl, 1988).

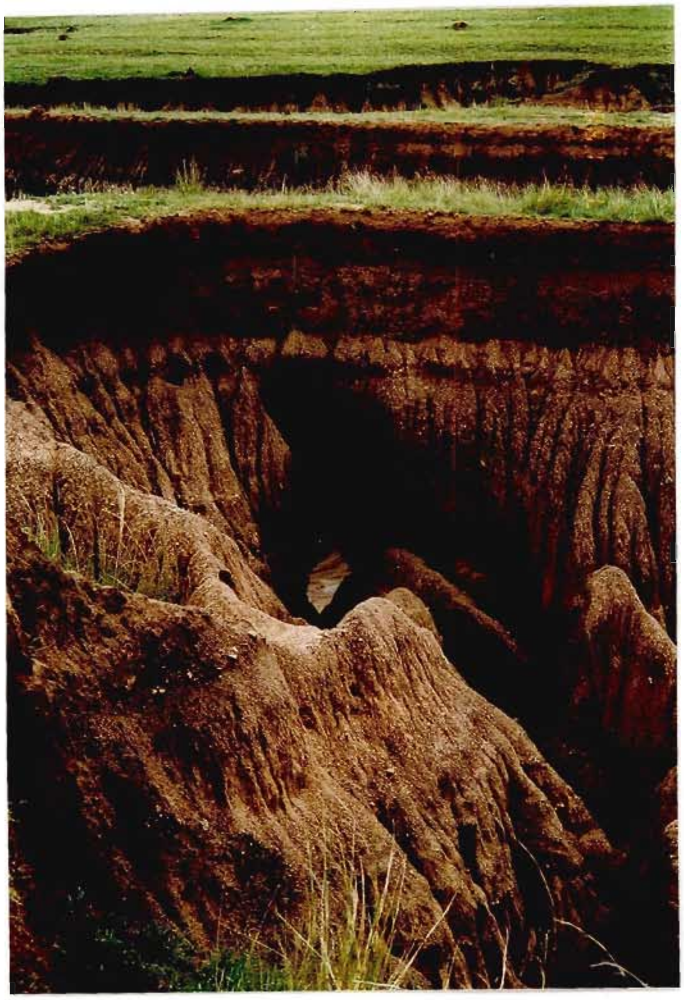


Figure 5.2.6: Photograph of the main exit tunnel of the Inxu Drift gully sidewall pipe system.

The results were plotted on a cumulative frequency curve (Figures 5.2.4; 5.2.8 and 5.2.9), from which the mean and median values were calculated. As the mean should strictly be calculated as one third of the sum of the seventy fifth, fiftieth and twenty fifth percentiles, and in excess of 25% of the sample was on occasion retained on the -2ϕ sieve, it was not always possible to calculate accurately the mean grain size as is indicated in Table 5.2.1.

As was the case at Ncise, the soils again have a high shear strength under field conditions, in part due to low field moisture levels. The Atterberg Limits (Table 5.2.1) are roughly constant with the exception of the Kutsolo B horizon which has an unusually high liquid limit of 42%. This may be ascribed primarily to the high clay content (57.2%) within that horizon.

By comparison to the Type 1 systems, the Type 2 systems are found in areas of significantly lower precipitation and, although the precipitation is still markedly seasonal with RDI values between 65% and 70%, it is less well distributed over the rainy season (Table 5.2.2). Periodic desiccation of the soil profile is thus likely - an interpretation supported both by the low field moisture values which were obtained for the soil during winter and by the relatively high values for saturation potential. The Kutsolo B horizon is again anomalous with a saturation potential of 68.7%, reflecting among other factors the high clay content already mentioned above.

The infiltration rates for Ncise, Kutsolo and Inxu Drift attest to these being duplex soils. The overall trend of decreasing infiltration rate is maintained irrespective of whether the soil is saturated or not. The Kutsolo site is, however, again somewhat anomalous in that the infiltration rates for both the saturated and unsaturated condition increase in the B horizon and then decline steadily throughout the remainder of the profile. This pattern is surprising in the light of the high clay content of the B horizon, and can only (albeit tentatively) be ascribed to the abundant pedogenic carbonate nodules within the horizon which would influence the macro porosity of that horizon.

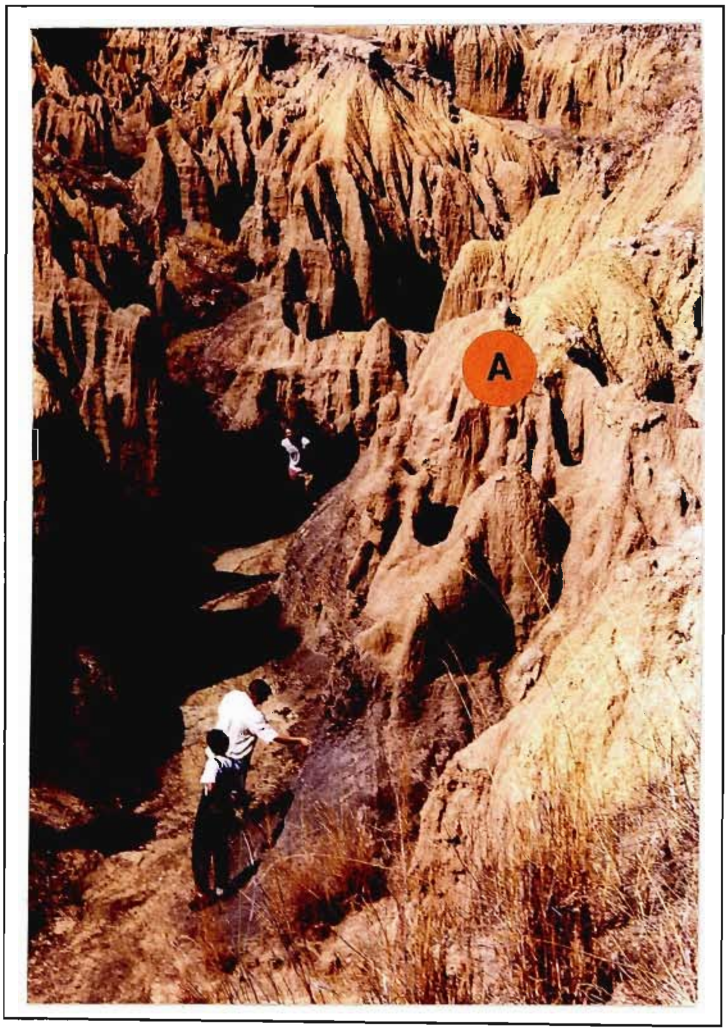


Figure 5.2.7(a): The degraded gully system at Kutsolo. Most of the sideways extension is due to sidewall piping.

Figure 5.2.7(b): Photograph of Kutsolo gully, showing the depth of the system. The `cones' designated as **A** are due to sidewall pipe collapse.

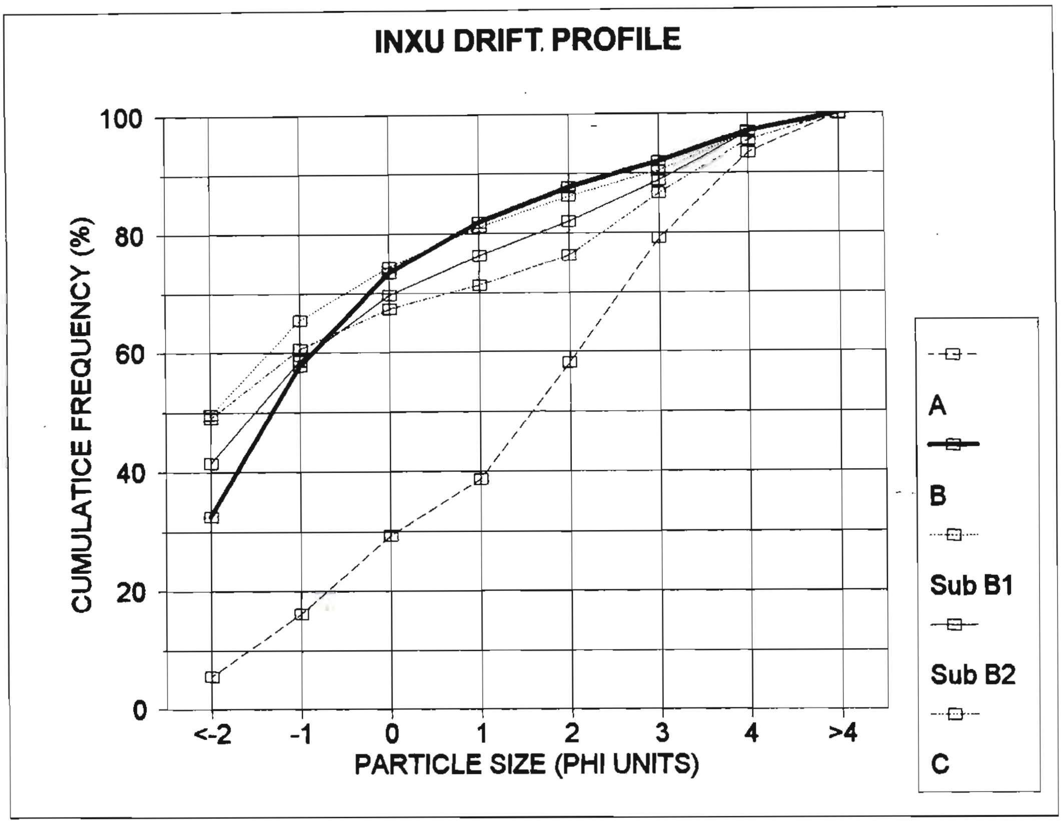


Figure 5.2.8: Cumulative frequency distribution of grain size for the Inxu Drift profile.

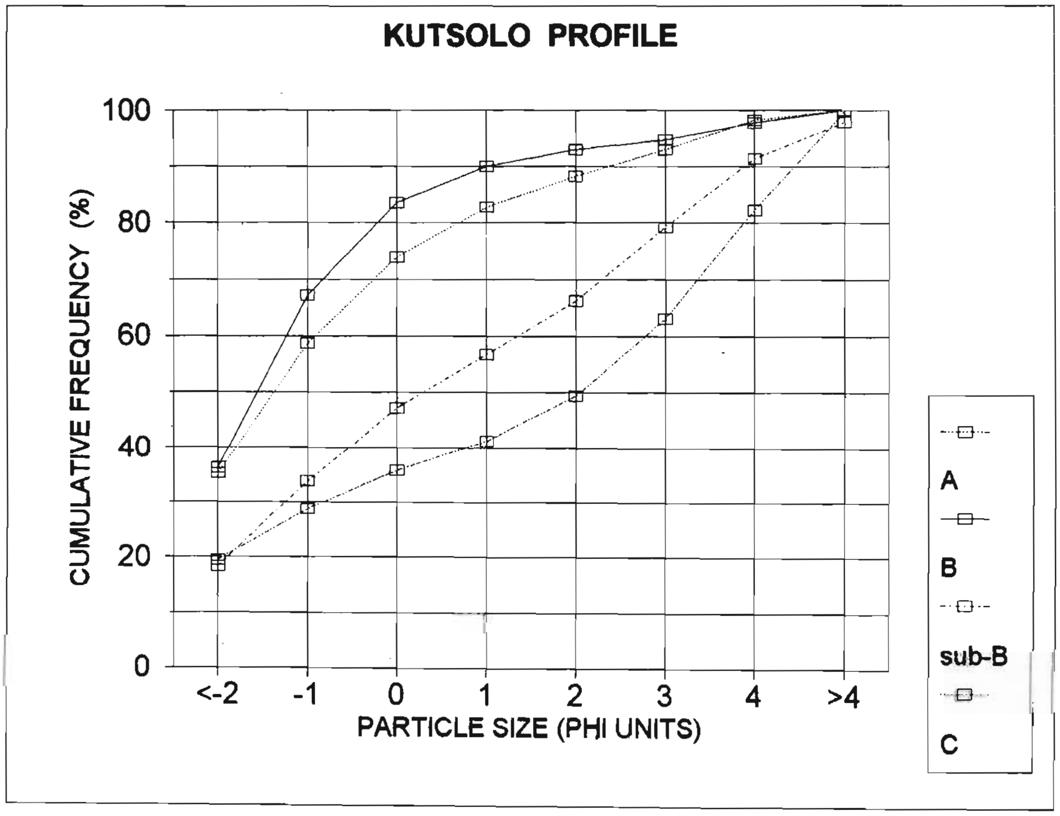


Figure 5.2.9: Cumulative frequency distribution of grain size for the Kutsolo profile.

Table 5.2.1: The physical properties of soils displaying gully sidewall pipes.

SITE AND SOIL HORIZON / PARAMETER	NCISE					KUTSOLO				INXU DRIFT				
	A	B	Pal A	Pal B	Pal C	A	B	sub B	C	A	B	subB1	subB2	C
THICKNESS (cm)	20	40	45	110	150	40	80	120	310	60	50	80	50	230
COLOUR	10YR5/6 YELLOWISH BROWN	7.5YR5/4 GRAYISH BROWN	10YR5/2 GRAYISH BROWN	7.5YR6/4 LIGHT BROWN	7.5YR7/2 PINKISH GRAY	10YR6/2 LIGHT BROWNISH GRAY	10YR6/2 LIGHT BROWN GRAY	10YR6/4 LIGHT YELLOWISH BROWN	5YR5/3 REDDISH BROWN	10YR5/4 YELLOWISH BROWN	10YR6/3 PALE BROWN	10YR4/2 DARK GRAYISH BROWN	10YR6/2 LIGHT BROWNISH GRAY	10YR7/4 10YR6/8 MOTTLED
SOIL FORM	ESTCOURT (*ALFISOL*)					OAKLEAF (*INCEPTISOL*)				OAKLEAF (*INCEPTISOL*)				
TEXTURE														
SAND %	60.3	44.0	45.9	62.6	51.4	44.5	17.8	47.9	35.6	72.7	34.9	19.5	39.2	46.1
SILT %	28.5	32.6	30.6	20.2	22.7	36.3	25.0	24.5	36.8	16.2	29.0	46.0	26.8	26.4
CLAY %	11.2	23.4	23.5	17.2	25.8	19.2	57.2	27.6	27.6	11.1	36.2	34.5	34.0	27.5
MEAN (ϕ)	1.6	0.4	-1.3	1.1	-0.3	0.6	-0.9*	-0.5	-1.1*	1.3	-1.2*	N/A	-1.4*	N/A
MEDIAN (ϕ)	2.3	0.4	-1.6	2.2	-0.8	0.4	-0.5	0.1	-1.2	1.6	-1.3	-2.0	-1.5	-1.8
DESCRIPTION	SANDY LOAM	CLAY LOAM	CLAY LOAM	SANDY LOAM	SANDY CLAY LOAM	LOAM	CLAY	CLAY LOAM	CLAY LOAM	SANDY LOAM	CLAY LOAM	CLAY	CLAY	CLAY LOAM
STRUCTURE	CRUMB	BLOCKY	COLUMNAR	PRISMATIC	PRISMATIC	PRISMATIC	PLATY	CRUMB	BLOCKY	PRISMATIC	BLOCKY	BLOCKY	BLOCKY	PRISMATIC
GEOTECHNICAL														
LIQUID LIMIT %	22	20	21	15	19	15	42	20	32	15	28	27	28	23
PLASTICITY INDEX %	3	5	5	4	4	5	19	8	10	3	14	11	10	8
LINEAR SHRINKAGE %	0.5	3	2.5	2	2	2.5	9.5	4	5	1	7	5.5	5	4
HAND SHEAR VANE (kPa)	118	68	116	87	146	> 150	115	76	124	107	78	136	84	146
BULK DENSITY (g/m³)	1.9	1.6	1.5	1.8	2.2	1.6	1.4	1.8	1.7	1.8	1.4	1.8	1.7	2.0
ERODIBILITY (K VALUE)	0.42	0.28	0.32	0.22	0.28	0.30	0.15	0.25	0.31	0.23	0.34	0.31	0.28	0.36

* not accurate due to methodology

Table 5.2.2: Soil hydrological and associated conditions for gully sidewall pipes.

SITE AND SOIL HORIZON / PARAMETER	NCISE					KUTSOLO				INXU DRIFT				
	A	B	Pal A	Pal B	Pal C	A	B	sub B	C	A	B	subB1	subB2	C
THICKNESS (cm)	20	40	45	110	150	40	80	120	310	60	50	80	50	230
TEXTURE														
SAND %	60.3	44.0	45.9	62.6	51.4	44.5	17.8	47.9	35.6	72.7	34.9	19.5	39.2	46.1
SILT %	28.5	32.6	30.6	20.2	22.7	36.3	25.0	24.5	36.8	16.2	29.0	46.0	26.8	26.4
CLAY %	11.2	23.4	23.5	17.2	25.8	19.2	57.2	27.6	27.6	11.1	36.2	34.5	34.0	27.5
DESCRIPTION	SANDY LOAM	CLAY LOAM	CLAY LOAM	SANDY LOAM	SANDY CLAY LOAM	LOAM	CLAY	CLAY LOAM	CLAY LOAM	SANDY LOAM	CLAY LOAM	CLAY	CLAY	CLAY LOAM
STRUCTURE	CRUMB	BLOCKY	COLUMNAR	PRISMATIC	PRISMATIC	PRISMATIC	APEDAL	CRUMB	BLOCKY	PRISMATIC	BLOCKY	BLOCKY	BLOCKY	PRISMATIC
PRECIPITATION TOTAL (mm pa)	648					588				588				
RDI %	66.4					69.6				69.6				
DISTRIBUTION OVER YEAR %	26.0					17.0				17.0				
RELATIVE INTENSITY %	24.6					34.6				34.6				
SOIL HYDROLOGY														
FIELD MOISTURE %	1.2	3.7	1.2	6.9	5.8	1.6	4.0	1.8	3.4	1.8	4.2	4.6	2.8	4.9
FIELD CAPACITY %	31.2	37.9	13.2	34.9	14.6	15.6	47.5	42.4	38.8	23.0	45.4	38.2	44.2	23.7
SATURATION POTENTIAL %	26.4	33.9	28.0	28.5	37.9	26.4	68.7	40.4	29.8	24.8	41.6	42.3	39.9	31.8
INFILTRATION RATE (ml.hr^{-1})	21.4	18.2	19.4	4.9	2.1	1.2	26.9	18.3	5.1	1.3	25.8	18.6	17.5	4.8
SATURATED INFILTRATION RATE (ml.hr^{-1})	4.1	3.6	3.7	0.2	0.3	0.3	1.3	0.8	0.2	0.3	1.4	0.8	0.7	0.2
BULK DENSITY (g.m^{3})	1.9	1.6	1.5	1.8	2.2	1.6	1.4	1.8	1.7	1.6	1.4	1.8	1.7	2.0
ERODIBILITY (K VALUE)	0.42	0.28	0.32	0.22	0.28	0.30	0.15	0.25	0.31	0.23	0.34	0.31	0.28	0.36

Figure 5.2.10: A view of the over-bank section of the Ncise gully sidewall, showing the depressions associated with sidewall piping.

When soil chemistry is examined as shown in Table 5.2.3, the following pattern becomes evident: With the exception of the A horizon at Ncise, all soil horizons are potentially dispersive when viewed against the criterion of a dispersion ratio in excess of 18%. If the criterion of an Exchangeable Sodium Percentage (ESP) greater than 6meq/100g is used, the B and paleao B horizons at Ncise, all but the C horizon at Kutsolo and the sub B1 horizon at Inxu Drift are dispersive.

By contrast, when analysing the Heede's (1971) measure of a Sodium Absorption Ratio (SAR) greater than 15, none of the horizons at Ncise meet the criterion, although the B and sub B1 horizons of Kutsolo and Inxu Drift respectively are then prone to piping. The last criterion cannot be significant for gully sidewall pipes as the Ncise system clearly exists (Figure 5.2.10) and at Kutsolo it is primarily the sub B and C horizons that display piping.

Table 5.2.3: The characteristic soil chemistry of soils prone to gully sidewall piping.

SITE AND SOIL HORIZON / PARAMETER	NCISE					KUTSOLO				INXU DRIFT				
	A	B	Pal A	Pal B	Pal C	A	B	sub B	C	A	B	subB1	subB2	C
THICKNESS (cm)	20	40	45	110	150	40	80	120	310	60	50	80	50	230
COLOUR	10YR5/6 YELLOW BROWN	7.5YR6/4 GRAYISH BROWN	10YR5/2 GRAYISH BROWN	7.5YR6/4 LIGHT BROWN	7.5YR7/2 PINKISH GRAY	10YR6/2 LIGHT BROWNISH GRAY	10YR6/2 LIGHT BROWN GRAY	10YR6/4 LIGHT YELLOWISH BROWN	5YR5/3 REDDISH BROWN	10YR5/4 YELLOW BROWN	10YR6/3 PALE BROWN	10YR4/2 DARK GRAYISH BROWN	10YR6/2 LIGHT BROWNISH GRAY	10YR7/4 10YR6/8 MOTTLED
TEXTURE														
SAND %	60.3	44.0	45.9	62.6	51.4	44.5	17.8	47.9	35.6	72.7	34.9	19.5	39.2	46.1
SILT %	28.5	32.6	30.6	20.2	22.7	36.3	25.0	24.5	36.8	16.2	29.0	46.0	26.8	26.4
CLAY %	11.2	23.4	23.5	17.2	25.8	19.2	57.2	27.6	27.6	11.1	36.2	34.5	34.0	27.5
DESCRIPTION	SANDY LOAM	CLAY LOAM	CLAY LOAM	SANDY LOAM	SANDY CLAY LOAM	LOAM	CLAY	CLAY LOAM	CLAY LOAM	SANDY LOAM	CLAY LOAM	CLAY	CLAY	CLAY LOAM
ORGANIC CARBON %	0.3	0.3	0.5	0.06	0.07	0.8	0.1	0.1	0.1	0.5	0.2	1.1	0.2	0.1
SOIL CHEMISTRY														
DISPERSION RATIO %	15.4	21.8	22.6	32.4	17.0	21.8	20.3	23.5	25.4	22.2	22.2	18.2	27.1	34.0
CEC ($cmol.kg^{-1}$)	14.3	20.3	21.3	14.9	22.1	11.7	45.8	25.1	21.0	14.3	39.8	40.1	27.0	21.8
EC ($mS.m^{-1}$)	38.2	487.0	128.3	696.0	56.9	717.0	359.0	289.0	54.7	52.5	319.0	433.0	75.3	145.0
ESP	0.5	7.5	5.0	14.6	6.0	6.9	10.5	8.2	3.3	0.5	5.0	7.0	1.7	5.4
SAR	2.4	8.2	9.9	11.0	3.4	5.9	17.2	8.8	3.7	2.0	7.3	21.9	5.8	8.5
pH	6.8	6.5	7.1	7.2	8.2	5.2	8.0	7.8	8.2	6.8	7.5	7.1	7.3	8.3
ERODIBILITY (K VALUE)	0.42	0.28	0.32	0.22	0.28	0.30	0.15	0.25	0.31	0.23	0.34	0.31	0.28	0.36

Throughout each of the three profiles the soil pH is slightly acidic in the A horizon and increases progressively down profile to the extent that the C horizon is markedly basic with a value greater than 8. Both Cation Exchange Capacity (CEC) and Electrical Conductivity (EC) increase towards the centre of the profile and then decrease towards the base of it. The very high EC values indicated in Table 5.2.3 are an indication of a high salt content within the soil profile; the decrease at the base of the profiles potentially indicating that some of the salts have been lost from the profile by elluviation. The values for erodibility (K) are as a rule moderately high, with two exceptions. The A horizon at Ncise is high at 0.42, reflecting the sandy texture and low organic carbon content of that horizon. Using similar reasoning, the clay content for the Kutsolo B horizon largely explains the low K value of 0.15 as indicated. That the K value oscillates about 0.30 suggests that these soils are not only prone to dispersion, but are susceptible to more conventional forms of erosion as well.

Discharge from the pipes is characteristically opaque in colour due to the high content of dispersed clays. On analysing the suspension associated with the pipe discharge from Type 2 systems by means of an Shimadzu SACP-3 centrifugal particle size analyser, the information shown in Figure 5.2.11 was obtained for Inxu Drift. The mean particle diameter of the dispersed fraction thus approximates 0.26 μm. The discharge registered a pH of 7.32 which is in keeping with the hypothesis that some of the bases are being leached out of the profile.

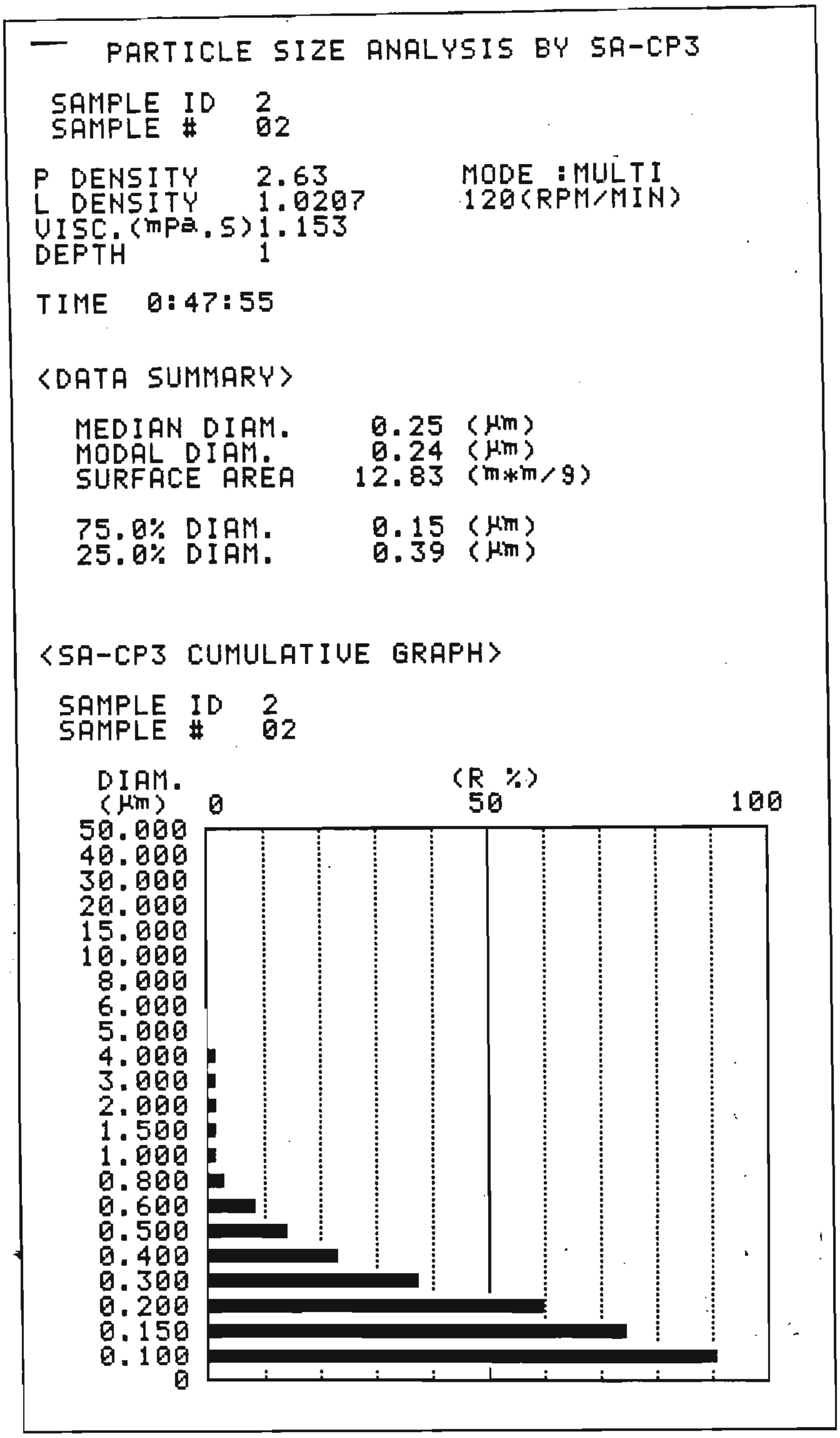


Figure 5.2.11: Print-out from the fine particle size analysis through the SA-CP3 Analyser. The mean particle size is 0.26μm.

On comparing the gully sidewall pipes of the three systems with one another (see Figures 5.2.2; 5.2.6 and 5.2.12) the strong influence of structure on morphology becomes apparent. Pipe systems are generally elongated in the vertical as in the case of Figures 5.2.6 and 5.2.12, or follow pseudo-bedding planes in the horizontal as illustrated by Figure 5.2.13. A similar pattern is evident on a smaller scale along the structure surfaces in the gully sidewalls (see Figure 5.2.14(a)and (b)).

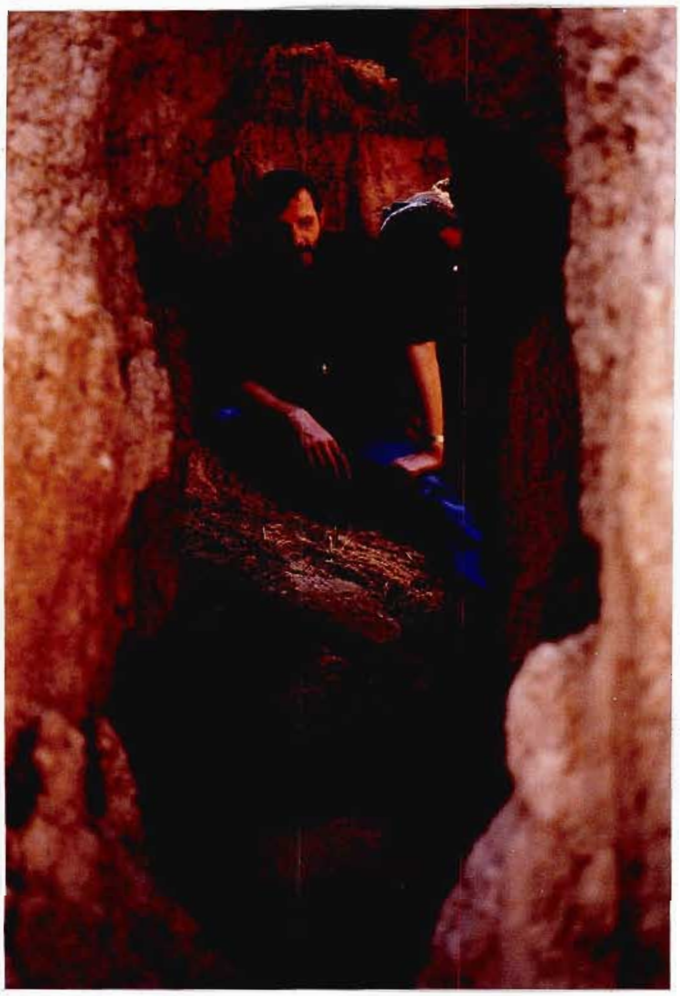


Figure 5.2.12: One of the pipes in the sidewall of the Ncise system. Note the elongate shape related to soil macro-structure.

Figure 5.2.13: A gully sidewall pipe showing the potential influence of bedding structures within the paleosediments on pipe morphology.

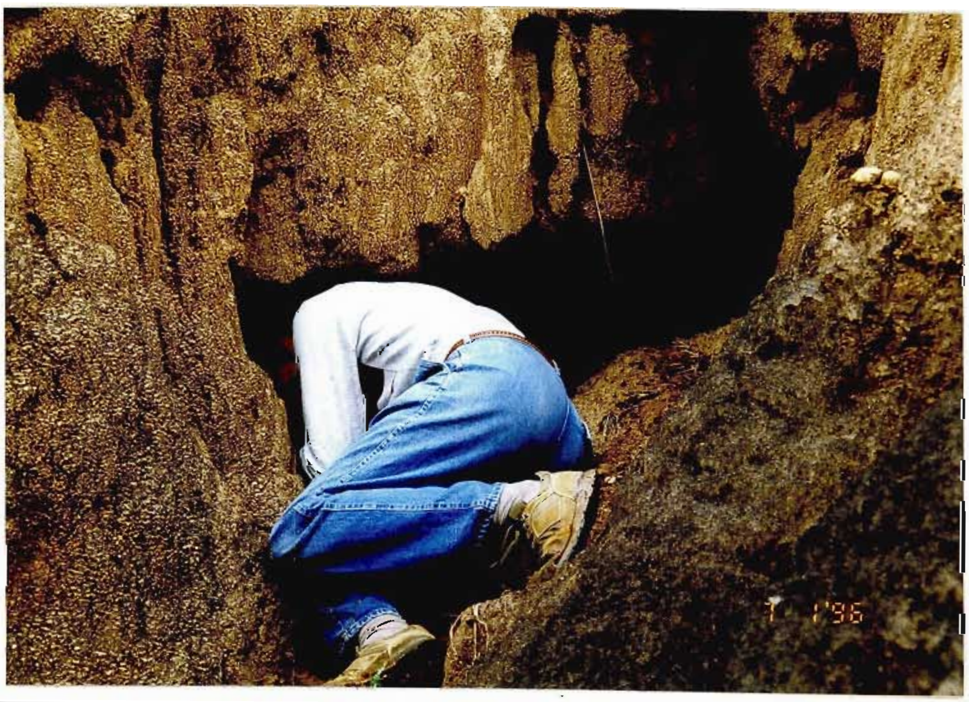
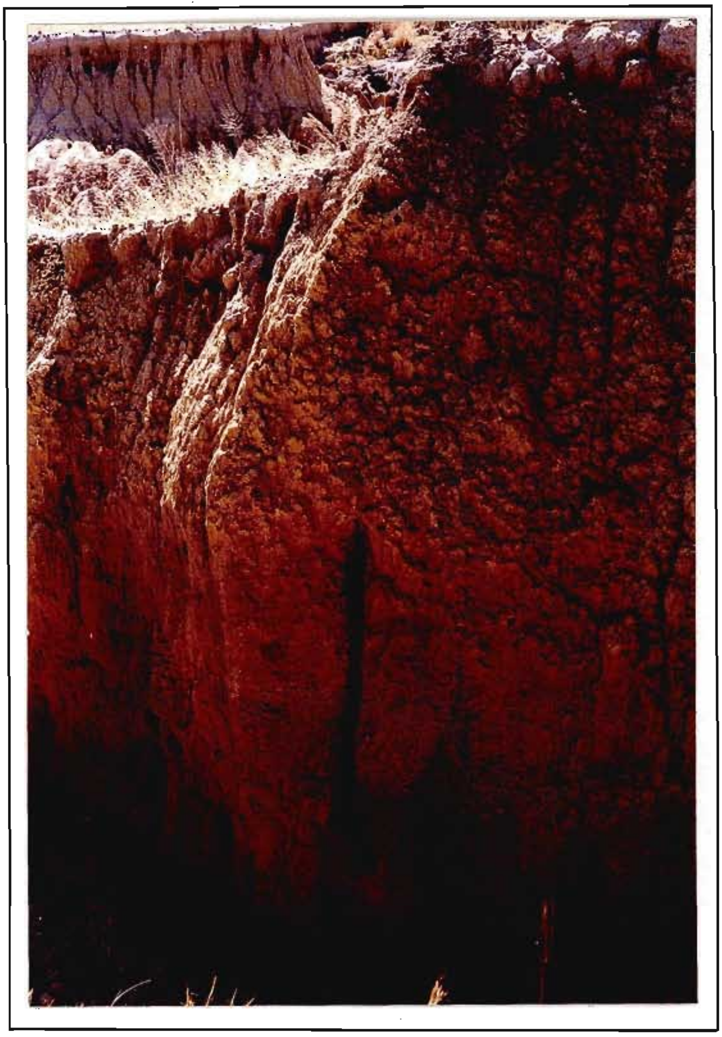


Figure 5.2.14(a): Vertical planes of weakness being enlarged through macro-pore activity that will ultimately lead to further sidewall piping.



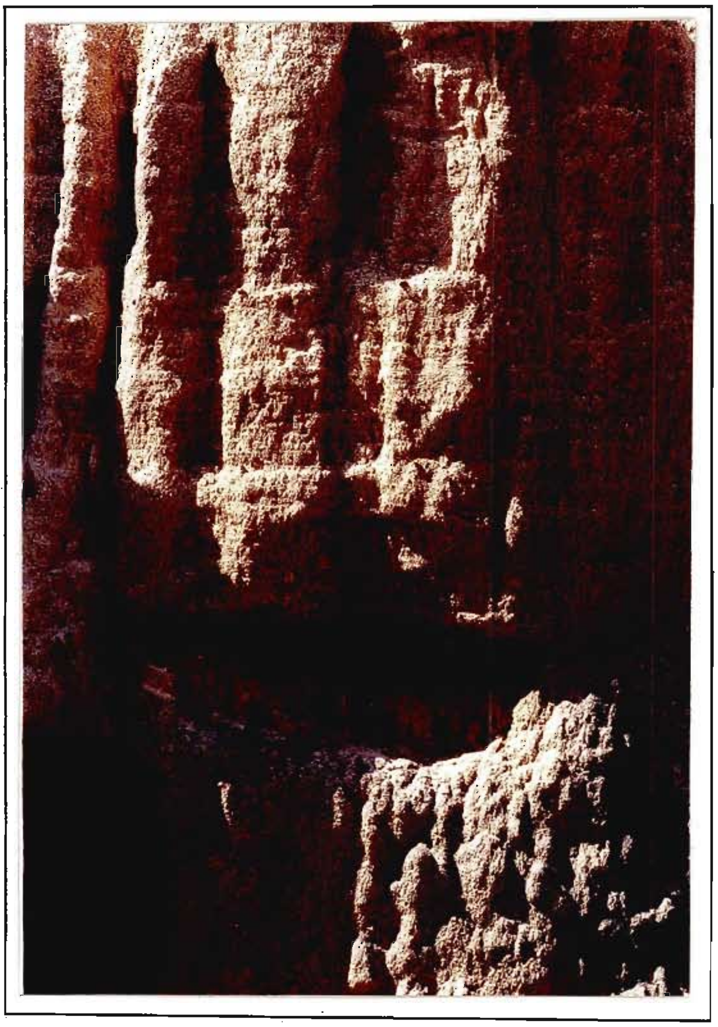


Figure 5.2.14(b): The opening up of macro-pores in the horizontal by utilizing weaknesses along pseudo-bedding planes.

The genesis of gully sidewall pipes (and their morphology) may be understood when these systems are viewed within their hydrodynamic context in conjunction with the gully system to which they are linked. The floor of the gully represents the local base level for the soil moisture within the soil profiles of the region adjacent to the gully. As such there will be a down-draw of moisture along the gully margins toward the local base level (see the analogous discussion pertaining to streams, given by Ward, 1975). As the soils are well structured, such movement will be preferential along the inter-ped boundaries, which then behave as vertical conduits. This is evident in Figure 5.2.15 and is supported by an infiltration rate of 12.8 $l.hr^{-1}$ using a standard ring infiltrometer above a ped surface, whereas the equivalent mean value for the infiltration rate into the centre of a ped from the same soil and using a similar instrument was only 7.41 $l.hr^{-1}$. The comparable values for saturated infiltration rate are 2.1 $l.hr^{-1}$ as opposed to 0.7 $l.hr^{-1}$. The existing inter-ped boundaries will be accentuated by any desiccation and related shrinkage of the soil in response to prolonged periods of dry weather.

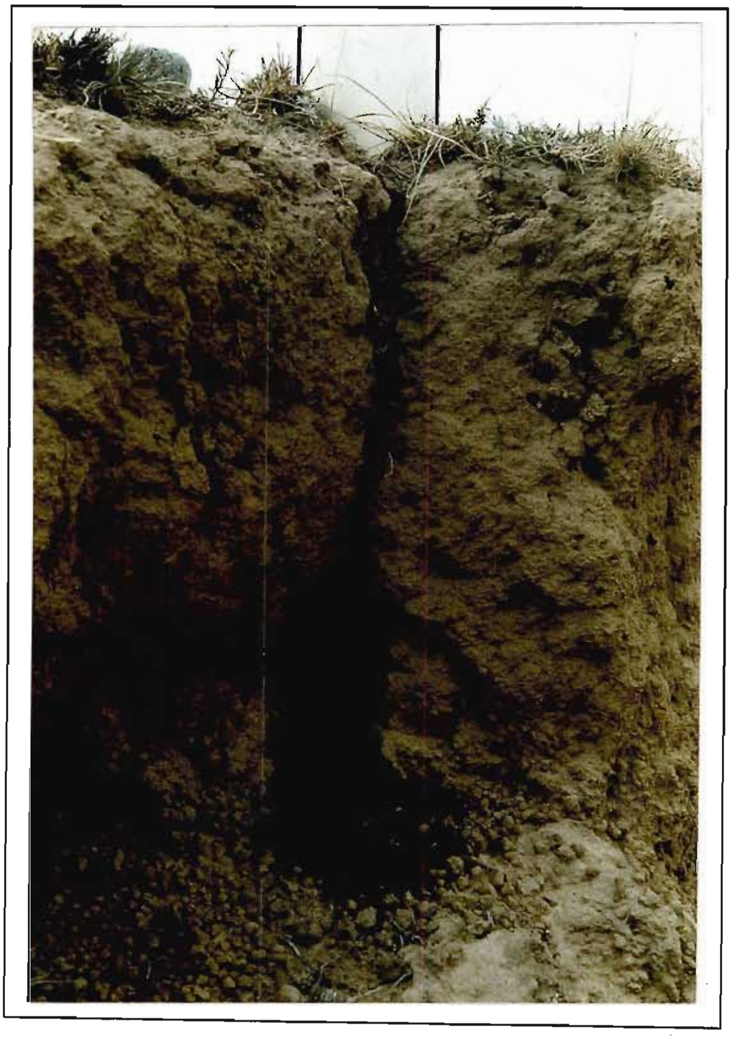


Figure 5.2.15: Photograph of the ring infiltrometer in use on the inter-ped surface. Note the position of the wetting front into the soil from the structural surface.

When precipitation occurs, water will filter down the vertical fissures; a process that is potentially enhanced by an increased surface water supply related to slope wash contributing water to the gully sides as would be the case with valley-bottom gullies.

Figure 5.2.16: A close-up view of the gully sidewall veneer which is easily transformed into a mobile slurry.

A combination of moderately high infiltration rates into the side of the ped surface coupled with the relatively low liquid limit and a highly efficient dispersion process results in the surface veneer of the soil becoming mobile. The efficiency of this process may be gauged from the fact that observation of gully sidewalls during precipitation events with a maximum intensity of 5 mm per hour and antecedent moisture conditions of the same order of magnitude as shown in Table 5.2.2 caused the outer soil veneer of the gully sidewall shown in Figure 5.2.16 to become a slurry which was mobile under the influence of gravity. Such processes also occur along the inter-ped surfaces. This mechanism will clearly be enhanced by the more rapid throughflow of water during conditions of higher antecedent soil moisture. Once initiated, this process of cavity development becomes self-sustaining.

The above genesis accounts for the characteristic short mean value of the gully sidewall pipe systems, as the length is directly related to the down-draw of moisture in proximity to the gully sidewall, which is itself in part a function of the depth to which the gully system has incised. Once sidewall piping has resulted in an embayment of the sidewall, the potential exists for further piping to re-develop, thus creating a tributary extension to the gully system.

5.3 Type 3 Systems: Anthropogenically Induced Subsurface Erosion

As discussed in Chapter 2, the prevailing consensus among researchers at present is that subsurface erosion, and specifically piping, is a form of natural erosion within the landscape. If this view is indeed correct, the causative mechanisms and genesis of this form of erosion is primarily of academic interest and has little, if any, practical value. It is evident from the work of Jones (1981; 1990) as well as from Sections 5.1 and 5.2 that under favourable pedogenic conditions all that is required to trigger the onset of pipe development is a concentration of water on the soil surface so as to ensure a period of sustained flow of water through the soil profile,removing the fine clay fraction in suspension. Clearly, such situation may occur relatively commonly when surficial slope wash is concentrated in topographic depressions as in the case studies cited by *inter alia* Beckedahl (1977); Jones (1981) and Nordström (1988). A similar situation may, however, arise where surface water is concentrated as a direct result of human interference within the landscape; the criterion now generally accepted to classify particular phenomena as forms of accelerated erosion (Hóly, 1980; Boardman *et al.*, 1990).

The systems reported in detail in this section occur in road embankments near the Langeni Forest Station and at the Qabata store near Umtata; in poorly drained contour

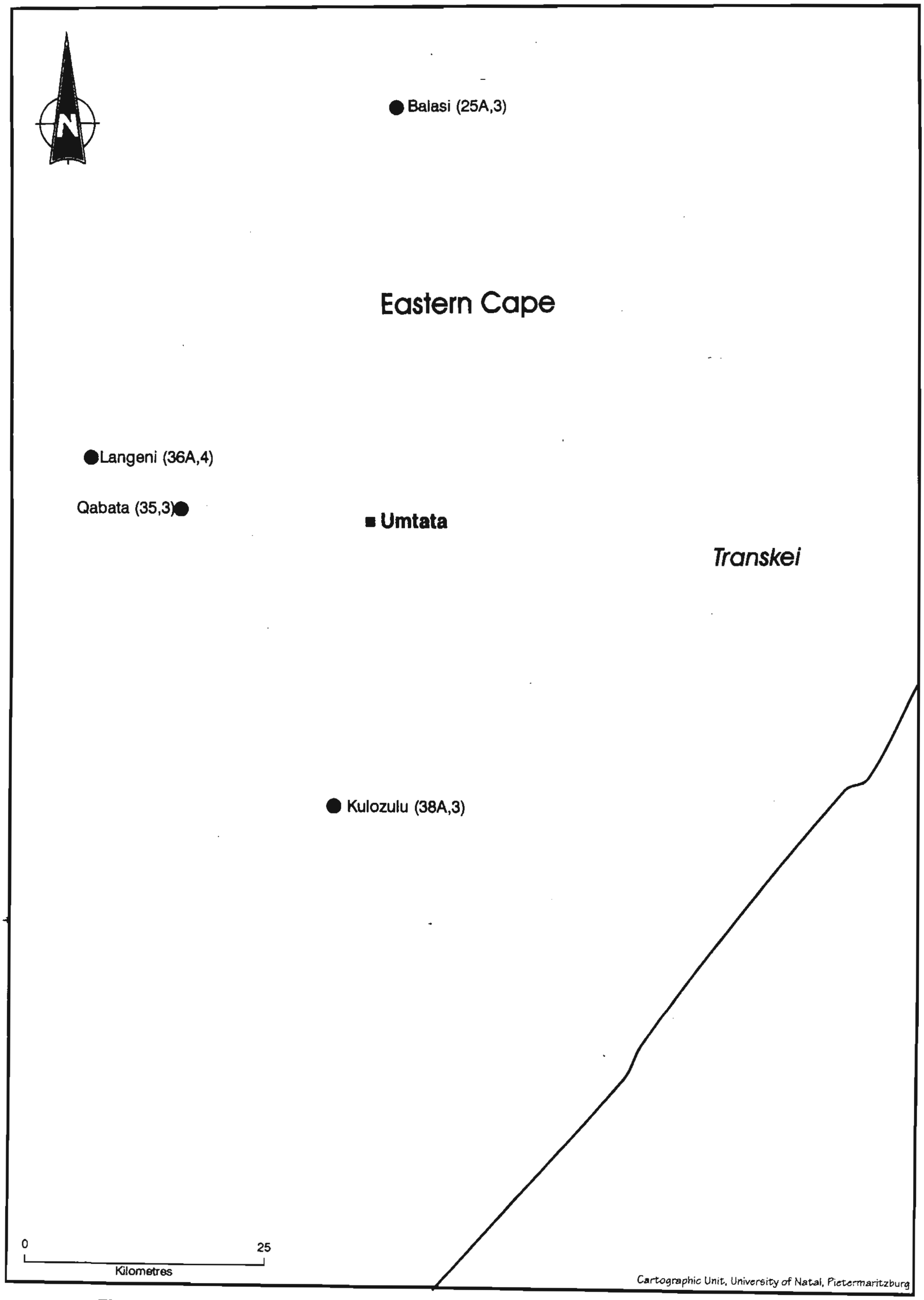


Figure 5.3.1: Location of field sites for anthropogenically induced subsurface erosion.

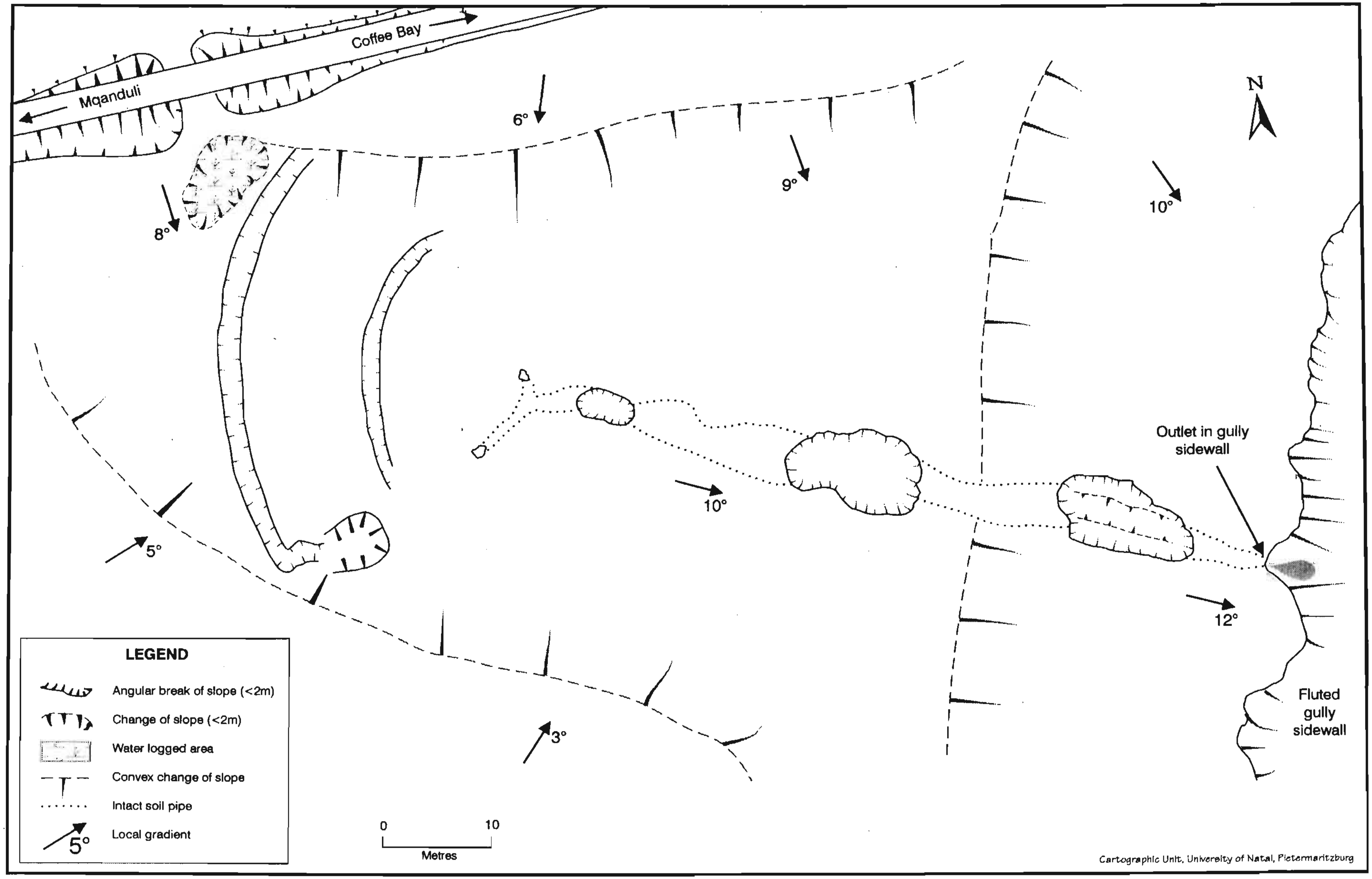


Figure 5.3.1.1: Map of the KuLozulu site, showing the piping associated with the road drainage.

embankments at Balasi near Qumbu, and as a consequence of road drainage at KuLozulu in the Mqanduli district (Figure 5.3.1). Although there is a large degree of commonality between the forms of anthropogenically induced subsurface erosion, they will be treated separately for ease of discussion.

5.3.1 Piping Associated with Road Drainage

Piping related to infrastructural development (*ie.* as a consequence of anthropogenic influence) was first recorded in the region by Beckedahl and Dardis (1988) for two sites west of Umtata. The best developed system associated with the concentration of runoff from road surfaces, however, occurs near Mqanduli south east of Umtata at the KuLozulu site (Figure 5.3.1.1). The system is developed in a relatively thick (0.5 to 8 m) veneer of stratified colluvium above weathered mudstone. The pipe system itself attains a maximum depth of 2 m below surface, but feeds into an extensive gully system, which itself has developed in response to a culvert (Figure 5.3.1.2) on a hillside in a topographic hollow and attains a maximum depth of 8m.

The pipe system has developed on the down-slope side of a road culvert immediately below a small depression in which surface runoff has ponded (Figure 5.3.1.3). Analysis of aerial photography indicates that the pipe system has developed subsequent to 1984 when the main tar road to Coffee Bay was constructed. The soil varies between a loam and a silty loam and is well structured. The field soil has a high shear resistance in the A and C horizons, decreasing slightly in the B horizon (Table 5.3.1).

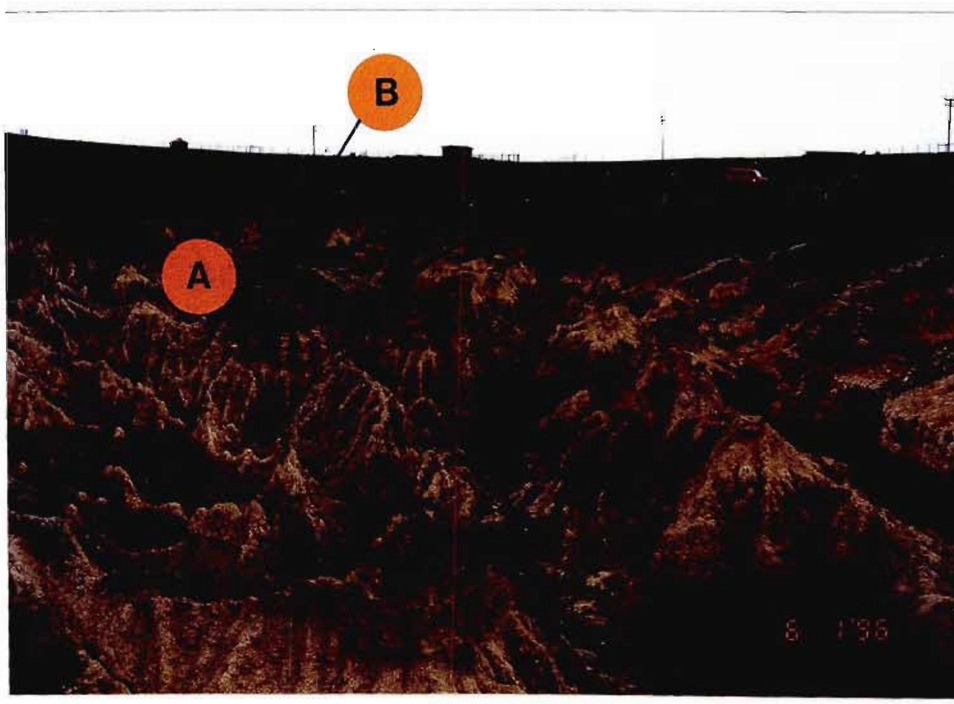


Figure 5.3.1.2: The KuLozulu site, showing the relative position of the topograpnhic depression (A), and a second culvert (B).

Figure 5.3.1.3: The pipe system downslope of the road culvert shown in Figure 5.3.1.2.

Table 5.3.1: The physical properties of soils displayong pipes related to anthropogenic influence.

SITE AND SOIL HORIZON / PARAMETER	LANGENI		QABATA			BALASI			KULOZULU		
	A	B	A	B	C	A	B	C	A	B	C
PROFILE THICKNESS	25	70	40	60	90	40	50	70	30	25	45
COLOUR	10YR6/6 BROWNISH YELLOW	5YR6/6 REDDISH YELLOW	10YR6/3 PALE BROWN	10YR5/4 YELLOWISH BROWN	5YR5/3 REDDISH BROWN	10YR6/3 PALE BROWN	10YR7/6 10YR6/8 MOTTLED	7.5YR6/4 LIGHT BROWN	10YR5/4 YELLOWISH BROWN	2.5Y6/4 LIGHT YELLOWISH BROWN	2.5Y6/3 LIGHT YELLOWISH BROWN
SOIL FORM	GLENROSA (*LITHOSOL*)		VALSRIVIER (*ALFISOL*)			STERKSPRUIT (*ALFISOL*)			OAKLEAF (*INCEPTISOL*)		
TEXTURE											
SAND %	46.4	36.6	52.2	54.0	55.6	52.3	46.1	45.8	36.3	34.9	26.4
SILT %	36.4	33.3	28.5	24.6	12.4	28.4	26.5	24.5	44.5	35.1	56.0
CLAY %	17.2	30.1	19.3	21.5	32.0	19.3	27.5	29.7	19.2	31.0	17.6
MEAN ϕ	0.3	1.5	0.8	0.5	-1.1*	0.4	0.0	-0.5	-0.6	-0.7	-1.4
MEDIAN ϕ	0.0	2.0	1.2	0.4	-1.8*	0.5	-0.3	-1.0	-1.0	-0.6	-1.5
DESCRIPTION	LOAM	CLAY	SANDY LOAM	SANDY CLAY LOAM	SANDY CLAY	SANDY LOAM	CLAY LOAM	CLAY LOAM	LOAM	CLAY LOAM	SILTY LOAM
STRUCTURE	BLOCKY	PRISMATIC	COLUMNAR	BLOCKY	BLOCKY PLINTHIC	COLUMNAR	PRISMATIC	BLOCKY	COLUMNAR	CRUMB	PLATY (WEATHERED MDS)
GEOTECHNICAL											
LIQUID LIMIT %	16.0	42.0	17.0	16.0	28.0	16.0	19.0	21.0	21.0	22.0	31.0
PLASTIC LIMIT %	5.0	18.0	6.0	6.0	11.0	4.0	8.0	6.0	4.0	8.0	11.0
LINEAR SHRINKAGE %	2.5	9.0	3.0	3.0	5.5	2.0	4.0	3.0	2.0	4.0	5.5
HAND SHEAR VANE (kPa)	117.0	7150.0	118.0	72.0	7150.0	115.0	86.0	7150.0	135.0	89.0	145.0
BULK DENSITY ($g.m^{-3}$)	1.79	2.01	1.69	1.82	1.89*	1.24	1.95	1.71*	1.75	1.71	2.19
ERODIBILITY (K VALUE)	0.33	0.34	0.25	0.26	0.10	0.31	0.19	0.20	0.41	0.33	0.51

The liquid limit increases down profile as does the plasticity index. There is an overall concentration of fines in the C horizon at the expense of the sand fraction. This is, however, not evident from the sieve analysis (**Figure 5.3.1.4**) due to an increase in the degree of aggregation down profile. The bulk density of the A and B horizons is similar but there is a sharp increase in density within the C horizon. Such increase in density may be ascribed to the greater concentration of fines within that horizon.

The KuLozulu site receives a higher annual precipitation than the Type 2 systems, but the precipitation is still strongly seasonal and has a slightly poorer distribution over the year with a value of only 24.4% *ie.* precipitation is concentrated into only a few events (**Table 5.3.2**). The consequence of this is that the relative intensity of the precipitation is higher at effectively 40 units for KuLozulu in contrast to 25 units at Ncise. As has already been discussed, the relative intensity is an indirect measure both of the rainfall energy and therefore also of the relative abundance of water available for surface runoff. The KuLozulu value for mean annual precipitation is therefore misleading, as it does not adequately reflect the increased surface water availability due to the artificial concentration of artificial concentration of part of the road- and slope wash.

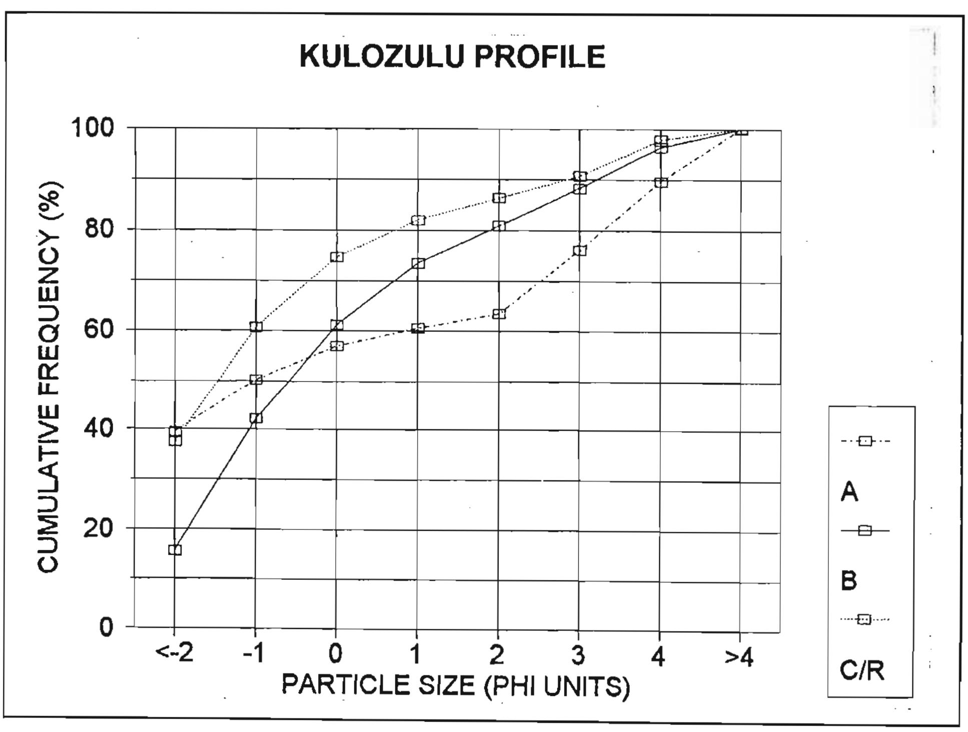


Figure 5.3.1.4: Cumulative frequency of grain size for the KuLozulu soil profile.

Table 5.3.2: Soil hydrological and associated conditions for pipes related to anthropogenic influence.

PARAMETER \ SITE AND SOIL HORIZON	LANGENI		QABATA			BALASI			KULOZULU		
	A	B	A	B	C	A	B	C	A	B	C
PROFILE THICKNESS (cm)	25	70	40	60	90	40	50	70	30	25	45
TEXTURE											
SAND %	46.4	36.6	52.2	54.0	55.6	52.3	46.1	45.8	36.3	34.9	26.4
SILT %	36.4	33.3	28.5	24.6	12.4	28.4	26.5	24.5	44.5	35.1	56.0
CLAY %	17.2	30.1	19.3	21.5	32.0	19.3	27.5	29.7	19.2	31.0	17.6
DESCRIPTION	LOAM	CLAY	SANDY LOAM	SANDY CLAY LOAM	SANDY CLAY	SANDY LOAM	CLAY LOAM	CLAY LOAM	LOAM	CLAY LOAM	SILTY LOAM
STRUCTURE	BLOCKY	PRISMATIC	COLUMNAR	BLOCKY	BLOCKY PLINTHIC	COLUMNAR	PRISMATIC	BLOCKY	COLUMNAR	CRUMB	PLATY (WEATHERED MDS)
PRECIPITATION TOTAL (mm pa)	1020.0		1020.0			783.6			966.3		
SEASONALITY %	78.8		78.7			78.8			65.7		
DISTRIBUTION OVER YEAR %	27.1		27.1			20.8			24.4		
INTENSITY %	37.6		37.6			37.6			39.6		
SOIL HYDROLOGY											
FIELD MOISTURE %	1.1	9.4	2.4	3.8	7.2	2.8	4.8	4.2	2.3	6.1	3.0
FIELD CAPACITY %	30.6	45.9	15.2	26.0	18.7	15.5	33.0	24.2	17.5	34.0	40.7
SATURATION POTENTIAL %	26.8	43.4	30.9	24.1	28.2	20.1	40.7	37.1	30.6	38.4	50.9
INFILTRATION RATE (ml.hr^{-1})	19.4	5.5	28.6	11.7	N/A	27.5	10.9	N/A	12.7	8.3	0.3
SATURATED INFILTRATION RATE (ml.hr^{-1})	2.8	1.2	11.0	2.7	N/A	10.8	3.0	N/A	4.1	8.0	0.1
BULK DENSITY (g.m^{3})	1.79	2.01	1.69	1.82	1.89'	1.24	1.95	1.71'	1.75	1.71	2.19
ERODIBILITY (K VALUE)	0.33	0.34	0.25	0.26	0.10	0.31	0.19	0.20	0.41	0.33	0.51

Table 5.3.3: The characteristic soil chemistry of soils prone to piping related to anthropogenic influence.

PARAMETER / SITE AND SOIL HORIZON	LANGENI		QABATA			BALASI			KULOZULU		
	A	B	A	B	C	A	B	C	A	B	C
PROFILE THICKNESS (cm)	25	70	40	60	90	40	50	70	30	25	45
TEXTURE											
SAND %	46.4	36.6	52.2	54.0	55.6	52.3	46.1	45.8	36.3	34.9	26.4
SILT %	36.4	33.3	28.5	24.6	12.4	28.4	26.5	24.5	44.5	35.1	56.0
CLAY %	17.2	30.1	19.3	21.5	32.0	19.3	27.5	29.7	19.2	31.0	17.6
DESCRIPTION	LOAM	CLAY	SANDY LOAM	SANDY CLAY LOAM	SANDY CLAY	SANDY LOAM	CLAY LOAM	CLAY LOAM	LOAM	CLAY LOAM	SILTY LOAM
ORGANIC CARBON %	0.4	0.3	1.0	0.4	0.3	0.5	0.2	0.0	1.2	0.4	0.2
SOIL CHEMISTRY											
DISPERSION RATIO %	18.9	16.4	14.9	13.3	11.6	12.8	17.0	17.0	11.1	22.2	14.1
CEC ($cmol.kg^{-1}$)	14.2	21.0	16.5	13.5	23.3	11.3	27.8	18.9	20.3	26.3	29.3
EC ($mS.m^{-1}$)	44.9	11.0	59.1	30.0	21.7	96.6	250.0	83.5	211.0	234.0	580.0
ESP	0.3	0.2	0.8	0.6	0.5	1.6	2.2	3.1	1.7	7.4	19.0
SAR	1.6	2.9	2.4	3.4	2.8	2.4	4.6	7.0	3.3	12.8	17.8
pH	5.6	5.3	5.4	6.5	6.7	6.6	5.9	7.4	5.4	7.1	7.7
ERODIBILITY (K VALUE)	0.33	0.34	0.25	0.26	0.10	0.31	0.19	0.20	0.41	0.33	0.51

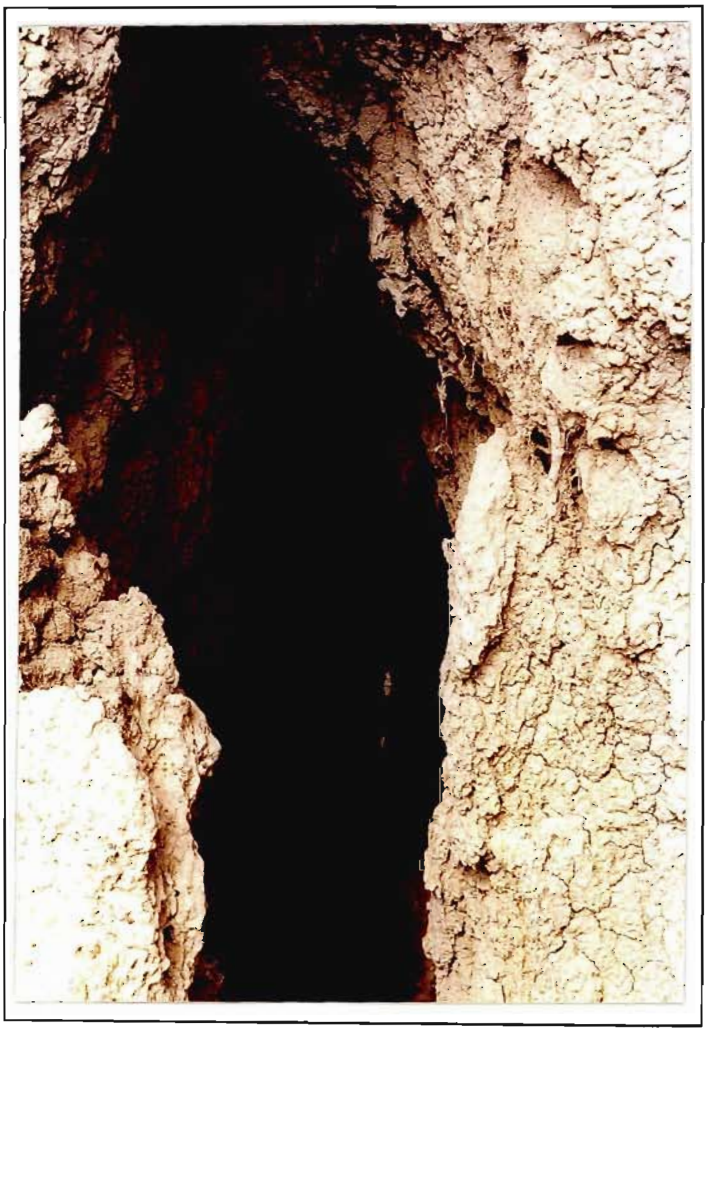


Figure 5.3.1.5(a): Pipe outlet form as determined by soil macro-structure.

Figure 5.3.1.5(b): A close-up view of the oultet pipe into the Mqanduli gully system, near KuLozulu.

Although seasonal desiccation will still occur which, in combination with soil structure accounts for pipe outlet form (Figure 5.3.1.5(a) and (b)), the effects of such desiccation will be somewhat mitigated by the relative increase in water availability. The A and C horizons have high erodibility (K) values of 0.41 and 0.51 respectively, whereas the B horizon has a moderate erodibility value of 0.33. The increased field moisture of 6% within the B horizon may be explained by the greater overall moisture availability for the reasons already discussed, combined with the increased clay content within this horizon. The high saturation potential of the C horizon is due to the combined moisture availability, the increased bulk density and the larger percentage of fines within that layer.

From the perspective of soil chemistry indicated in Table 5.3.3 there is again an increase in pH, CEC and EC values down profile, indicative of illuviation and partial leaching of the fine fraction. High values of ESP and the dispersion ratio indicate that the B horizon is susceptible to piping but although high, the SAR value of 12.8 is below the arbitrary value of 15 considered by Heede (1971) to be critical. The situation in the C horizon is the reverse - the dispersion ratio of 14 is less than the arbitrary 18 used as a critical value, but *both* the ESP and SAR values are greater than the critical values. It can therefore be concluded that *both* the B and C horizons are at least partially susceptible to pipe development.

The K values mentioned previously now become significant in that, once a soil pipe has formed and provided that one accepts the limitations of the nomograph as outlined at the beginning of this Chapter, the values are a first approximation of the potential for pipe enlargement by flow entrainment and *quasi* fluvial erosion processes.

5.3.2 Piping Associated with Contour Embankments

The data and discussion in Section 5.3.1 attest to the potential effect which water may have when ponded on a dispersive soil, as previously reviewed in Section 2.3.1.

Figure 5.3.2.1(a): A pipe intake developed along desiccation cracks on the up slope side of a contour embankment, Balasi, Qumbu district.

Figure 5.3.2.1(b): The vertically-elongated outlet of the pipe shown in Figure 5.3.2.1(a) on the down slope side of the contour embankment. The notebook denotes scale.

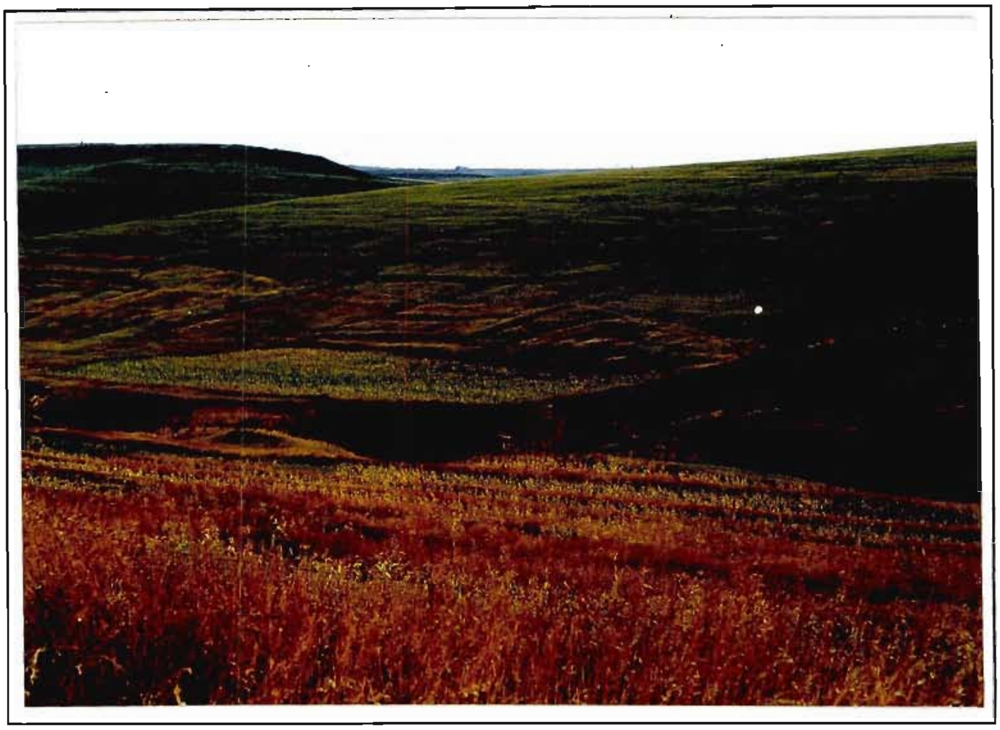


Figure 5.3.2.2(a): A slope dissected by gullies that were initiated by piping.

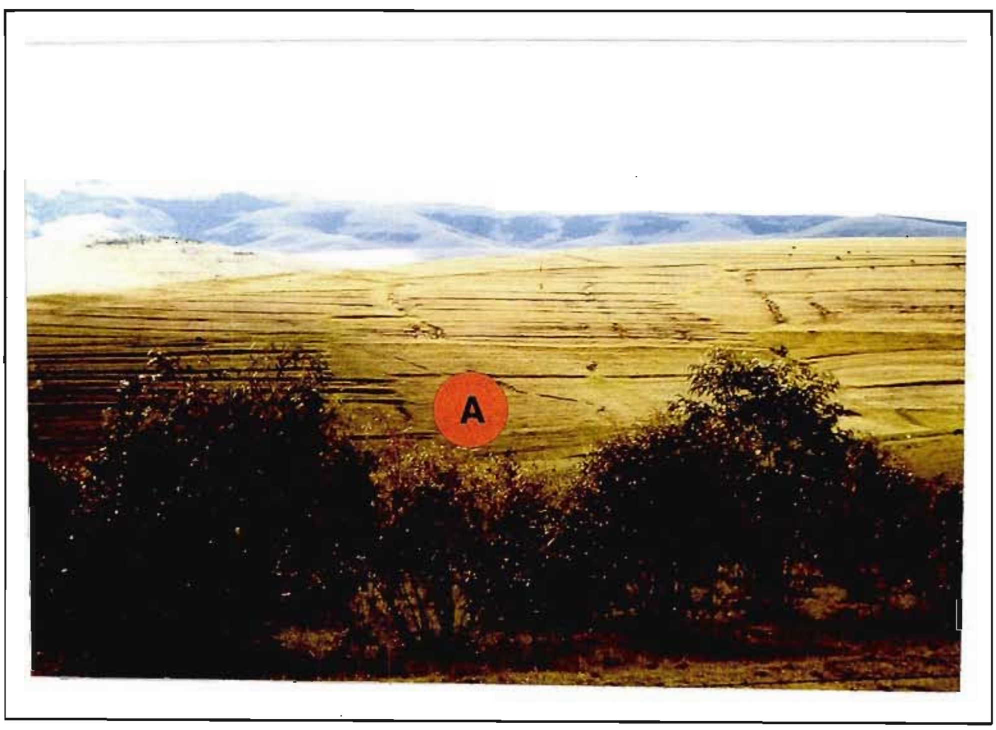


Figure 5.3.2.2(b): A contoured slope at Balasi near Qumbu, on which pipes have cut through beneath the contour embankments. Note that the pipes (eg. A) do not necessarily follow the topographic gradient.

By contrast with those in North America and many European countries, very few contour embankments in the KwaZulu-Natal-Transkei region are drained by the use of porous pipes. For economic reasons embankments are generally constructed with a regional slope of some 0.5° to 1° towards the nearest topographic depression and are then drained by using a system of grassed waterways (Schwab *et al.*, 1981). Although this system is functional, implicit within it is the tacit acceptance of a high infiltration of slope wash along the embankment itself. This may initiate piping as shown in Figure 5.3.2.1(a) and (b). The mean length of such pipes is approximately 3 m but this figure is misleading as a single slope usually contains several piped embankments which then rapidly progress to open gully systems as seen on two slopes at Balasi near Qumbu (Figure 5.3.2.2(a) and (b)).

The soil at Balasi (Table 5.3.1) consists of a sandy loam in the A horizon and shows marginal clay enrichment down profile. As these are agricultural soils, the boundaries (especially between the A and B horizons) are seldom as distinct as suggested in the three tables showing the pedogenic properties (Table 5.3.1; 5.3.2 and 5.3.3). Agricultural activities tend to destroy the strong structure of the soil horizons, such that the idealised profile discussed here only exists at isolated points near the down slope side of existing contour embankments. The overall coarsening of material down profile indicated in Figure 5.3.2.3 for the sieve analysis is again a function of the degree of aggregation of the soil.

The Atterberg Limits are comparable to those discussed for the other pipe systems. Shear strength values show the same pattern of a decrease for the B horizon and an increase again into the C horizon. The bulk density for the B horizons at Balasi is anomalously high and, although there is no immediate explanation for this observation, it may well be related to agricultural practice and incipient plough-pan development. Hydrologically, Balasi receives some 780 mm of precipitation annually, which is relatively low. The RDI shows a distinct seasonality as before and, given the poor distribution of rainfall during the year (20.8%), it would appear that the profile is subjected to periodic desiccation despite the additional slope wash collected by the contour embankment. The A horizon has a relatively high infiltration rate and a very high saturated infiltration rate (10.8 $l.hr^{-1}$), suggesting that water is readily fed into the B and C horizons where it is retained as indicated by the high saturation potential which, in turn, is related to the clay content of these horizons.

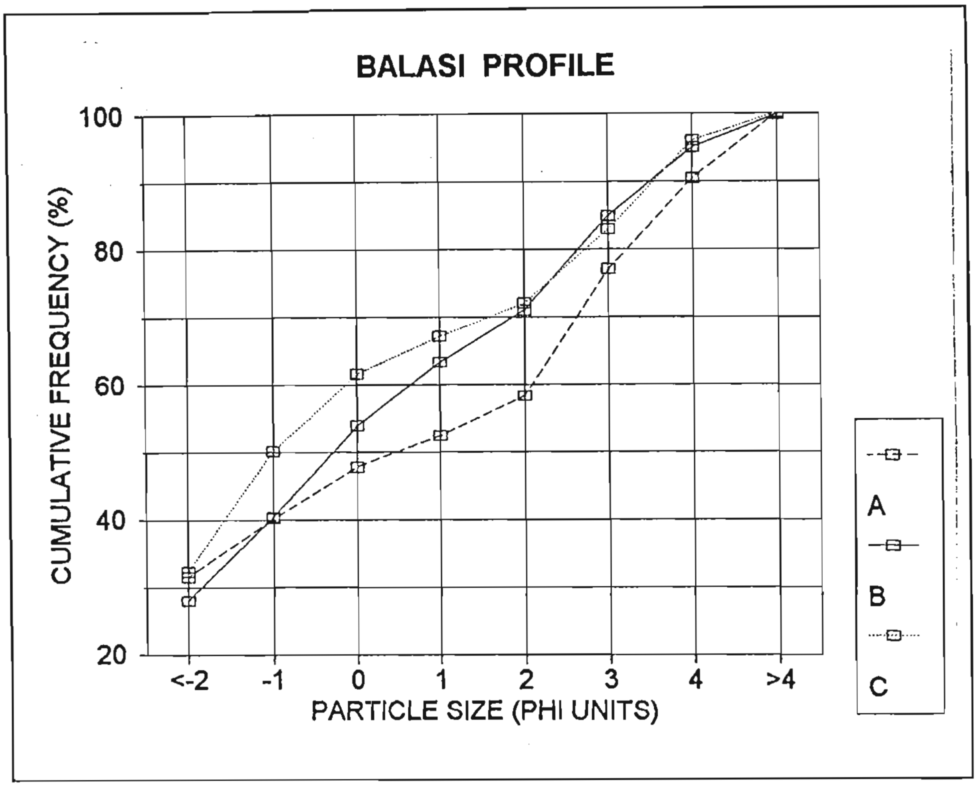


Figure 5.3.2.3: Cumulative frequency distribution of grain size for the Balasi soil profile.

The soil chemistry again reflects the downward translocation of fines with the associated increase in pH values. The profile is, however, anomalous in that although the B and C horizons approximate to the critical value for the dispersion ratio, all other indexes used to ascertain the susceptibility of a soil to dispersion are well below accepted critical levels. The K values at Balasi are relatively low, other than for the A horizon which is susceptible to wash erosion. This does, however, have important implications in terms of the contour embankments, because there is clearly a further risk beyond that associated with infiltration and piping: if the A horizon is removed, the dispersive B horizon is exposed. Although this layer has a low K value, it is erodible in that material will be entrained by surface water subsequent to having been dispersed.

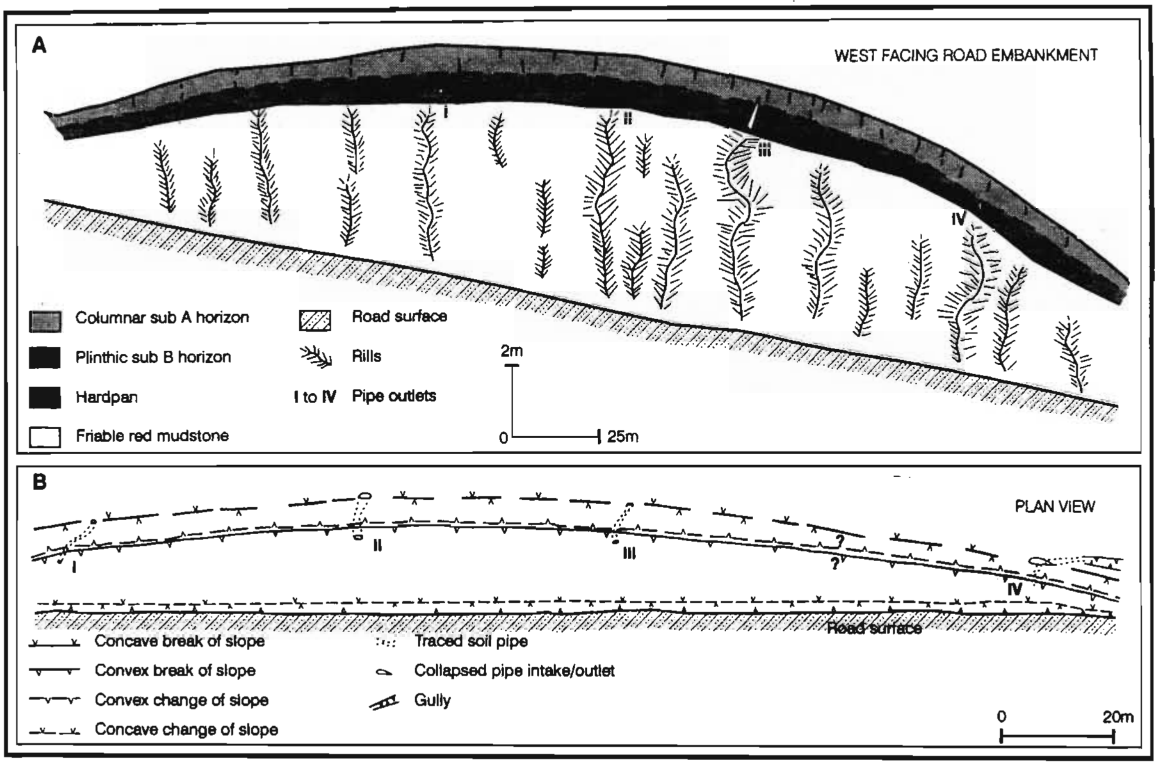


Figure 5.3.3.1: Map of the Qabata road embankment (**A**) and the associated pipes. (**B**) is a plan view showing the extent of the pipes.

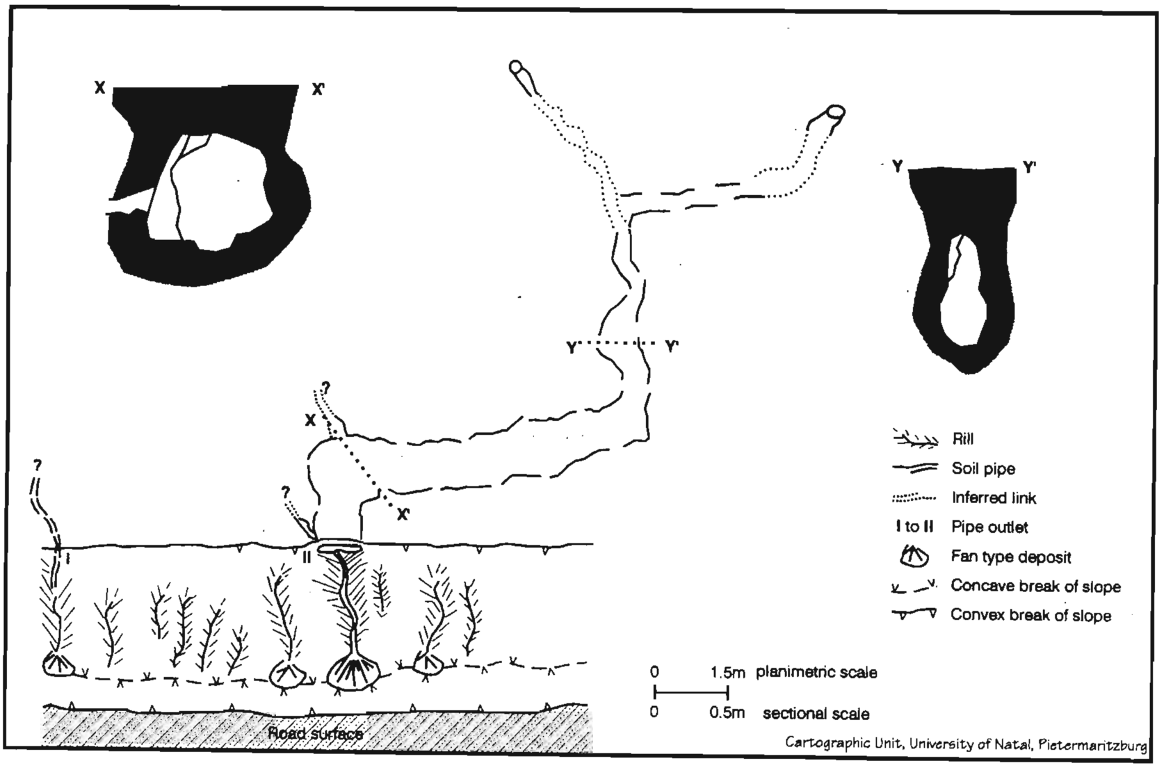


Figure 5.3.3.2: The Langeni system, showing the embankment pipe (**I**) and the main pipe(**II**)

5.3.3 Piping Associated with Cut Embankments

In construction (and specifically, though not exclusively, road engineering) it is conventional practice to drain the back slopes of cut embankments. There are two principal reasons given for this:

- to restrict the quantity of water flowing over the cut slope which for practical and economic reasons is as steep as is sustainable with respect to concerns regarding geotechnical rather than erosional stability, and
- to limit the quantity of water accumulating at the base of the cut section.

Such drainage is generally achieved by means of a 0.5 m deep ditch constructed some 1.5 to 2 m upslope of the cut section. This practice does, however, have two potential disadvantages. The soil is disturbed to the extent that the A horizon is generally destroyed and further, these drainage lines are seldom armoured, so that they are susceptible to wash erosion unless vegetated, in which case they represent a zone of concentrated infiltration.

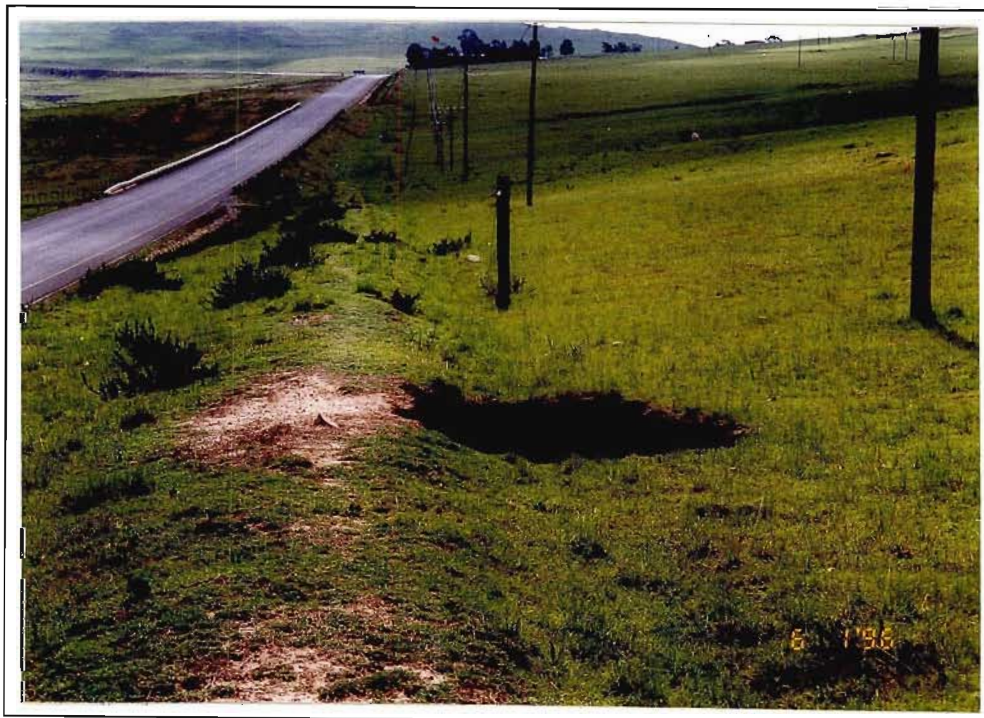


Figure 5.3.3.3: Collapsed pipe intake developed within the back slope drainage line at Qabata and opening onto the embankment in Figure 5.3.3.4.

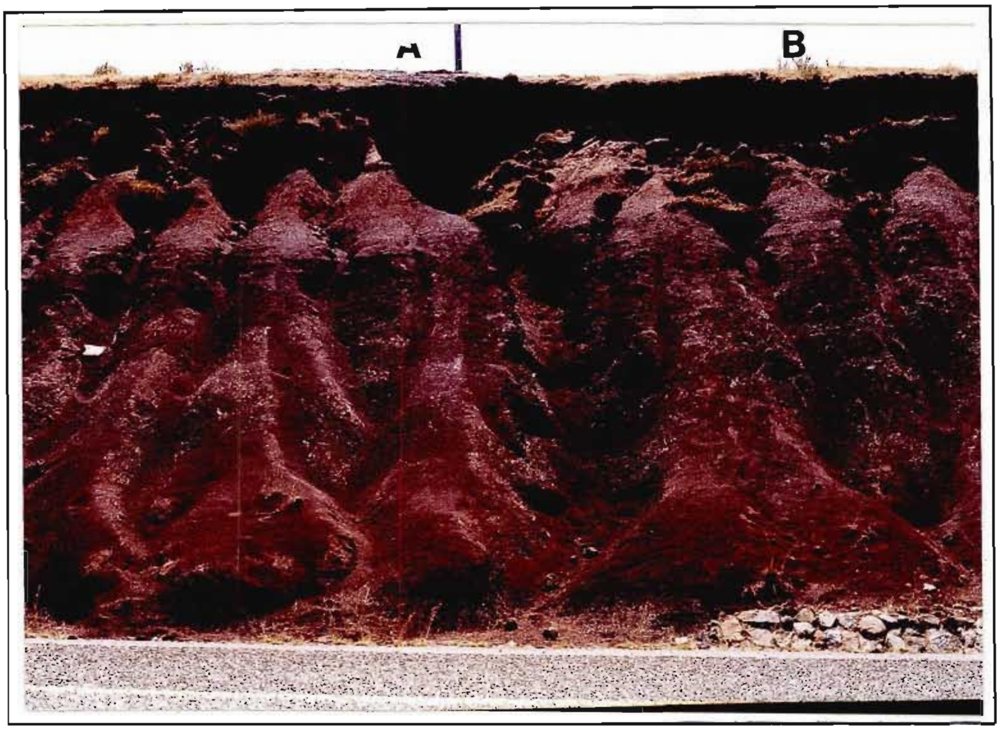


Figure 5.3.3.4(a): View of the Qabata embankment, showing pipes (II) and (III) from Figure 5.3.3.1 at points A and B respectively.

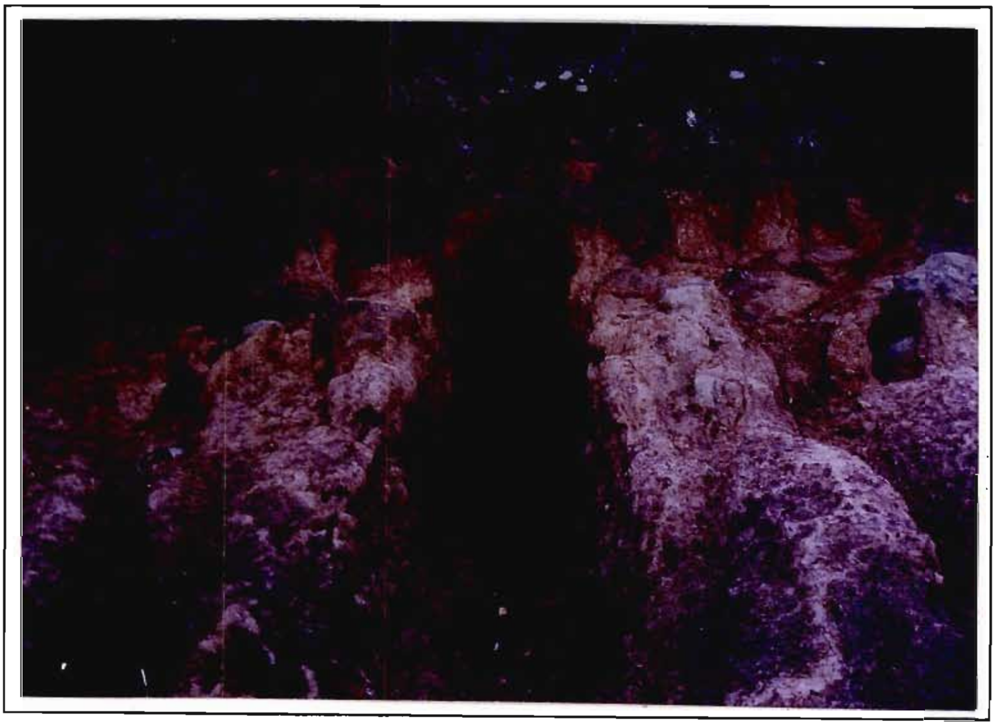


Figure 5.3.3.4(b): The Langeni cutting, showing pipe (I) from Figure 5.3.3.2.

The discussion in Section 5.2 has focussed attention on the role of local base levels within the soil hydrology. In essence a situation analogous to the drop of local base level associated with gully incision is created when a spur is truncated to create a cut embankment. Such situations are a common occurrence throughout the study area, and are typified by the Qabata and Langeni sites shown in Figures 5.3.3.1 and 5.3.3.2 respectively. A total of four short pipes have developed within the backslope drainage line at Qabata (Figure 5.3.3.3), through beneath the soil profile and opening onto the upper part of the cut embankment, illustrated in Figures 5.3.3.4(a), and (b). The soil texture (Table 5.3.1) reflects the soil as being well structured, varying down profile from a sandy loam to a sandy clay. The C horizon at Qabata is plinthic and it is primarily these concretions which account for the coarse fraction within the C horizon. Some 80% of the material by weight is coarser than 1 mm (Figure 5.3.3.5). This coarse material is largely excluded from the hydrometer analysis of texture but is included in the determination of the mean and median size fractions. The size fractions of the Langeni profile (Figure 5.3.3.6) are by contrast evenly distributed.

Hand shear vane values again show the decrease in strength of the B horizon already discussed in the context of several of the other sites. Values for the Atterberg Limits too are similar to those of the profiles at Balasi and KuLozulu; the increased liquid limit, linear shrinkage values and increased bulk density for the C horizon again being ascribed to the concentration of clays at this point within the two type-profiles.

The precipitation at Qabata and Langeni has mean values of 1020 mm pa. and is strongly seasonal with a Rainfall Distribution Index (RDI) of 78.7%. It is slightly more evenly distributed than at the Balasi and KuLozulu sites, but shows no meaningful difference with respect to relative rainfall intensity (Table 5.3.2). At both the Langeni and the Qabata sites field moisture conditions show a marked increase towards the base of the profile in response to both the hydrological and topographic gradients. As at other sites, the saturation potential in the basal horizons is increased due to the increased presence of clays although the pattern is masked somewhat at Qabata due to the iron pan nodules. The infiltration rates into the A horizon are high, especially at Qabata, and again attest to the duplex nature of the soils.

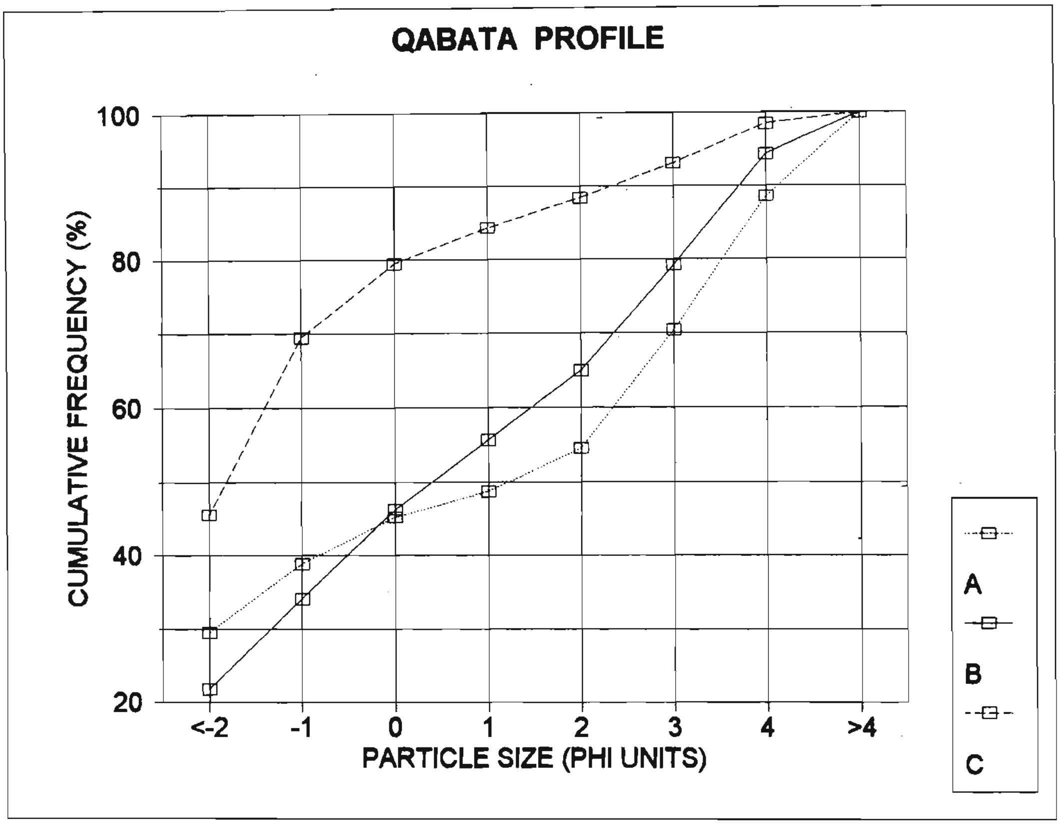


Figure 5.3.3.5: Cumulative grain size distribution for the Qabata-type soil profile.

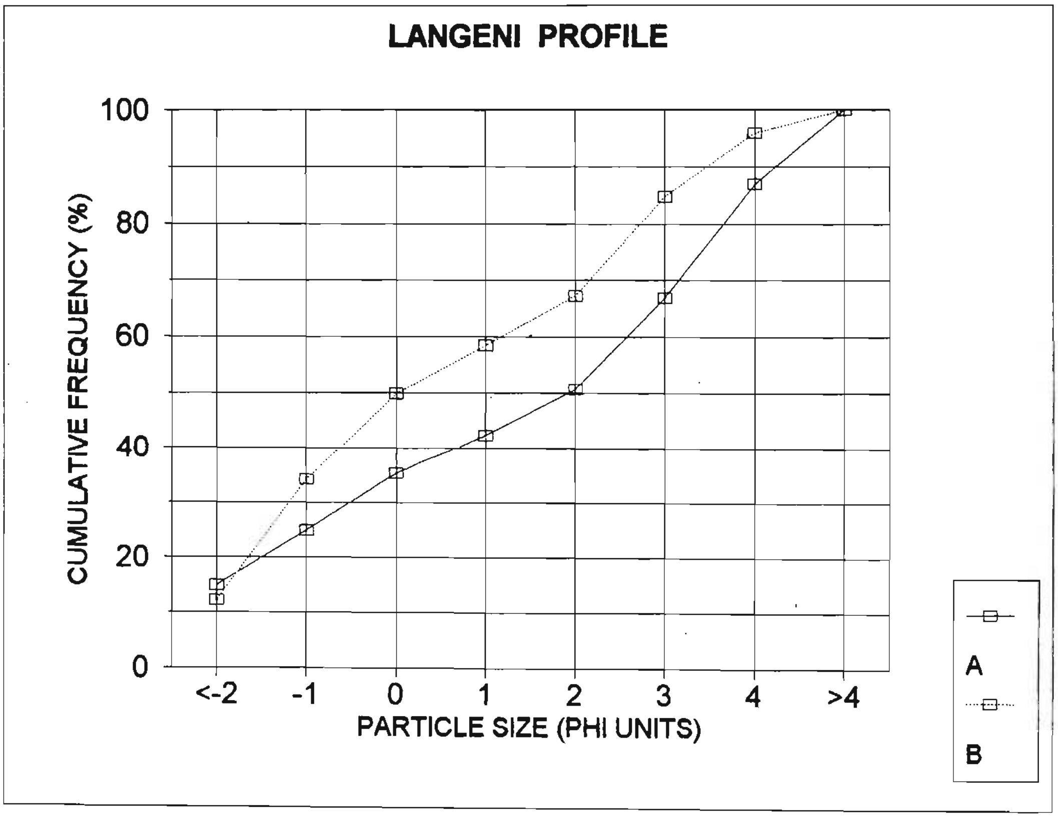


Figure 5.3.3.6: Cumulative grain size distribution for the Langeni-type soil profile.

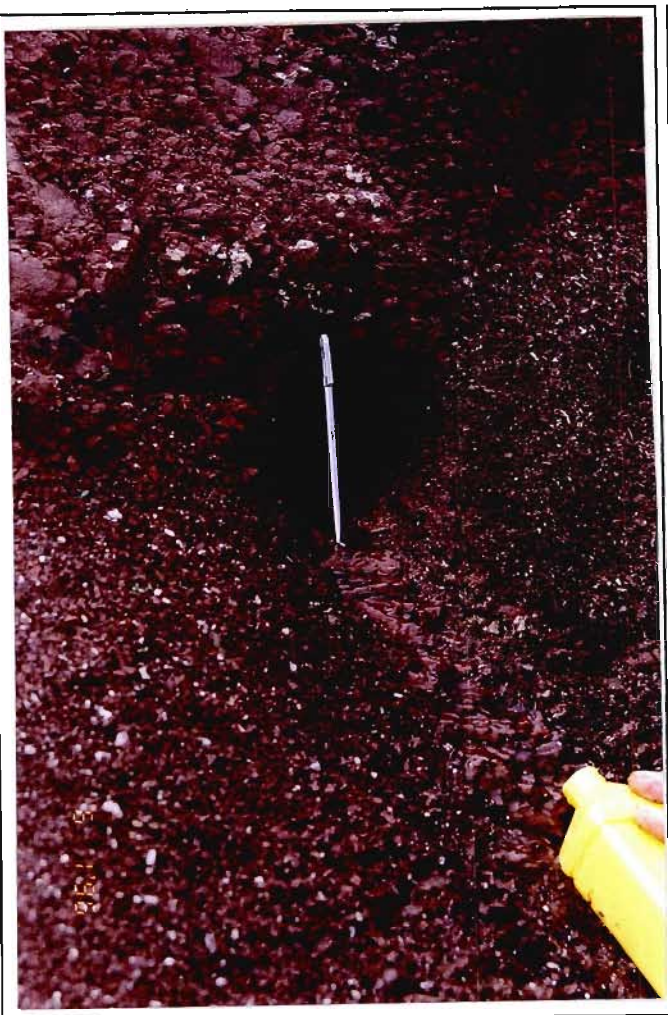


Figure 5.3.3.7: Discharge from a micro-pipe formed within the weathered red mudstones at Qabata.

PARTICLE SIZE ANALYSIS BY SA-CP3

SAMPLE ID 01
SAMPLE # 01

P DENSITY 2.63 MODE :MULTI
L DENSITY 1.0707 240(RPM/MIN)
VISC.(mPa.S)2.157
DEPTH 2

TIME 0:18:38

<DATA SUMMARY>

MEDIAN DIAM. 16.35 (μm)
MODAL DIAM. 23.05 (μm)
SURFACE AREA 0.388 (m*m/g)

<PARTICLE SIZE DISTRIBUTION DATA>

	DIAM. (μm)		TIME	ABS.	CHANGE (%)	CUM (R %)
01	100.000	G	0:00:04	0.983		0
02	80.000	G	0:00:08	0.980	3.4	3.4
03	60.000	G	0:00:14	0.976	4.5	7.8
04	50.000	G	0:00:20	0.972	3.8	11.6
05	40.000	G	0:00:32	0.965	5.5	17.2
06	30.000	G	0:00:56	0.949	9.1	26.3
07	20.000	G	0:02:07	0.911	15.1	41.4
08	15.000	G	0:03:46	0.872	11.8	53.2
09	10.000	G	0:08:28	0.813	13.1	66.3
10	8.000	G	0:13:14	0.776	5.5	71.7
11	6.000	C	0:13:31	0.721	6.2	78.0
12	5.000	C	0:13:44	0.704	1.5	79.5
13	4.000	C	0:14:06	0.653	3.8	83.3
14	3.000	C	0:14:40	0.563	4.6	87.9
15	2.000	C	0:15:47	0.384	5.6	93.5
16	1.500	C	0:16:48	0.286	2.1	95.6
17	1.000	C	0:18:38	0.188	1.7	97.3
18	0			0	2.7	100.0

<SA-CP3 CUMULATIVE GRAPH>

SAMPLE ID 01
SAMPLE # 01

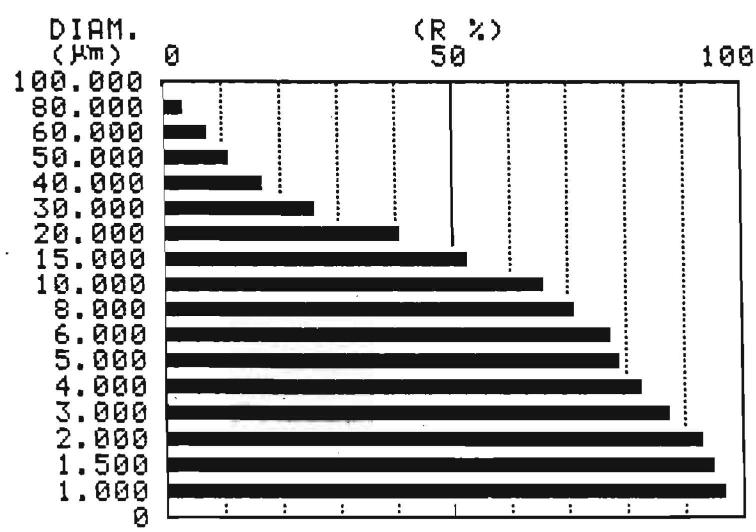


Figure 5.3.3.8: The plot obtained from the SA-CP3 partcle size analyzer for the discharge obtained from the pipe shown in Figure 5.3.3.7.

Soil chemistry is problematic for both the Qabata and the Langeni sites, as the data do not accord with current scientific opinion. Both soil profiles are acidic; the Langeni soil more so, as is to be expected given that the site occurs under a stand of mature commercial pine forest (*sp. Pinus pinaster*). What is unusual, however, is that there is a slight increase in *acidity* down profile despite clear increases in clay content. This pattern can only be explained by a significant down profile movement of humic acids occurring along the well structured inter-ped surfaces rather than by true infiltration through the soil itself. Concentration of the acids then occurs in the basal B horizon as a consequence of water retention reflected by the high value for the saturation potential and the low values for saturated infiltration rate. Although the Qabata soil also shows an acidic A horizon, it exhibits the anticipated down profile increase in pH.

The major difficulty related to soil chemistry is that, according to Jones' (1981) criterion of a dispersive ratio greater than 18%, *only* the A horizon at Langeni is dispersive; the pipes at Langeni are, however, both developed in the B horizon and partially incised into the underlying weathered red mudstone bedrock. At Qabata none of the chemical criteria for pipe development apply (Table 5.3.3) yet dispersed sediment was still observed in discharge with a pH of 6.5, several days after a period of sustained precipitation. On investigation of a sediment sample using the Shimadzu SA-CP3 analyser, the mean diameter of the dispersed sediment was obtained as 17.45 μm (see Figures 5.3.3.7 and 5.3.3.8).

After the profiles were re-analysed and similar results were again obtained (hence largely ruling out any significant experimental error), two possible interpretations exist:

i) The critical values for dispersion which have been cited in the literature do not hold under the present circumstances - a situation which is not totally improbable as, according to Heede (1971), Parker (1990) and Jones (1990), several of the 'critical' values used are rather arbitrary but, perhaps more significantly, however, none of the 'critical' values have been verified as being applicable to African (let alone southern African) conditions. The values have been largely derived in England and North America and then merely transposed and *assumed* to hold, despite the misgivings and criticisms raised previously by local researchers (eg. Rooyani, 1985) concerning the soil-chemical criteria currently in use.

ii) It would appear that soil piping may develop in response to conditions related more to soil physics than to soil chemistry, in which case the dispersed sample obtained needs to be viewed as anomalous; perhaps the consequence of in-pipe turbulence with insignificant quantities of dispersed sediment having been carried through the soil macro-pores. Although this explanation is likely to be an over-simplification, some credence is given to the hypothesis as some flocculation of material from the Qabata site was observed after 24 hours. The same cannot be said regarding the Inxu Drift sample, discussed in Section 5.2. Caution is, however, of fundamental importance in making such comparisons regarding the mean diameters of the dispersed particles from the two discharges are very different (0.26 μm as opposed to the present 17.45 μm). A direct consequence of such difference in diameter will also be a difference in the respective flocculation rates of the two samples.

The earlier discussion on the potential role of soil structure does, however, lend some credence to the second scenario. In all probability some elements of both interpretations hold, and further research is necessary both to validate the indicators for chemical dispersion within southern African soils and to further elucidate the role of soil physics in relation to soil piping and subsurface erosion.

The following scenario may partially explain the observations and triangular cross-sectional pipe morphology at Qabata. Figure 5.3.3.9(a) shows pipe A (Figure 5.3.3.4(a)) beneath a widened inter-ped surface, whereas Figure 5.3.3.9(b) shows the interior morphology of the same pipe. It would appear that water initially filters along the inter-ped surface from the ponded water in the surficial drainage ditch and from normal rain-fed infiltration from the surface.

Figure 5.3.3.9(a): The outlet of pipe two (III, Figure 5.3.3.1(a)), showing the basal undercut of the pipe sidewall (A).

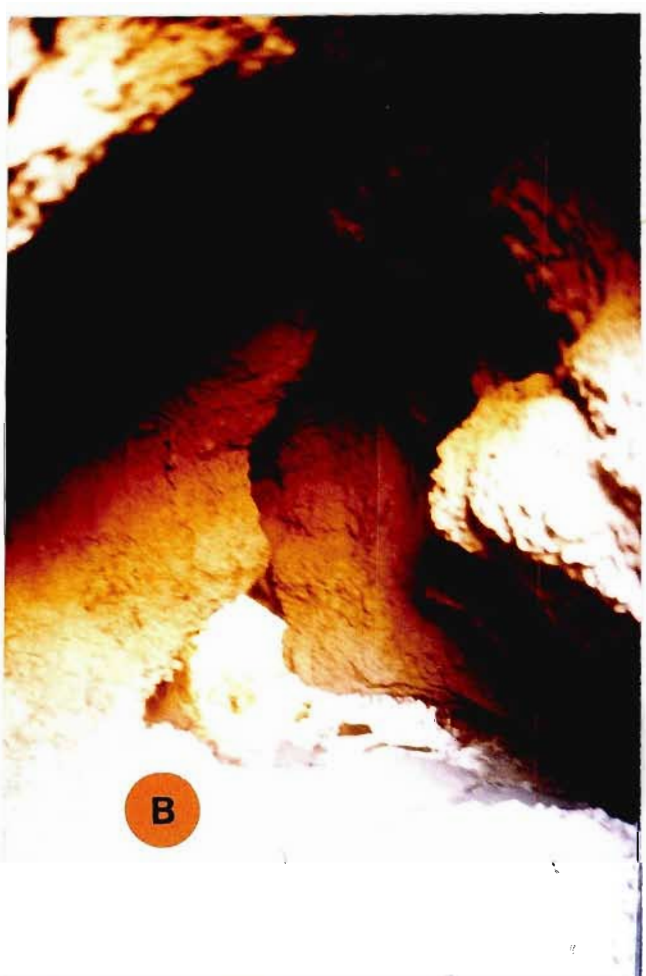


Figure 5.3.3.9(b): View of the inside of the pipe system shown in Figure 5.3.3.9(b), showing debris (B) on the pipe floor.

The water moving down the inter-ped surface *and* the water moving as interflow along the bedrock-soil interface in response to the hydrological and topographical gradients combine, causing an increased pore water pressure at the base of the soil profile and hence potentially exceed the value of 28% soil moisture by weight - the liquid limit. The implication then is that the base of the C horizon starts to move as a viscous flow in response to gravity. The A horizon has sufficient strength to maintain the pipe roof, especially as the A horizon will seldom be water-saturated. By contrast the C horizon, although having a *dry* shear strength in excess of that of the A horizon, loses its strength rapidly under moist or saturated conditions.

An analogue to this phenomenon was observed when an attempt was made to do shear box analyses: Following the conventional operating procedures, the porous plate at the base of the shear box was kept moist. As soon as the sample absorbed water, it failed catastrophically *without* the application of additional stress. This phenomenon is in accordance with geotechnical theory (Lee *et al.*, 1983) and accounts not only for the triangular shape, but also for the basal undercut at the sides of the pipe (A, Figure 5.3.3.9(b)). The debris on the floor of the pipe, (B) in both Figures 5.3.3.9(a) and (b), suggest that the pipe system undergoes enlargement primarily through spalding of ped fragments off the pipe roof under the combined effects of gravity and periodic desiccation.

Notwithstanding the scenario presented, it is also important that the relationship between rock weathering and macro-pore flow should not be disregarded, as illustrated by the micro-pipe developed within weathered red mudstones, some 1.5 m below the base of the soil profile in the Qabata section (Figure 5.3.3.7). As the mudstone initially weathers along micro fractures into particles ranging from -3 to -2 phi (between 4 and 8 mm) in size, the pipe shown must in the first instance be ascribed to the influence of water moving along joints and fractures within the rock itself.

5.4 Large Soil Pipe Systems Associated with Dispersive Soils

Figure 5.4.1(a): The outlet of the Langeni embankment pipe (Type 3).

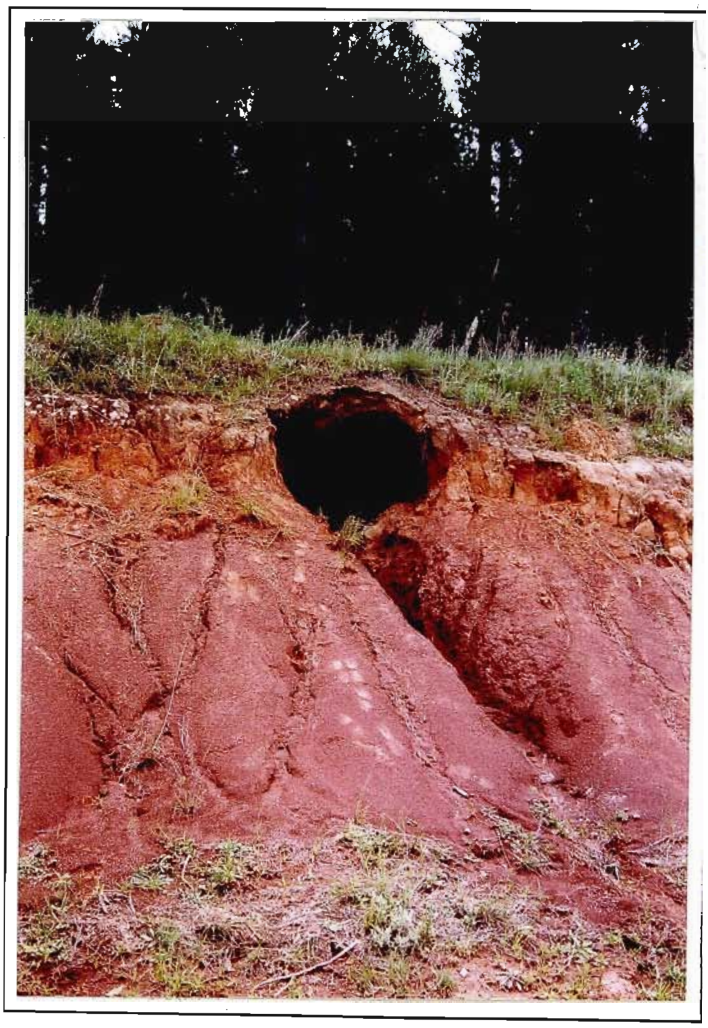
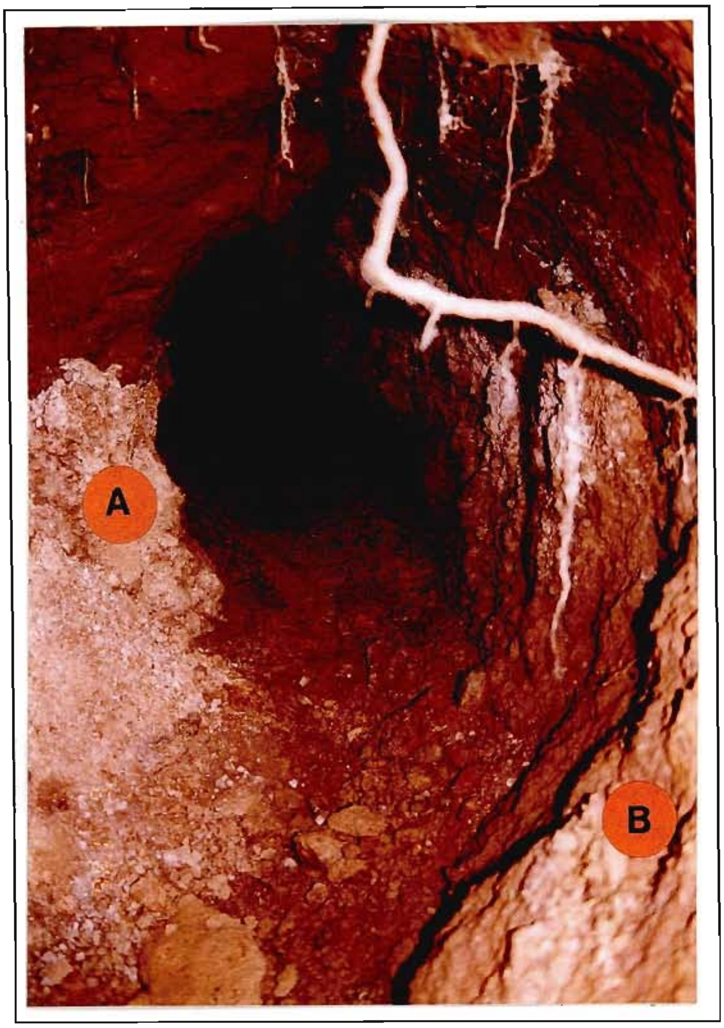


Figure 5.4.1(b): The outlet of the large pipe system (II, Figure 5.3.3.2) that extends well beyond the back slope drainage system at the Langeni site.

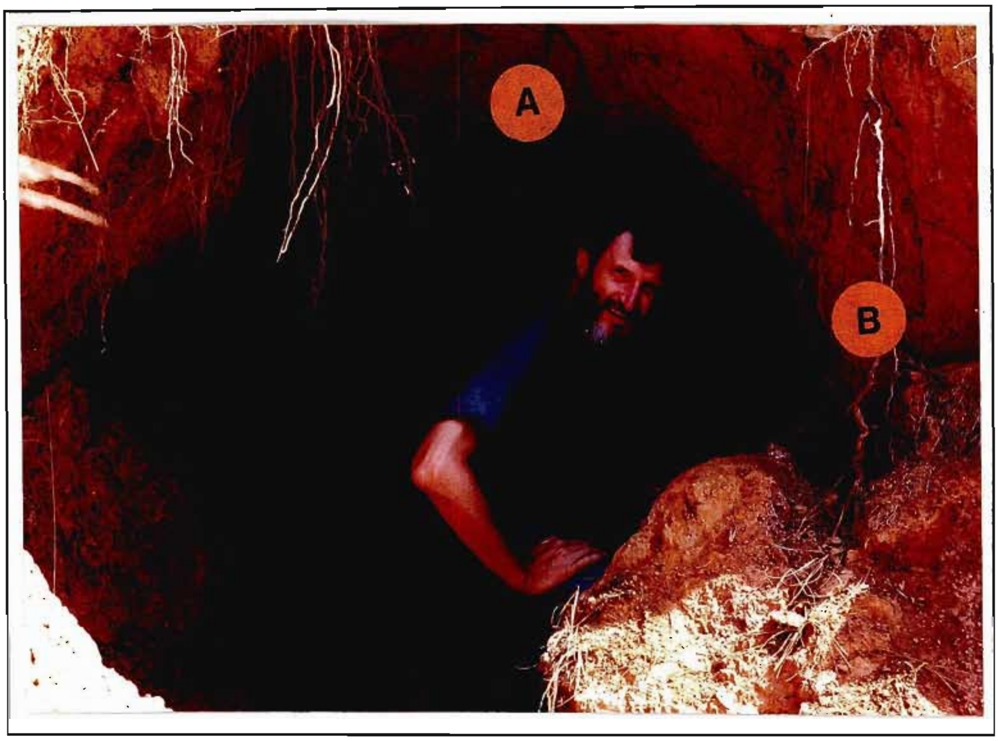
The Langeni site is complex in that one of the pipes (System I, Figure 5.3.3.2 and Figure 5.4.1(a)) is clearly typical of the Type 3 system and is related to the cutting of the road embankment. The second system (System II, Figure 5.3.3.2 and Figure 5.4.1(b)) extends well beyond the possible influence of the backslope drainage system into the commercial forest. Attention will now be focussed briefly on this system, which has many of the characteristics of the Type 4 variety of subsurface system, prior to discussing the Luxgoxgo system - the main representative of pipe genesis for systems developed in dispersive soils.

The Langeni system first became visible four years ago, at which stage the outlet was some 15 cm long and 5 cm wide. Discharge is ephemeral and highly variable. As already indicated, it was not possible to monitor systems autographically due to considerations of both vandalism to equipment and of the likelihood of monitoring seriously affecting the function of the system itself. However, 10 days after a 52 mm rainfall (mean intensity 5 $mm.hr^{-1}$) the discharge was estimated at 60 $l.hr^{-1}$. There had been no rain for two weeks prior to that rainfall event. On a different occasion, the pipe had a discharge of 10 $l.hr^{-1}$, eight days after an event of 48 $mm.hr^{-1}$ with a mean intensity of 6 $mm.hr^{-1}$, ten days prior to which twenty millimetres of rain had fallen. Although no record of rainfall intensity was available for that event, scour marks in the pipe walls (A, Figure 5.4.2), related to the second episode of 48$mm.hr^{-1}$, show that discharge through the pipe had reached peak values of at least 200 $l.hr^{-1}$, although probably for only a short period of time. These rough, largely qualitative values do, however, serve to highlight the fact that precipitation-antecedent moisture-discharge relationships within pipe systems (especially in dispersive soils) are complex and require careful investigation if the rate and duration of pipe discharge is to be understood and meaningfully incorporated into hydrological and land-management systems and models.

Figure 5.4.2: A view inside the Langeni pipe, showing the scour marks (A) and pipe-wall slumping (B).



The angular orientation of the main system at Langeni (II, Figure 5.3.3.2) is attributable to development along enhanced inter-ped surface boundaries in a manner similar to that described previously for Qabata (Figure 5.4.3(a) and (b)). These figures also illustrate that once formed, pipes will increase in cross-sectional size by sidewall slumping (B, Figure 5.4.2); spalding off the roof (partly related to seasonal desiccation of the soil and to micro-climatic conditions within the pipe (A, Figure 5.4.3(a)), and by fluvial incision into the pipe floor. The soil-hydrological gradient near the outlet is, however, of less overall significance for the large Langeni Type 4 system than for the Type 3 systems, as the downdraw of moisture to the local base level is of significance only near a pipe outlet.



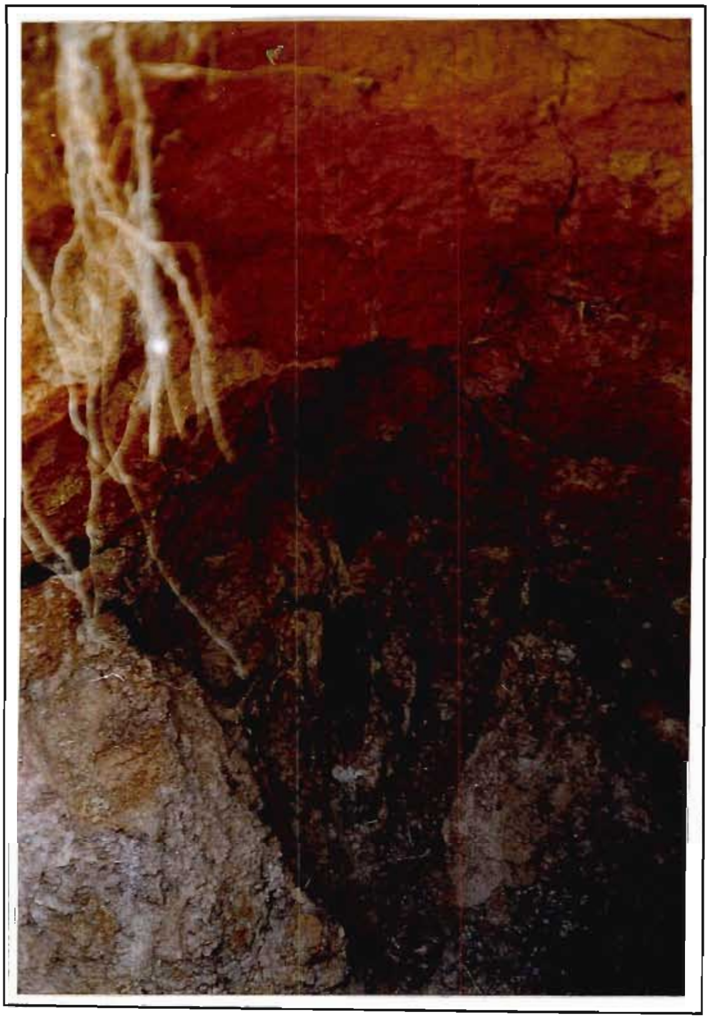


Figure 5.4.3(a): The outlet of the main Langeni pipe, showing the inter-ped surface in the centre of the pipe roof, (A), and spalding from the roof occurring in response to desiccation(B).

Figure 5.4.3(b): A close-up view of the pipe-sidwall of the main Langeni system, showing a tributary micro-pipe at the interface between the B and R horizons of the soil profile.

Table 5.4.1: The physical properties of dispersive soils displaying relatively large pipe systems.

SITE AND SOIL HORIZON / PARAMETER	LANGENI		LUXGOXGO			
	A	B	A	sub A	B	C
PROFILE THICKNESS	25	70	35	20	60	140
COLOUR	10YR6/6 BROWNISH YELLOW	5YR6/6 REDDISH YELLOW	7.5YR6/2 PINKISH GRAY	7.5YR6/4 LIGHT BROWN	5YR5/4 REDDISH BROWN	5YR5/4 REDDISH BROWN
SOIL FORM	HUTTON (*LITHOSOL*)		ESTCOURT (*ALFISOL*)			
TEXTURE						
SAND	46.4	36.6	58.7	52.6	53.9	31.5
SILT	36.4	33.3	26.2	28.2	28.7	36.8
CLAY	17.2	30.1	15.1	19.2	17.4	31.7
MEAN	0.3	1.5	1.8	-0.9	-1.9	-1.5
MEDIAN	0.0	2.0	2.4	-1.2	-1.8	-1.8
DESCRIPTION	LOAM	CLAY	SANDY LOAM	SANDY LOAM	LOAM	CLAY
STRUCTURE	BLOCKY	PRISMATIC	CRUMB	COLUMNAR	BLOCKY PLINTHIC	COLUMNAR
GEOTECHNICAL						
LIQUID LIMIT	16.0	42.0	17.0	15.0	29.0	29.0
PLASTIC LIMIT	5.0	18.0	5.5	5.0	11.0	11.0
SHRINKAGE	2.5	9.0	2.0	2.5	6.0	6.0
HAND SHEAR VANE	117.0	7150.0	68.0	142.0	77.0	74.0
BULK DENSITY	1.79	2.01	1.67	1.88	2.01	2.28
ERODIBILITY (K VALUE)	0.33	0.34	0.25	0.33	0.31	0.38

Together with the steep gradient of the embankment, the change in local base level does, however, account for the incision visible in Figure 5.4.4.

The data describing the soil physics, chemistry and hydrology for Langeni have already been discussed with reference to Section 5.3 and are included in Tables 5.4.1, 5.4.2 and 5.4.3 merely for comparative purposes with the Luxgoxgo system.

Figure 5.4.4: The outlet of the Langeni pipe system. Note the extent to which incision into the embankment has occurred.

5.4.1 The Luxgoxgo System

The Luxgoxgo pipe and gully system is located some forty kilometres away from Umtata near the Umtata-Queenstown road. The complexity of the system is evident from Figure 5.4.5. This map was compiled using an enlarged orthophoto map of the area and by the incorporation of accurate positional data for pipe intakes, outlets and other points of pertinent morphological information obtained from theodolite surveys. Pipe orientations were derived from internal compass traverses and when this was no longer possible, by the insertion of commercial drain pull-throughs and ranging rods into the pipes. The following characteristics are evident from Figures 5.4.5 and 5.4.6:

- many of the pipe systems are orientated at an angle to the prevailing topographic gradient,
- both major and minor roof collapse are common occurrences, and
- some controlling mechanism exists resulting in clearly defined, angular junctions within the pipe and gully system.

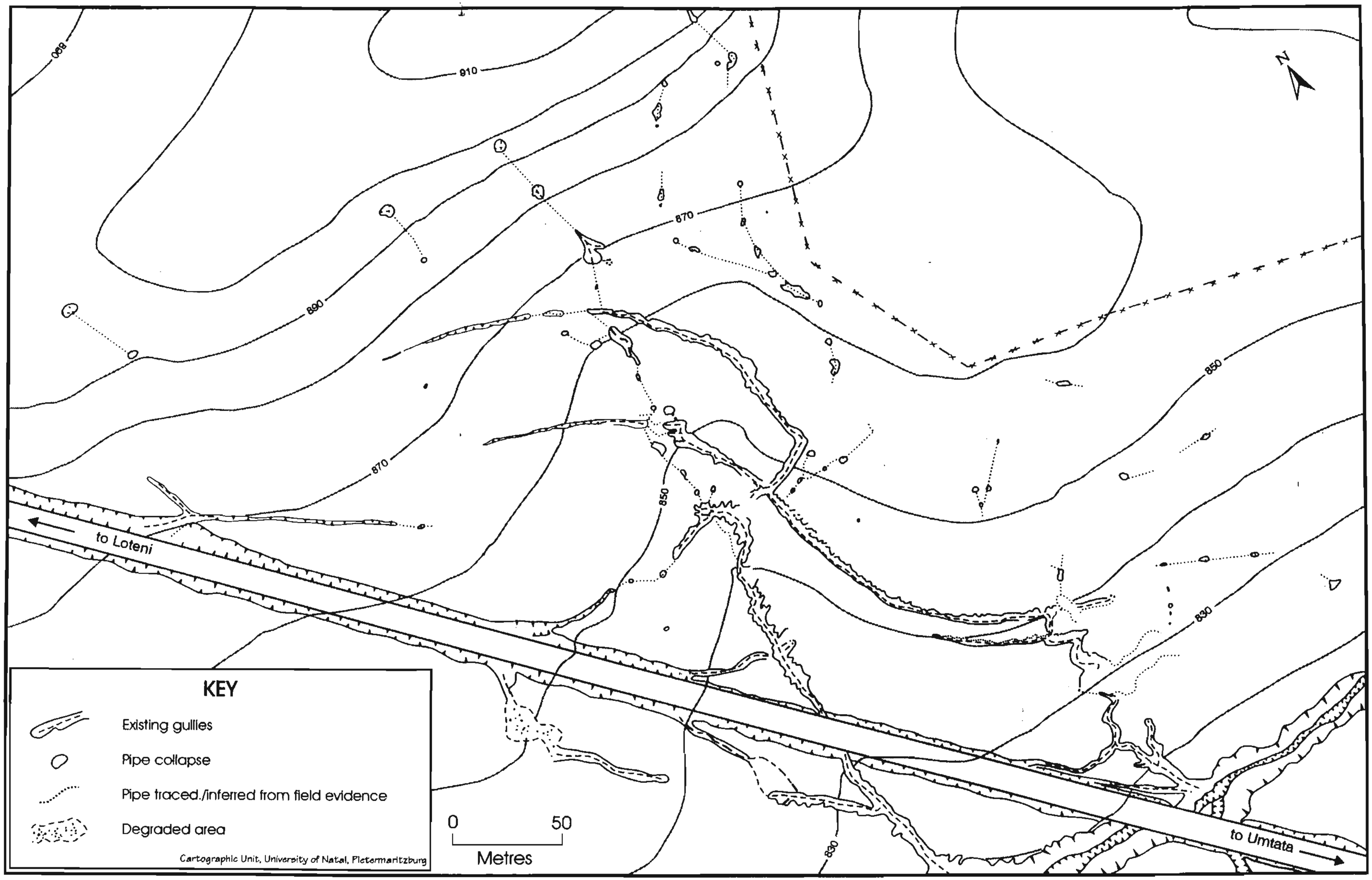


Figure 5.4.5: Map of the Luxgoxgo system

Figure 5.4.6: Overview of the Luxgoxgo pipe-gully system.

Figure 5.4.7: One of the gullies at Luxgoxgo related to pipe roof collapse.

An analysis of the physical character of the soils of the Luxgoxgo system (Table 5.4.1) shows the following pattern with increasing depth down the soil profile (Figure 5.4.7): The A horizon represents a sandy loam with a mean particle size slightly above 250 μm (specifically 1.8ϕ, Figure 5.4.8), and a relatively low shear strength of 68 kPa. The horizon is only 15 cm thick and hence the infiltration rates obtained were difficult to stabilize; some doubt therefore exists regarding the accuracy of these rates (see the discussion by Hills (1970) for an in-depth treatise on the pertinent methodology under such conditions). The inability to obtain a steady infiltration rate may be explained, using Figure 5.4.9, as follows:

> Water infiltrates through the sandy A horizon and then moves laterally along the surface of the sub A horizon, infiltrating preferentially along inter-ped surfaces. The sub A horizon has been described by Dardis (1989) as a palaeosol *of ca.* 2 000 yr BP age, although some uncertainty exists that this is indeed a true palaeosol. The sub A horizon is very well structured, well aggregated and has a high shear strength. As at previous sites, the stable aggregates were retained in the dry sieve analysis, thereby yielding coarser mean and median values than would be expected from the hydrometer analysis. The B horizon contains an abundance of plinthic concretions with the result that almost 80% of the material is coarser than 2 mm (-1ϕ, Figure 5.4.8). The C horizon has a relative increase in the clay content, probably as a result of the dual influence of illuviation and from the close proximity to the weathered mudstone. As would be expected, the bulk density of the soil shows a sustained increase down profile and together with the increased clay content accounts for the high saturation potential of the C horizon (Table 5.4.2).

The region has a moderately high rainfall with an RDI of 78.7% indicating that precipitation is strongly seasonal; a fact supported further by the low distribution index of 27.1%. In consequence, the relative rainfall intensity is fairly high when compared with many of the other sites, as the annual precipitation is derived from only a small number of indiviual events.

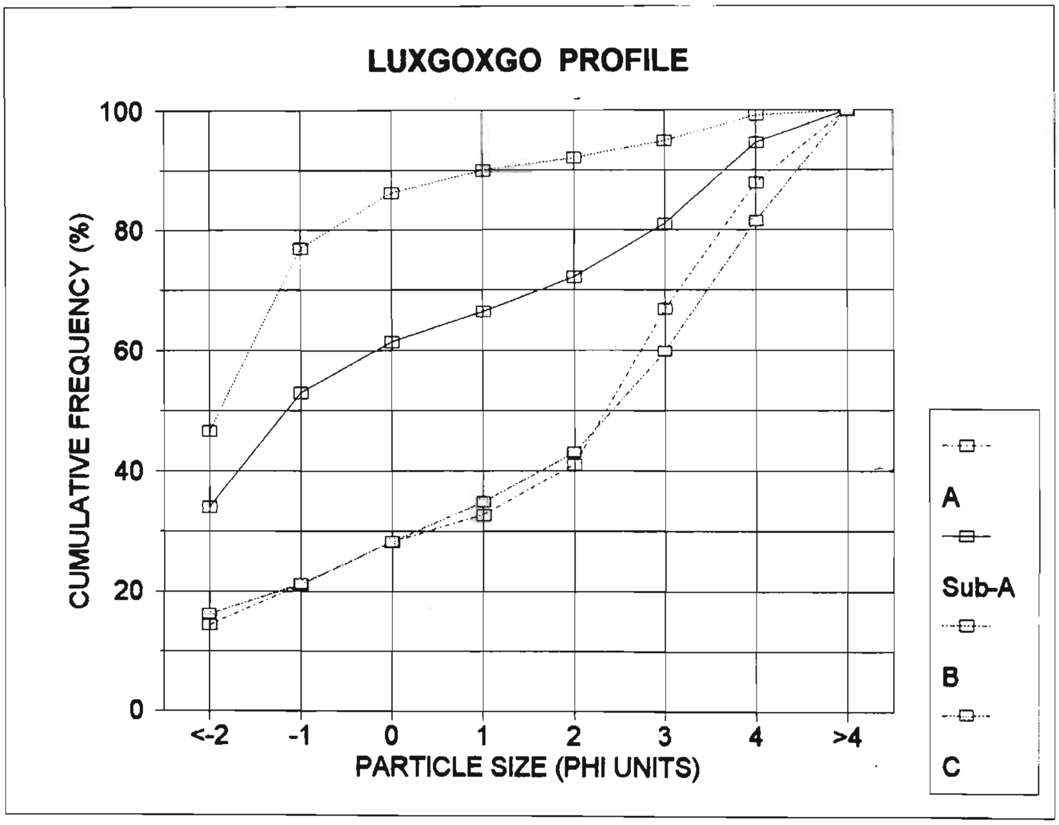


Figure 5.4.8: Graph of cumulative frequency for grain size of the Luxgoxgo-type soil profile.

Figure 5.4.9: One of the gully sidewalls at Luxgoxgo, showing soil moisture seepage at the boundary between the A and Sub A horizons. Note that the further infiltration of this inferflow-seepage occurs preferentially along the inter-ped surfaces.

Table 5.4.2: Soil hydrological and associated conditions for dispersive soils displaying relatively large pipe systems.

PARAMETER \ SITE AND SOIL HORIZON	LANGENI		LUXGOXGO			
	A	B	A	sub A	B	C
PROFILE THICKNESS (cm)	25	70	35	20	60	140
TEXTURE						
SAND %	46.4	36.6	58.7	52.6	53.9	31.5
SILT %	36.4	33.3	26.2	28.2	28.7	36.8
CLAY %	17.2	30.1	15.1	19.2	17.4	31.7
DESCRIPTION	LOAM	CLAY	SANDY LOAM	SANDY LOAM	LOAM	CLAY
STRUCTURE	BLOCKY	PRISMATIC	CRUMB	COLUMNAR	BLOCKY PLINTHIC	COLUMNAR
PRECIPITATION TOTAL (mm pa)	1020.0		1020.0			
SEASONALITY %	78.8		78.7			
DISTRIBUTION OVER YEAR %	27.1		27.1			
INTENSITY %	37.6		37.6			
SOIL HYDROLOGY						
FIELD MOISTURE %	1.1	9.4	5.2	3.4	6.8	2.1
FIELD CAPACITY %	30.6	45.9	17.2	41.6	15.8	37.2
SATURATION POTENTIAL %	26.8	43.4	21.9	22.6	23.6	48.0
INFILTRATION RATE ($ml.hr^{-1}$)	19.4	5.5	7.4	8.6	4.2	0.4
SATURATED INFILTRATION RATE ($ml.hr^{-1}$)	2.8	1.2	0.7	1.8	0.7	0.1
BULK DENSITY ($g.m^3$)	1.79	2.01	1.67	1.88	2.01	2.28
ERODIBILITY (K VALUE)	0.33	0.34	0.25	0.33	0.31	0.38

It is evident from Table 5.4.3 that the soils of the Luxgoxgo site have a low organic carbon content, which is reflected in the infiltration rates obtained for the field soils. When the soil chemistry is analysed relative to the accepted critical values for dispersion, it is clear that the A, to a limited extent the sub A, and the C horizons are prone to piping on the basis of the dispersion ratio. When the ESP value is considered, only the C horizon is prone to piping with a value of 11.7meq/100g, as opposed to the critical value of 6meq/100g given by Heede(1971) and Jones (1981). On testing the profile for the SAR, the highest values were obtained for the C horizon. The value of 13.4% is however still well below the theoretical 15% required. There is thus at present no acceptable correspondence between the criteria of 'critical' values of soil chemistry and field observations.

Table 5.4.3: The characteristic soil chemistry of dispersive soils prone to developing relatively large pipe systems.

PARAMETER \ SITE AND SOIL HORIZON	LANGENI		LUXGOXGO			
	A	B	A	sub A	B	C
PROFILE THICKNESS (cm)	25	70	35	20	60	140
TEXTURE						
SAND %	46.4	36.6	58.7	52.6	53.9	31.5
SILT %	36.4	33.3	26.2	28.2	28.7	36.8
CLAY %	17.2	30.1	15.1	19.2	17.4	31.7
DESCRIPTION	LOAM	CLAY	SANDY LOAM	SANDY LOAM	LOAM	CLAY
ORGANIC CARBON %	0.4	0.3	0.7	0.4	0.4	0.5
SOIL CHEMISTRY						
DISPERSION RATIO %	18.9	16.4	22.0	17.0	15.6	17.9
CEC (cmol.kg^{-1})	14.2	21.0	8.4	18.6	26.3	24.8
EC (mS.m^{-1})	44.9	11.0	138.7	122.2	108.5	256.0
ESP	0.3	0.2	1.8	1.2	0.6	11.7
SAR	1.6	2.9	5.1	5.7	4.3	13.4
pH	5.6	5.3	5.0	5.9	6.2	6.9
ERODIBILITY (K VALUE)	0.33	0.34	0.25	0.33	0.31	0.38

Figure 5.4.10 shows one of the gully sidewalls of the Luxgoxgo System, and shows clearly the abundance of micro-piping which occurs, apparently in conjunction with ped surfaces within the soil, and again highlights the polemic of the applicability of the 'critical' values under the prevailing environmental conditions. Although the values for CEC and EC broadly mirror the pattern visible for the ESP, it is not at present possible to interpret these parameters further. The soil is again acid but becomes progressively more basic with depth.

The already mentioned angular pattern of the junctions within the pipe-gully system, and the role of the very dominant vertical structure of the soil was investigated further. The results of that analysis are discussed at length in Chapter 6.

Figure 5.4.10: One of the gully sidewalls at Luxgoxgo, showing the abundance of micro-piping which exists.

5.5 Subsurface Erosion Associated with Seepage on Slopes

In many respects these are the most difficult systems to identify in the field due to the general absence of roof collapse or any obvious in- and outlets to the system. Water accumulates within the soil profile (along the convergence of percolines) either as a consequence of interflow and flow convergence along percolines within the soil as outlined in Section 2.3.3.1 (page 24), or by water ponding on the surface of a slope, filtering into the soil and moving to a lower elevation along the hydraulic gradient. These two modes of origin are clearly not mutually exclusive.

Once sufficient accumulation of slope water has occurred for the field moisture conditions to approximate the field capacity of the soil, the soil moisture is effectively forced back to the surface, leading to a saturated profile at the outlet. Such condition may be related to either the total volume of slope water which has accumulated within the soil, or to the depth to a horizon of low permeability relative to the situation further up slope. Such conditions of soil saturation may have a variety of reasons, ranging from a perched water table due to local geological conditions to the decrease in permeability related to the presence of an illuviated clay layer, or to the existence of an indurated iron pan within the soil.

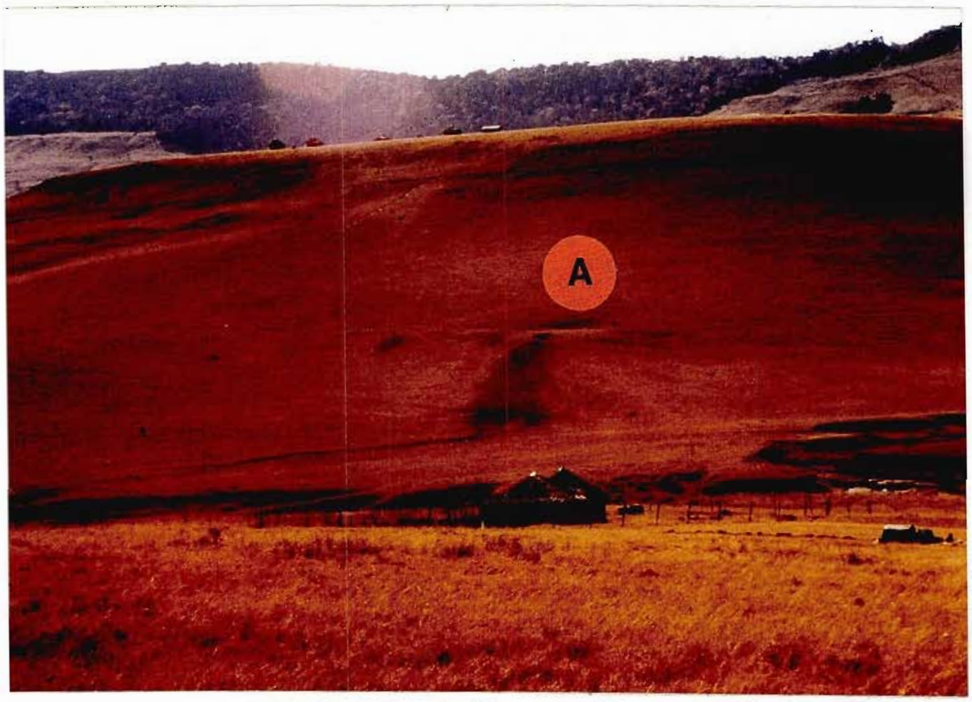


Figure 5.5.1: A Seepsage system (A) near Mt. Frere. Note the distinct change in vegetation brought about by the locally increased availabilty of moisture.

The simplest method for identifying these seepage systems in the study area is by using the change in vegetation type and colour in the field in winter, as illustrated in Figure 5.5.1. Although this is the simplest method of identification and the most cost effective (particularly as it can also be combined with the interpretation of aerial photography), it is not absolute. The identification of vegetation colour will only be effective where seepage continues for appreciable periods after precipitation ceases. Where a system is primarily reliant on quickflow through the system, alternative, but more expensive methods need to be applied. One such method, at least in principle, is shallow Ground Penetrating Radar (GPR). According to the available instrument specifications, GPR has the capability to identify small-scale fluctuations in soil density up to a depth of 5m but, due to the high financial considerations associated with the operation of a GPR system (ca. R25 000.- for one week in the field), this could not be verified.

A second option which is somewhat less accurate but probably more suited to the constraints of a developing region in that it is less technologically-sophisticated and is considerably cheaper, is a very detailed field survey by suitably trained field staff. This approach would rely on the survey site's being covered on foot to at least the same intensity (and porobably slightly greater) as with a GPR system.

Figure 5.5.2: Type 5 seepage systems (as indicated) in proximity to the Type 4 system at Luxgoxgo.

Also of significance is that the Type 4 systems frequently have seepage (*ie.* Type 5) systems associated with them (see, for example, Figure 5.5.2) and it is likely that the Type 5 systems represent the stage of macropore flow which, on enlargement through further dispersion and/or disaggregation, spalding and turbulent flow produce the range of other subsurface erosion already discussed.

The reason for presenting what is interpreted as an early stage of pipe development at the end of this chapter rather than at the beginning is related to the complexity of these systems. The size of the micro-pipes and/or macro-pores is such that it is difficult to trace them, hence few morphological and morphometric data are available from the seven Type 5 systems studied. The discussion of these systems is therefore of necessity based more on qualitative rather than quantitative analysis.

Table 5.5.1: The physical properties of soils displaying seepage systems.

PARAMETER \ SITE AND SOIL HORIZON	GUNGULULU		
	A	B	C
PROFILE THICKNESS (cm)	35	30	40
COLOUR	10YR6/2 LIGHT BROWNISH GRAY	10YR6/6 BROWNISH YELLOW	5YR5/4 REDDISH BROWN
SOIL FORM	VALSRIVIER (*ALFISOL*)		
TEXTURE			
SAND %	48.2	29.6	31.5
SILT %	34.5	34.7	36.8
CLAY %	17.3	35.7	31.7
MEAN (ϕ)	1.9	-1.4	-1.5
MEDIAN(ϕ)	2.5	-1.5	-1.8
DESCRIPTION	LOAM	CLAY	CLAY
STRUCTURE	COLUMNAR	BLOCKY PLINTHIC	COLUMNAR
GEOTECHNICAL			
LIQUID LIMIT %	16.0	33.0	29.0
PLASTICITY INDEX %	5.0	14.0	11.0
LINEAR SHRINKAGE %	2.5	7.0	6.0
HAND SHEAR VANE (kPa)	118.0	83.0	74.0
BULK DENSITY g/m³	1.88	1.80	2.18
ERODIBILITY (K VALUE)	0.36	0.19	0.30

The reference site for systems related to slope seepage is the Gungululu site (Figure 5.5.3) which is dominated by seepage systems but has one incipient pipe (A, Figure 5.5.3) which could, however, not be successfully traced as the pipe diameter was too small. The soil data presented are the mean values obtained for the two systems some 15 m above the seepage points.

Figure 5.5.3: The seepage system at Gungululu, denoted as A. Despite the good vegetation growth, the system is still clearly visible.

Texturally the A horizon is a loam (Table 5.5.1) with a mean size of 1.9ϕ, or slightly more than 250μm, and a median diameter of 2.50ϕ or approximately 200μm (Figure 5.5.3). The B and C horizons show a significant increase in clay content relative to the A horizon. Although there is some aggregation within the A horizon, the extent thereof is considerably greater in the B and C horizons, where the situation is worsened by the existence of plinthic nodules towards the base of the B horizon. The soil is well structured throughout the profile.

Table 5.5.2: Soil hydrological and associated conditions for soils displaying seepage systems.

PARAMETER \ SITE AND SOIL HORIZON	GUNGULULU		
	A	B	C
PROFILE THICKNESS (cm)	35	30	40
TEXTURE			
SAND %	48.2	29.6	31.5
SILT %	34.5	34.7	36.8
CLAY %	17.3	35.7	31.7
DESCRIPTION	LOAM	CLAY	CLAY
STRUCTURE	COLUMNAR	BLOCKY PLINTHIC	COLUMNAR
PRECIPITATION TOTAL (mm pa)	587.8		
SEASONALITY %	69.6		
DISTRIBUTION OVER YEAR %	17.0		
INTENSITY %	34.6		
SOIL HYDROLOGY			
FIELD MOISTURE %	3.5	5.2	2.1
FIELD CAPACITY %	23.9	32.8	37.2
SATURATION POTENTIAL %	27.1	49.5	47.9
INFILTRATION RATE ($ml.hr^{-1}$)	2.6	3.6	0.4
SATURATED INFILTRATION RATE ($ml.hr^{-1}$)	0.5	0.7	0.1
BULK DENSITY ($g.m^{3}$)	1.88	1.80	2.18
ERODIBILITY (K VALUE)	0.36	0.19	0.30

The A horizon has a high shear strength, which decreases notably down the profile and, while the decrease in strength of the B horizon may be explained in terms of the increased field moisture content, such explanation cannot be used for the C horizon particularly where this has an unusually high bulk density. The A horizon is susceptible to wash processes, as indicated by a K value of 0.36. This value is significantly greater than the 0.19 for the B horizon (Table 5.5.1) and is attributed to the low organic content of the A horizon. The high K value does, however also attest to the susceptibility of the soil to surface erosion, especially where the protective vegetation has been damaged.

Table 5.5.3: The characteristic soil chemistry of dispersive soils displaying seepage systems.

PARAMETER \ SITE AND SOIL HORIZON	GUNGULULU		
	A	B	C
PROFILE THICKNESS (Cm)	35	30	40
TEXTURE			
SAND %	48.2	29.6	31.5
SILT %	34.5	34.7	36.8
CLAY %	17.3	35.7	31.7
DESCRIPTION	LOAM	CLAY	CLAY
ORGANIC CARBON %	0.2	0.1	0.5
SOIL CHEMISTRY			
DISPERSION RATIO %	23.5	14.5	17.9
CEC (cmol.kg^{-1})	9.9	20.6	24.8
EC (mS.m^{-1})	38.7	106.5	256.0
ESP	1.1	5.4	11.7
SAR	4.2	9.4	13.4
pH	6.4	7.0	6.9
ERODIBILITY (K VALUE)	0.36	0.19	0.30

The Gungululu system has developed in a region of low precipitation with a mean of only 587.8 mmpa. What is significant here is that the precipitation is seasonal and poorly distributed over the year with a distribution of only 17% (Table 5.5.2). The consequence is that, despite the low precipitation the relative rainfall intensity is comparable to that for the other systems. It may therefore be inferred that, on average, for part of each year the soil moisture conditions will be sufficiently high to facilitate the occurrence of subsurface erosion, whereas for the dry season conditions are likely to be conducive to promoting desiccation of the soil, further facilitating the development of subsurface erosion.

The low infiltration rate of the A horizon is seen as further support for the role of the inter- ped surfaces in channelling water into the subsoil, as discussed previously. If the criterion of a dispersion ratio of 18% and more is applied to the soil at Gungululu, the

A and C horizons are dispersive, yet the A horizon has a low ESP value of only 1.1 and all three horizons have SAR values below 15. According to the criteria of soil chemistry it is only the C horizon which can be regarded as dispersive, yet on exploring the system by digging a sectional trench, the micro-pipes occur in the B horizon, again emphasizing the shortcomings of the present understanding of the role of soil chemistry in subsurface erosion phenomena.

The following Chapter will focus on the relationship between structure and subsurface erosion alluded to in the present chapter, and will consider the significance of subsurface erosion processes within the KwaZulu-Natal and Transkei regions.

Chapter 6

6. Structural Relationships and Implications of Subsurface Erosion

6.1 The Relationship Between Structure and Subsurface Erosion

The potential role of inter-ped surfaces in relation to the development of several of the types of subsurface erosion has been discussed in the previous chapter. Further, the angular junction of particularly the Type 4 pipe systems and the gullies associated with these need to be accounted for (see Figure 5.4.5 and Figure 6.1.1). A hypothetical causal relationship between the orientation of erosion phenomena and geological structure was established on the strength of field evidence in the form of bedrock joints paralleling several of the gully sections at Luxgoxgo, as shown in Figure 6.1.2. Additional support for such an hypothesis was found in the existence of soil ridges (Figure 6.1.3) at Ngqugqu near Mqanduli, and which were mapped in detail as indicated in Figure 6.1.4. In order to investigate this hypothetical relationship further, the following measurements were obtained:

i) bedrock joint orientations at Langeni, Qabata, Luxgoxgo and Ngqugqu.

ii) the orientation of ped surfaces at the same locations as in (i).

iii) the orientation of gully segments at Ngqugqu, Kulozulu and Luxgoxgo at 5 m intervals.

iv) the orientation of Type 4 soil pipes which were longer than 10 m at Langeni and Luxgoxgo (shorter pipes were not considered for reasons of accuracy; longer pipes were frequency-weighted *eg.* the orientation of a 31 m pipe was included three times), and

v) the orientation of soil ridges at Ngqugqu and Mqanduli based on 1 m lengths.

Figure 6.1.1: Photograph showing a near 90^0 angle in the Luxgoxgo pipe-gully system.

Figure 6.1.2: Bedrock joint paralleling a segment of the Luxgoxgo pipe-gully system.

Figure 6.1.3(a): A series of soil ridges at Ngqugqu, near Mqanduli, Transkei.

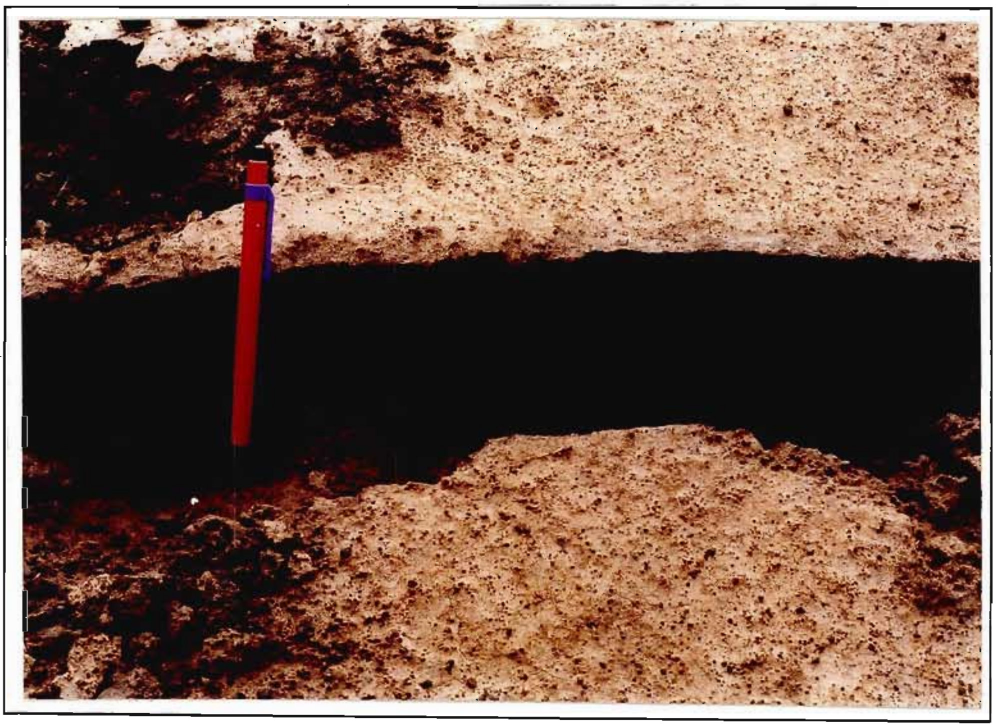


Figure 6.1.3(b): A close-up view of one of the soil ridges from Figure 6.1.3(a). Note the sharp boundaries which exist at the margins of the ridge.

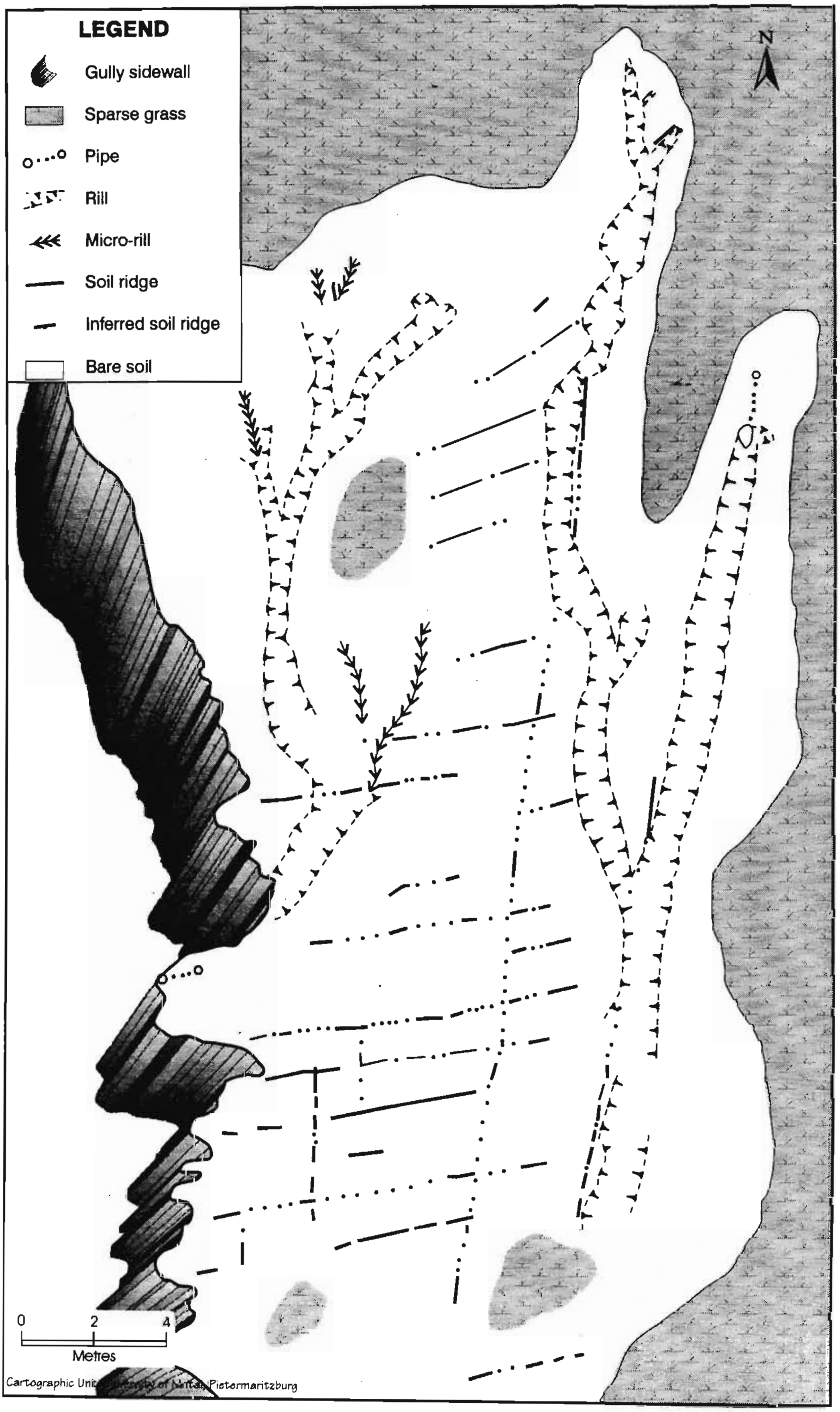


Figure 6.1.4: A detailed map of the soil ridges found at Ngqugqu.

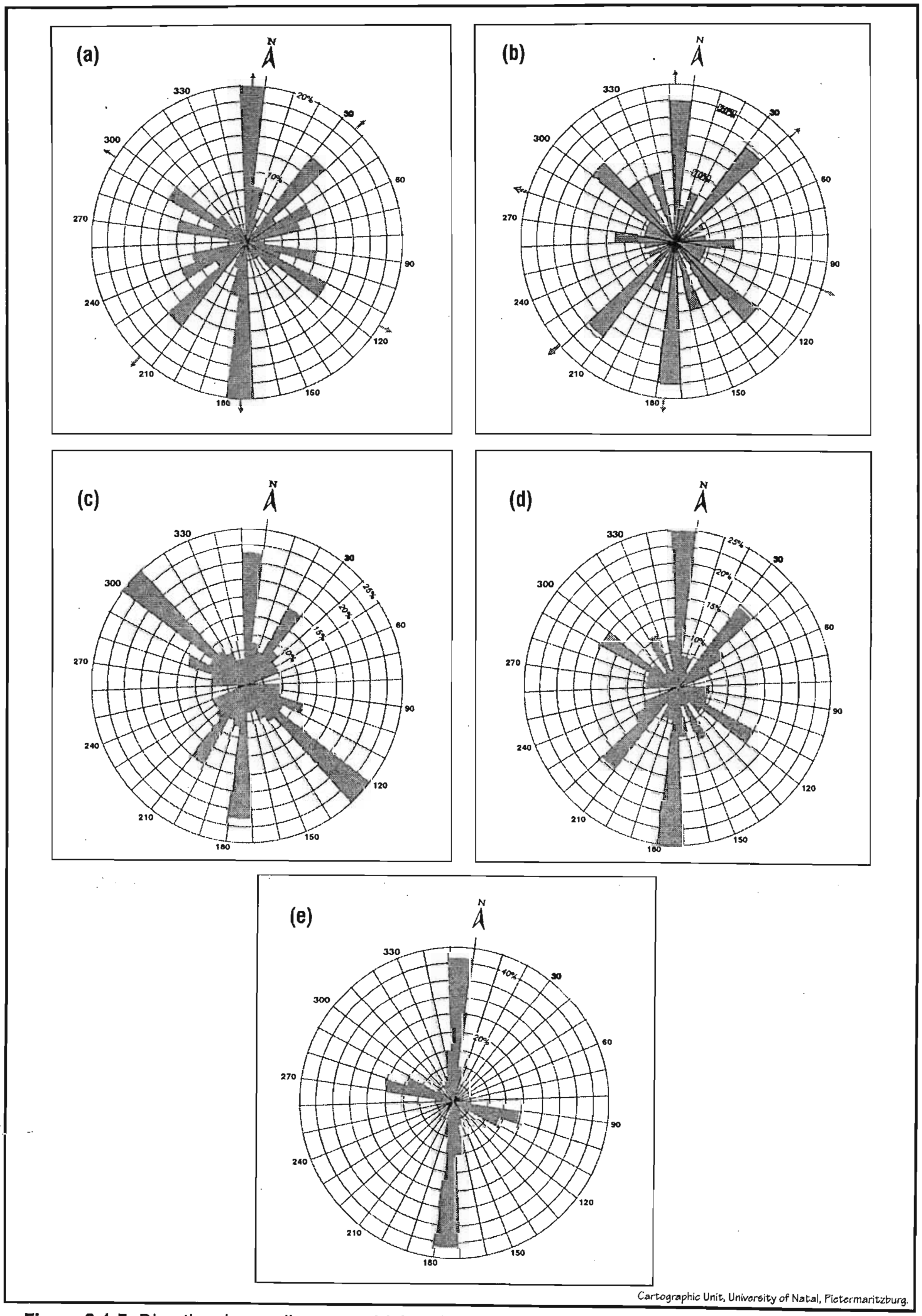


Figure 6.1.5: Directional rose-diagrams of **(a)** regional bedrock joint orientation; **(b)** regional ped-surface orientation; **(c)** gully segment orientation; **(d)** soil pipe segment orientation; and **(e)** orientation of the soil ridges at Ngqugqu.

The directional values thus obtained were then plotted as frequency-rose diagrams in 10° classes (Figure 6.1.5a to e).

When the directional-frequency data (Table 6.1) from which the rose diagrams were originally drawn are subjected to a Chi-squared randomness test using the methods outlined by Mark (1984), the following results were obtained:

$$\chi^2 = \sum \frac{(O - \varepsilon)^2}{\varepsilon} \qquad \text{....... Equation 6.2}$$

where: χ^2 is the chi-squared statistic

O is the observed frequency percent per class

ε is the expected frequency percent per class (100/18 = 5.56)

As there are 18 frequency classes, there are 17 degrees of freedom. The χ^2 statistic at the 99.99% level is given by Matthews (1981) as 40.79. It is evident from Table 6.1 that in all five cases shown in Figure 6.1.5 the calculated values for the Chi-squared distribution significantly exceeds the critical value for the two-tailed Chi-squared test, indicating that there is less than a 0.01% probability that the distributions observed are random. Although the number of readings for each of the five parameters is not constant, the criterion cited by Cheeney (1983) that the sample population should exceed 40 has been met in all cases, apart from the consideration that by using percentage frequencies the data have been rendered more comparable.

As the inter-ped surfaces and joints are defined by dip and strike directions, it was possible to plot pole density diagrams on a stereographic projection (Figure 6.1.6(a) and (b)) and hence to determine the mean orientations as indicated in Figures 6.1.5(a) and (b). If these means are plotted as vectors on a rose diagram and the direction of greatest frequency for gully-, pipe- and soil ridge orientations are included as in Figure 6.1.7, a marked degree of directional correspondence is evident.

Table 6.1: Directional frequencies and data for the determination of the χ^2 statistic to test for randomness in orientation of the respective phenomena.

CLASS	DIRECTIONAL FREQUENCIES														
10° INTERVALS	INTER-PED SURFACES			BEDROCK JOINTS			SOIL PIPE ORIENTATION			SOIL-RIDGE ORIENTATION			GULLY ORIENTATION		
	ACTUAL %	Σ%	χ^2 CALC.	ACTUAL %	Σ%	χ^2 CALC.	ACTUAL %	Σ%	χ^2 CALC.	ACTUAL %	Σ%	χ^2 CALC.	ACTUAL %	Σ%	χ^2 CALC.
0 - 9	3	3	1.18	8	8	1.07	3	3	1.18	7	7	0.37	5	5	0.06
10 - 19	6	9	0.03	2	10	2.28	2	5	2.28	0	7	5.56	2	7	2.28
20 - 29	0	9	5.56	0	10	5.56	2	7	2.28	0	7	5.56	15	22	16.03
30 - 39	15	24	16.03	15	25	16.03	18	25	27.83	0	7	5.56	4	26	0.44
40 - 49	1	25	3.74	3	28	1.18	7	32	0.37	0	7	5.56	2	28	2.28
50 - 59	3	28	1.18	10	38	3.55	4	36	0.44	0	7	5.56	2	30	2.28
60 - 69	1	29	3.74	8	46	1.07	0	36	5.56	0	7	5.56	0	30	5.56
70 - 79	3	32	1.18	0	46	5.56	0	36	5.56	0	7	5.56	0	30	5.56
80 - 89	8	40	1.07	2	48	2.28	3	39	1.18	1	8	3.74	2	32	2.28
90 - 99	2	42	2.28	10	58	3.55	5	44	0.06	18	26	27.83	2	34	2.28
100 - 109	2	44	2.28	3	61	1.18	3	47	1.18	13	39	9.96	8	42	1.07
110 - 119	3	47	1.18	13	74	9.96	14	61	12.81	1	40	3.74	4	46	0.44
120 - 129	13	60	9.96	3	77	1.18	4	65	0.44	0	40	5.56	25	71	67.97
130 - 139	10	70	3.55	1	78	3.74	1	66	3.74	0	40	5.56	5	76	0.06
140 - 149	0	70	5.56	0	78	5.56	7	73	0.37	1	41	3.74	2	78	2.28
150 - 159	10	80	3.55	1	79	3.74	1	74	3.74	3	44	1.18	1	79	3.74
160 - 169	0	80	5.56	1	80	3.74	1	75	3.74	15	59	16.03	1	80	3.74
170 - 179	20	100	37.50	20	100	37.50	25	100	67.97	41	100	225.90	20	100	37.50
χ^2 VALUES			105.12			108.71			140.73			342.53			155.84
TOTAL READINGS	92			120			81			94			63		

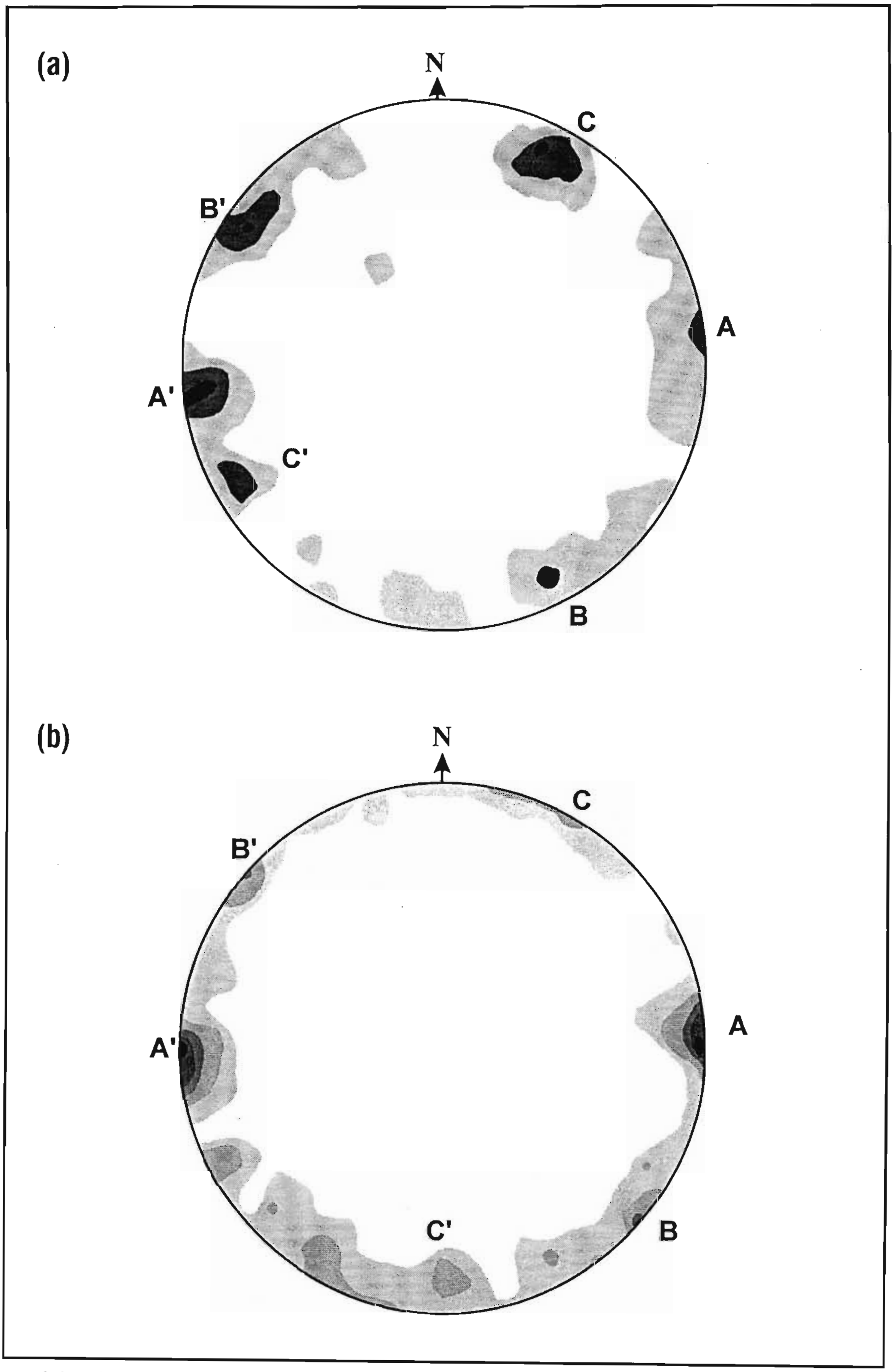


Figure 6.1.6: Stereographic plots of pole densities for regional bedrock joints (a), and inter-ped surfaces (b). (A - A', B - B' and C - C' are the respective principle axes)

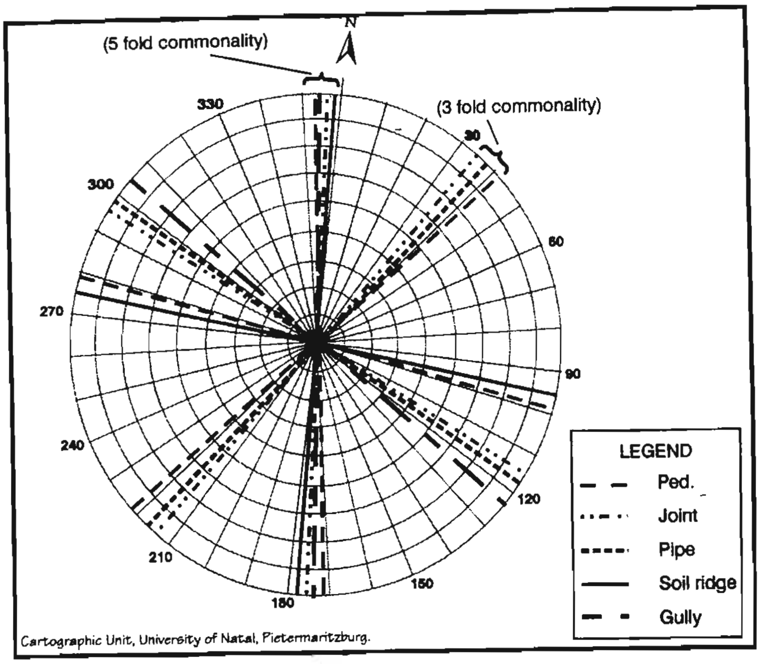


Figure 6.1.7: The mean directional vectors for bedrock joints, inter-ped surfaces, gullies, soil pipes and the soil ridges at Ngqugqu.

Table 6.2: Directional frequencies obtained from the data from Table 6.1 needed to determine the D-value of the Kolmogorov-Smirnov test.

CLASS	DIRECTIONAL FREQUENCIES									
10° INTERVALS	INTER-PED SURFACES		BEDROCK JOINTS		SOIL PIPE ORIENTATION		SOIL-RIDGE ORIENTATION		GULLY ORIENTATION	
	ACTUAL %	Σ %	ACTUAL %	Σ %	ACTUAL %	Σ %	ACTUAL %	Σ %	ACTUAL %	Σ %
0 - 9	3	3	8	8	3	3	7	7	5	5
10 - 19	6	9	2	10	2	5	0	7	2	7
20 - 29	0	9	0	10	2	7	0	7	15	22
30 - 39	15	24	15	25	18	25	0	7	4	26
40 - 49	1	25	3	28	7	32	0	7	2	28
50 - 59	3	28	10	38	4	36	0	7	2	30
60 - 69	1	29	8	46	0	36	0	7	0	30
70 - 79	3	32	0	46	0	36	0	7	0	30
80 - 89	8	40	2	48	3	39	1	8	2	32
90 - 99	2	42	10	58	5	44	18	26	2	34
100 - 109	2	44	3	61	3	47	13	39	8	42
110 - 119	3	47	13	74	14	61	1	40	4	46
120 - 129	13	60	3	77	4	65	0	40	25	71
130 - 139	10	70	1	78	1	66	0	40	5	76
140 - 149	0	70	0	78	7	73	1	41	2	78
150 - 159	10	80	1	79	1	74	3	44	1	79
160 - 169	0	80	1	80	1	75	15	59	1	80
170 - 179	20	100	20	100	25	100	41	100	20	100
TOTAL READINGS	92		120		81		94		63	

In order to determine the extent to which the correspondence of the directional vectors is indicative of an underlying similarity in the five frequency distributions, these were compared with one another using the Kolmogorov-Smirnov test in accordance with the basic methodology outlined by Cheeney (1988) and Mark (1984). Although the Kolmogorof-Smirnov test is conventionally used to compare only two frequency distributions that are not necessarily statistically 'normal', a similar approach was adopted as in Chapter 4 with the Student's t-test to derive a 'matrix of comparison'.

The data from Table 6.1 were extracted to obtain Table 6.2, and were used to determine the comparative D-statistic for the relevant distributions as shown in Table 6.3. The values of $D_{critical}$ are obtained from equation 6.2 (Matthews, 1981), *viz.*:

$$D_{critical} = \left(\frac{n_1 + n_2}{n_1 n_2} \right)^{½} \qquad \text{.......... Equation 6.2}$$

Where: $D_{critical}$ is the critical value at the 95% level of probability, and n_1 and n_2 are the respective sample sizes of the two distributions.

The Kolmogorov-Smirnov test operates on the null hypothesis that for $D_{observed} < D_{critical}$ there is no significant difference between the two distributions. The converse applies when $D_{observed} > D_{critical}$. The interpretation of the results of Table 6.3(a) and 6.3(b) is, however, relatively difficult to interpret fully due to the absence of any clear patterns. This may be ascribed to the nature of the distributions, such that the distribution for the soil ridges is inherently different from those of the joint orientations and inter-ped surfaces as it is two-directional whereas the other distributions are three-directional. A further complication arises from the difficulties inherent in obtaining consistent values for inter-ped surfaces and gully orientation under field conditions where they are subject to modification by erosion.

Table 6.3(a): Differences between the respective cumulative directional frequency distributions used in the determination of the D-value of the Kolmogorov-Smirnov test.

CLASS	DIFFERENCE IN CUMULATIVE DIRECTIONAL FREQUENCIES									
10^{0} INTERVALS	PED - JOINT	PED - PIPE	PED - SOIL RIDGE	PED - GULLY	JOINT - PIPE	JOINT - SOIL RIDGE	JOINT - GULLY	PIPE - SOIL RIDGE	PIPE - GULLY	SOIL RIDGE - GULLY
0 - 9	-0.05	0.0	-0.04	-0.02	0.05	0.01	0.03	-0.04	-0.02	0.02
10 - 19	-0.01	0.04	0.02	0.02	0.05	0.03	0.03	-0.02	-0.02	0.0
20 - 29	-0.01	0.02	0.02	-0.13	0.03	0.03	-0.12	0.0	-0.15	-0.15
30 - 39	-0.01	-0.01	0.17	-0.02	0.0	0.18	-0.01	0.18	-0.01	-0.19
40 - 49	-0.03	-0.07	0.18	-0.03	-0.04	0.21	0.0	0.25	0.04	-0.21
50 - 59	-0.10	-0.08	0.21	-0.02	0.02	0.31	0.08	0.29	0.06	-0.23
60 - 69	-0.17	-0.07	0.22	-0.01	0.10	0.39	0.16	0.29	0.06	-0.23
70 - 79	-0.14	-0.04	0.25	0.02	0.10	0.39	0.16	0.29	0.06	-0.23
80 - 89	-0.08	0.01	0.32	0.08	0.09	0.40	0.16	0.31	0.07	-0.24
90 - 99	-0.16	-0.02	0.16	0.08	0.14	0.32	0.24	0.18	0.10	-0.08
100 -109	-0.17	-0.03	0.05	0.02	0.14	0.22	0.19	0.08	0.05	-0.03
110 -119	-0.27	-0.14	0.07	0.01	0.13	0.34	0.28	0.21	0.15	-0.06
120 -129	-0.17	-0.05	0.20	-0.11	0.12	0.37	0.06	0.25	-0.06	-0.31
130 -139	-0.08	0.04	0.30	-0.06	0.12	0.38	0.02	0.26	-0.10	-0.36
140 -149	-0.08	-0.03	0.29	-0.08	0.05	0.37	0.0	0.32	-0.05	-0.37
150 -159	0.01	0.06	0.36	0.01	0.05	0.35	0.0	0.30	-0.05	-0.35
160 -169	0.0	0.05	0.21	0.0	0.05	0.21	0.0	0.16	-0.05	-0.21
170 -179	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
D VALUE	0.27	0.14	0.36	0.13	0.14	0.40	0.28	0.32	0.15	0.37
$D_{CRITICAL}$	0.23	0.25	0.24	0.27	0.23	0.22	0.25	0.25	0.27	0.26

Table 6.3(b): Interpretation of the D-values obtained from the Kolmogorov-Smirnov test for the distributions.

	INTER-PED SURFACES	BEDROCK JOINTS	SOIL PIPES	SOIL RIDGES
BEDROCK JOINTS	DIFFERENT			
SOIL PIPES	SIMILAR	SIMILAR		
SOIL RIDGES	DIFFERENT	DIFFERENT	DIFFERENT	
GULLIES	SIMILAR	DIFFERENT	SIMILAR	DIFFERENT

In an attempt to address this problem, a two-class moving average was used to 'smooth' the irregularities in the frequency distributions. The distributions after smoothing are given in Table 6.4 and the results of the analysis in Table 6.5(a) in a similar manner as before, with the interpretation of the D values being shown in Table 6.5(b).

Table 6.4: Directional frequencies obtained from using a two-class moving average on the data from Table 6.1 to smooth the frequency values per class interval.

CLASS	SMOOTHED DIRECTIONAL FREQUENCIES									
10° INTERVALS	INTER-PED SURFACES		BEDROCK JOINTS		SOIL PIPE ORIENTATION		SOIL-RIDGE ORIENTATION		GULLY ORIENTATION	
	ACTUAL %	Σ%	ACTUAL %	Σ%	ACTUAL %	Σ%	ACTUAL %	Σ%	ACTUAL %	Σ%
0 - 9	4.5	4.5	5	5	2.5	2.5	3.5	3.5	8	8
10 - 19	3	7.5	1	6	2	4.5	0	3.5	9	17
20 - 29	7.5	15	7.5	13.5	10	14.5	0	3.5	10	27
30 - 39	8	23	9	27.5	12	26.5	0	3.5	3	30
40 - 49	2	25	7	29.5	5	31.5	0	3.5	2	32
50 - 59	2	27	9	38.5	2	33.5	0	3.5	1	33
60 - 69	2	29	4	42.5	0	33.5	0	3.5	0	33
70 - 79	5.5	34.5	1	43.5	1.5	35	0.5	4	1	34
80 - 89	5	39.5	6	49.5	4	39	10	14	2	36
90 - 99	2	41.5	6.5	56	4	43	15	29	5	41
100 - 109	2.5	44	8	64	9	52	7	36	6	47
110 - 119	8	52	8	72	9	61	0.5	36.5	15	62
120 - 129	11.5	63.5	2	74	2.5	63.5	0	36.5	15	77
130 - 139	5	68.5	0.5	74.5	4	67.5	0.5	37	3.5	80.5
140 - 149	5	73.5	0.5	75	4	71.5	2	39	1.5	82
150 - 159	5	78.5	1	76	1	72.5	9	48	1	83
160 - 169	10	88.5	11	87	13	85.5	28	76	9	92
170 - 179	12	100	13	100	14.5	100	24	100	8	100
TOTAL READINGS	92		120		81		94		63	

As is evident, a clear pattern of interdependence emerges for the distributions with the exception of the soil ridges. Although these have a similar distribution to that of the bedrock joints, the available data indicate that there is a 95% probability that the spatial orientation of the soil ridges does not correspond with the distribution of the ped surfaces, the pipes nor the gully systems measured.

Table 6.5(a): Differences between the respective cumulative smoothed direction frequency distributions used in the determination of the D-value of the Kolmogorov-Smirnov test.

CLASS	DIFFERENCE IN CUMULATIVE SMOOTHED DIRECTIONAL FREQUENCIES									
10° INTERVALS	PED - JOINT	PED -PIPE	PED - SOIL RIDGE	PED - GULLY	JOINT - PIPE	JOINT - SOIL RIDGE	JOINT - GULLY	PIPE - SOIL RIDGE	PIPE - GULLY	SOIL RIDGE - GULLY
0 - 9	-0.01	0.02	0.01	-0.04	0.025	0.015	-0.03	-0.01	-0.055	-0.045
10 -19	0.02	0.03	0.04	-0.10	0.015	0.02	-0.11	0.01	-0.125	-0.135
20 - 29	0.02	0.005	0.115	-0.12	-0.01	0.1	-0.135	0.11	-0.125	-0.235
30 - 39	-0.05	-0.035	0.195	-0.07	0.01	0.12	-0.025	0.23	-0.035	-0.265
40 - 49	-0.05	-0.065	0.215	-0.07	-0.02	0.05	-0.025	0.28	-0.005	-0.285
50 - 59	-0.12	-0.065	0.235	-0.06	0.05	0.02	0.055	0.3	0.005	-0.295
60 - 69	-0.14	-0.045	0.255	-0.04	0.09	0 .0	0.095	0.3	0.005	-0.295
70 - 79	-0.09	-0.005	0.305	0.01	0.085	0.01	0.095	0.31	0.01	-0.3
80 - 89	-0.10	0.005	0.255	0.04	0.105	-0.06	0.135	0.25	0.03	-0.22
90 - 99	-0.15	-0.015	0.125	0.01	0.13	-0.11	0.15	0.14	0.02	-0.12
100 -109	-0.20	-0.08	0.08	-0.03	0.12	0.02	0.17	0.16	0.05	-0.11
110 -119	-0.20	-0.09	0.155	-0.10	0.11	0.085	0.1	0.245	-0.01	-0.255
120 -129	-0.11	0 .0	0.27	-0.14	0.105	0.025	-0.03	0.27	-0.135	-0.405
130 -139	-0.06	0.01	0.315	-0.12	0.07	0.035	-0.06	0.305	-0.13	-0.435
140 -149	-0.02	0.02	0.345	-0.09	0.035	0.02	-0.07	0.325	-0.105	-0.43
150 -159	0.03	0.06	0.305	-0.05	0.035	-0.08	-0.07	0.245	-0.105	-0.35
160 -169	0.02	0.03	0.125	-0.04	0.015	-0.15	-0.05	0.095	-0.065	-0.16
170 -179	0.00	0.0	0.0	0.00	0.0	-0.095	0.0	0.0	0.0	0.0
D VALUE	0.20	0.09	0.35	0.14	0.13	0.15	0.17	0.33	0.14	0.44
$D_{CRITICAL}$	0.23	0.25	0.24	0.27	0.23	0.22	0.25	0.25	0.27	0.26

Table 6.5(b): Interpretation of the D-values obtained from the Kolmogorov-Smirnov test for the distributions smoothed using a two-class moving average.

	INTER-PED SURFACES	BEDROCK JOINTS	SOIL PIPES	SOIL RIDGES
BEDROCK JOINTS	SIMILAR			
SOIL PIPES	SIMILAR	SIMILAR		
SOIL RIDGES	DIFFERENT	SIMILAR	DIFFERENT	
GULLIES	SIMILAR	SIMILAR	SIMILAR	DIFFERENT

The above results are primarily indicative of the already stated difference in the distributions and may well be a function of the limited exposure of the soil-ridge system, rather than any inherent differences in the distributions themselves. Considerably more research is required to address these considerations conclusively, as well as the whole question surrounding the genesis of the soil ridges themselves.

The ridges occur within a clay loam in a low-land area, some 500 m away from a stream on an incipient flood plain, and have yielded a C^{14} date of 105.3±1.1 year BP (Beta - 41501) by comparison to the surrounding soil with a date of 116.8±1.2 year BP (Beta - 41500). In real terms, however, these dates merely indicate that the ridges are formed in a modern soil. No meaningful difference appears to exist between the soil ridges and the adjacent A horizon (Table 6.6). This is corroborated by the results of a Students' t-test for paired samples, which shows that there is no significant statistical difference between the characteristics of the two samples at the 95% level.

The structural orientation of the joints and inter-ped surfaces reported in the present work correspond broadly with the data reported by Scheidegger (1990; 1995) for eastern southern Africa. It is hypothesized that the soil ridges may be related to earthquake activity of moderate intensity (to which this region is prone) at a time when the clay loam was water saturated. The underlying existing pattern at bedrock joints could then have been transferred to the near plastic soil above. It is considered necessary to invoke such semi-catastrophic process in order to account for the sharp divide that exists between the soil ridges and the surrounding A horizon, as shown in Figure 6.1.3(a) and (b). The fact that the soil ridges are not visible in the B horizon within the adjacent gully sidewall (see Figure 6.1.4) is interpreted that the ridges do not exist within the lower soil horizons principally as a consequence of the effects of confining pressure which would have existed at the time of formation. It is argued that the soil ridges taper with depth to become discontinuities within the soil in the lower horizons. Clearly the above hypothesis requires considerably more research before it can be accepted.

Table 6.6: A comparison of the characteristics of the soil ridges at Ngqugqu, Mqanduli district, with soil adjacent to them.

PARAMETER \ SOIL	NGQUGQU A HORIZON	NGQUGQU SOIL RIDGE
C^{14} AGE (yr .BP)	116.8+/-1.2	105.3+/-1.1
SAND %	35.73	35.85
SILT %	40.81	42.77
CLAY %	23.46	21.38
LIQUID LIMIT %	18	21
PLASTICITY INDEX %	7	5
LINEAR SHRINKAGE %	3.5	2.5
BULK DENSITY ($g.cm^{-3}$)	1.81	1.88
SHEAR STRENGTH (kPa)	83	125
FIELD MOISTURE %	3.4	2.6
FIELD CAPACITY %	26	18.7
DISPERSION RATIO	19.05	12.7
ORGANIC CARBON %	0.54	1.15
CEC ($cmol.kg^{-1}$)	24.75	32.25
ESP	2.24	2.02
SAR	7.58	5.13
EC ($mS.m^{-1}$)	168	155
OBSERVED t (paired samples)	-0.423	
$t_{CRITICAL}$	2.145	

The argument in favour of a relationship existing between bedrock joints and discontinuities within the soil profile is given credence by field evidence as shown in Figure 6.1.8 from Luxgoxgo, where the joint along which the gully segment in the foreground has incised may be traced through into the overlying soil.

The conceptual linkage between regional geological structure and prevailing drainage is well established in the geomorphological literature (see, for example, the work of Twidale, 1971; Tricart, 1974 and Summerfield, 1985; 1991). If the argument presented by Schumm (1973) that, under particular circumstances, gullies may be regarded as first order streams is accepted, the discussion presented in Section 6.1 attains the following significance: The data have shown that, provided the soil is susceptible to the development of subsurface erosion, regional geological structure related to the neotectonic stress field will be one of the principal determinants of the orientation of soil pipes. These systems will, over time, develop to the extent where

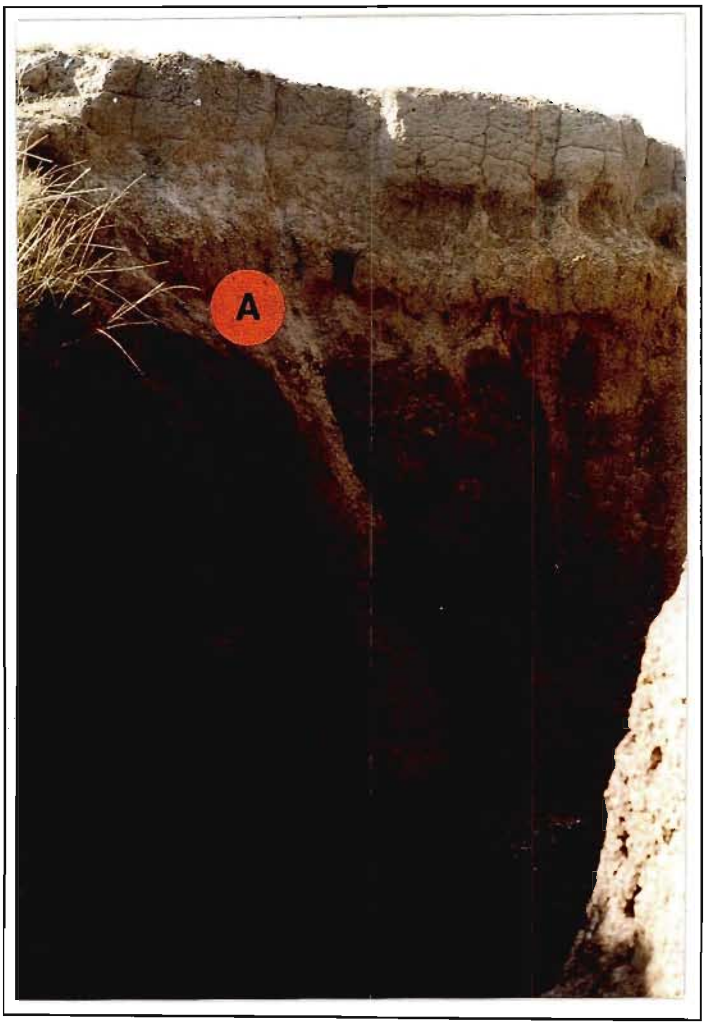


Figure 6.1.8: A bedrock joint runs parallel to a gully segment, yet corresponds with the extension of an inter-ped surface (A) in the soil horizon at Luxgoxgo.

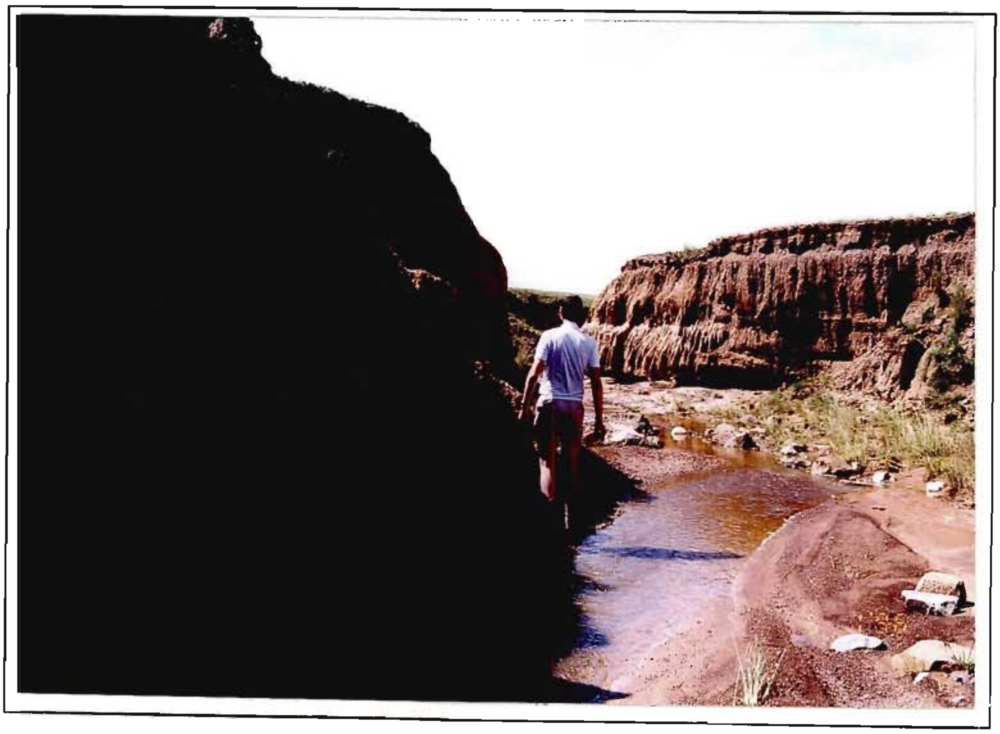


Figure 6.1.9: The position of a gully entrenched within the landscape.

roof collapse occurs and gully systems predominate which will themselves be aligned relative to existing joint patterns. Of some significance here is the recognition that crustal flexuring within a neotectonic stress field will frequently re-activate existing joints rather than create a new array (Cooper, 1990).

It is clear from observing gullies such as that shown in Figure 6.1.9 that, once initiated, the position of the gully within the landscape soon becomes entrenched, to the extent that any significant lateral shift is curtailed. Provided that the local hydrological regime is maintained, incision may progress to the extent where the gully is clearly established as a first order stream. Where denudation beyond the gully sidewalls proceeds either by extensive sidewall piping or by excessive surficial erosion, the local hydrological regime will be upset either resulting in badland-type topography as in Figure 6.1.10 or in choking and gradual aggradation within the gully system. The present work therefore provides a potential causal mechanism for the observed correspondence between geological structure and drainage pattern.

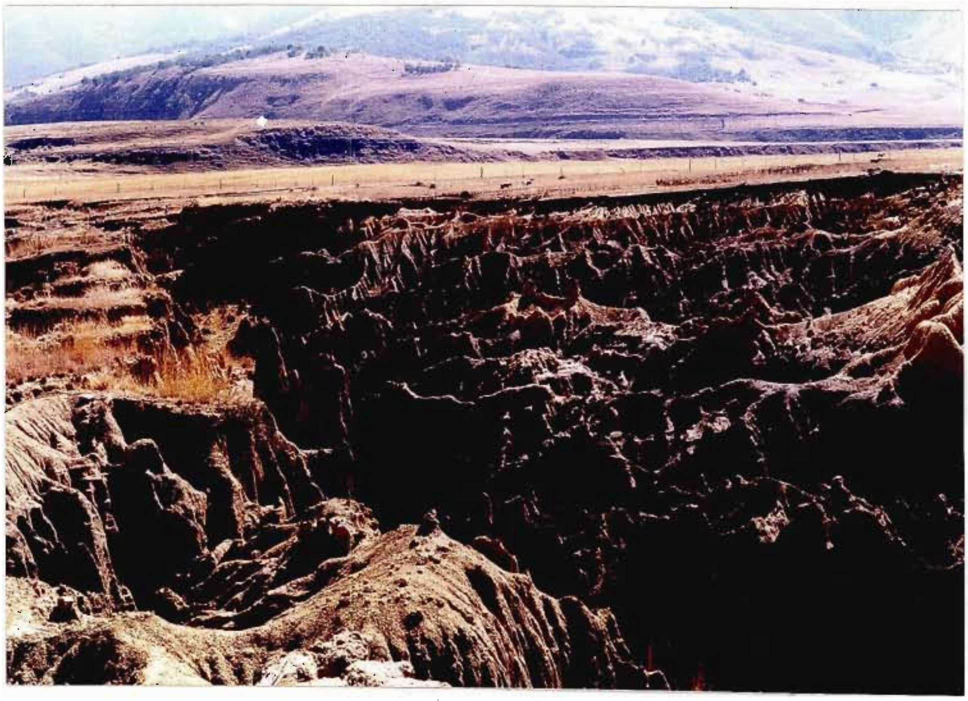


Figure 6.1.10: Badland topography near Kutsolo, resulting from subsurface erosion.

6.2 The Significance of Subsurface Erosion Processes in Southern KwaZulu - Natal and Transkei

The present study has shown that subsurface erosion is a common phenomenon with a far greater incidence in KwaZulu-Natal-Transkei than was previously recognised.

If the volumetric dimensions for the subsurface erosion forms of Types 1 to 4 as shown in Table 4.2 are summed, a conservative estimate of 628.5 m^3 of soil is obtained as an indication of the volume of soil lost out of the profile. A realistic value is likely to be closer to 850 m^3, given that the Type 5 erosion form has not been considered and that the tributary micro-pipes have also not been included. From the discussion in Chapter 5, it is seen that most of the pipes occur in the B horizon, with some effects on the A, C and, to a limited extent, the R horizons. When the horizons are weighted A:B:C in the proportion 10:80:10 relative to profile depth, and the mean bulk densities of the three horizons are used, an average bulk density for a representative pipe cross-section is obtained as 2.052 $g.cm^{-3}$. This in turn implies that some 1300 to 1750 metric tonnes of soil have been lost from the *documented* sites. It is again emphasized that no effort was made to record every pipe system in the region, hence no mean value of soil loss per area due to subsurface process can be quoted. Details are, however, available for three of the sites discussed in Chapter 5.

Fortuitously bone material was found *in situ* some 1.5 m below surface within the colluvium at Kutsolo. This was carefully removed and identified by Mr James Brink of the National Museum, Bloemfontein, as the pelvic bone of a small-plains zebra. This was subsequently found to have a C^{14} date of 158.4 BP ± 0.9 (Beta - 41502). The sedimentology of the site indicated that the bone had been buried by sediment, on which a juvenile A horizon has begun to develop. Analysis of air photographs of the Luxgoxgo site shows that the erosion here began some 15 years ago, prior to which there is *very* little evidence of its existence. The limitations associated with identifying subsurface erosion systems by remote sensing techniques as discussed previously imply that the absence of erosion is only strictly true for the gullies related to piping within the area. The age of the Langeni site has already been discussed. The volume of material removed may be roughly converted to mass as suggested before. The data for the three sites may now be broadly summarized as shown in Table 6.7:

Table 6.7: Estimates of nett soil loss due to piping for three sites.

PARAMETER / SITE	DRAINAGE AREA (ha.)	MASS OF SOIL LOST (t)	ABSOLUTE AGE	LOSS PER HECTARE	APPROXIMATE RATE (t/ha/a)
LUXGOXGO					
PIPE RELATED GULLIES	18	1050	15	58.3	4.6
PIPES	18	180	15	10.0	0.67
TOTAL	18	1230	15	68.3	4.6
LANGENI	0.15	8.5	4	56.6	14.2
KUTSOLO COMPOSITE SYSTEM					
MAXIMUM AGE	25	6500	200	260	1.3
ADJUSTED AGE*	25	6500	100	260	2.6

* adjusted to account for burial and re-excavation of the site

Notwithstanding the coarse approximations made to obtain the values in the above table, the following deductions may be made:

- There is a large disparity between the rates of soil loss obtained for the Langeni and Luxgoxgo systems, even if all soil loss for the latter system is ascribed to subsurface erosion rather than attributing a sizeable percentage of the gully erosion to processes related to surface wash.
- Such disparity may be accounted for firstly in terms of scaling factors akin to the problematique to extrapolating from individual runoff plots to the landscape scale, as discussed *inter alia* by Morgan (1986) and Bryan (1994), and secondly by scale dependant density of subsurface conduits per landscape area. Most of the infiltration water within the 0.15 ha. at Langeni would find its way into the pipe system, whereas within the Luxgoxgo site much of the infiltration will bypass the soil pipes. The

difficulty is essentially that of determining the drainage area of pipe systems which may differ markedly from the surface drainage area. The only reason for quoting rates of subsurface sediment loss relative to surface area is as a means of comparison with values of more conventional erosion forms. The rate of 14.2 t/ha/a for Langeni (equivalent to 1420 t/km^2/a) is, however, not too dissimilar to the suspended sediment yield of 2000 t/km^2/a measured by Makhoalibe (1984) under broadly similar conditions in Lesotho.

- Apart from variance resulting from the factors listed above, a large measure of the variability of rates shown in Table 6.7 may be ascribed to inherent perturbations in the runoff - infiltration - pipe flow - soil erosion system, which is itself poorly understood. It has been suggested that use of rainfall simulators in combination with detailed monitoring of pipe systems would give greater insights into the interrelationships that exist, (see for example Sumner, 1957). Although there is some merit to this suggestion, the difficulty arises in relating the data so obtained back to actual field conditions - it is likely that similar problems to those of Seuffert (1992) will be experienced, who found that as a consequence of the homogeneity of simulated rainfall both with respect to drop size and intensity, results obtained from plots under natural and under artificial precipitation in Sardinia, Italy, yielded significantly different results.
- The soil loss related to subsurface erosion ranges from potentially as low as 0.7 t/ha/a up to 14.2 t/ha/a, or in other words may account for as much as a *further* 77% of the erosion measured as a consequence of slope wash under natural veld (Le Roux and Roos, 1982). This factor alone may well account to a large measure for the periodic poor performance of mathematical erosion models within the study region because, as discussed in Chapter 2, the models do not adequately consider subsurface erosion processes.

6.3 The Socio - Economic Implications of Subsurface Erosion

6.3.1 The Problem of Soil Loss

It has been shown in the previous section that the total amount of soil lost through the various types of subsurface erosion system monitored amounts to only a small fraction of the total *annual* soil lost from the whole country - less than 0.002 million tons compared with the annual value of 360 million tons cited by Adler (1981) for the country. When the rates of development are however analysed, the values approximate the 'geological normal' rate 3 t/ha/a estimated by Murgatroyd (1979) and may be considerably greater, as in the case of Langeni.

The low total soil loss associated with soil pipes may well tempt researchers and soil conservationists to question the relevance of the research into subsurface erosion as anything other than an academic exercise. The answer to such question is multifaceted, namely:

- Table 6.7 indicates the multiplier effects 'triggered' by subsurface erosion of Luxgoxgo. Gullies related to piping (primarily through roof collapse) account for a near seven fold increase in the erosion rate when compared to the rate of pipe development only.
- The processes of pipe enlargement do not operate continuously, but are episodic in character. This is compounded further in that the present state of knowledge is too unreliable to enable the accurate prediction of either discharge events or the incidence and severity of erosion within pipes with any confidence.
- The severity of erosion should not be judged by the rate of soil loss *per se*, but rather the comparative rates of soil loss and soil formation. There is little knowledge of the rates of pedogenesis are within the KwaZulu-Natal - Transkei region. If one were, however, to accept the rates of soil formation by Bork (1988) for central Europe as some 1.5 t/ha/a and transpose these to the KwaZulu-Natal - Transkei region (with all the dangers inherent in such transference), more soil is on average lost through subsurface erosion

processes alone than what is generated by pedogenesis without surface erosion having been considered at all. A further problem exists with regard to subsurface soil loss. Where erosion is due to dispersion of hydrophilic clays, these frequently remain in suspension for several days in static water and hence pose a problem for the reticulation of potable water. Chemical flocculants are needed to precipitate the suspended material, increasing the cost of water purification.

6.3.2 Agricultural Considerations

Subsurface erosion phenomena are of direct socio-economic importance because of the threat posed to access to, and the economic viability of, communal fields as was seen in the Balasi case of Section 5.3.2. The Balasi case study has shown that once subsurface systems have developed to the extent where roof collapse occurs to form intermittent gullies, agricultural land becomes dissected to an extent where a portion of the land becomes inaccessible. Very few, if any, of the rural communities within the study area have access to the capital means necessary to attempt to rehabilitate land by deep ripping as recommended by Crouch (1979), quite apart from any considerations as to whether or not such action will have any lasting benefits. This is all the more pertinent a consideration, as the practice of deep ripping will bring the less fertile subsoil to the surface, necessitating the increased use of fertilizers to obtain a reasonable yield - again a question of affordability.

Along similar lines of reasoning, it is doubtful whether extensive liming of the soil is a viable solution where dispersion is a problem. Although good results have been reported, the major problem is again one of cost, both for the lime itself and for the agricultural machinery required to work the lime adequately into the soil.

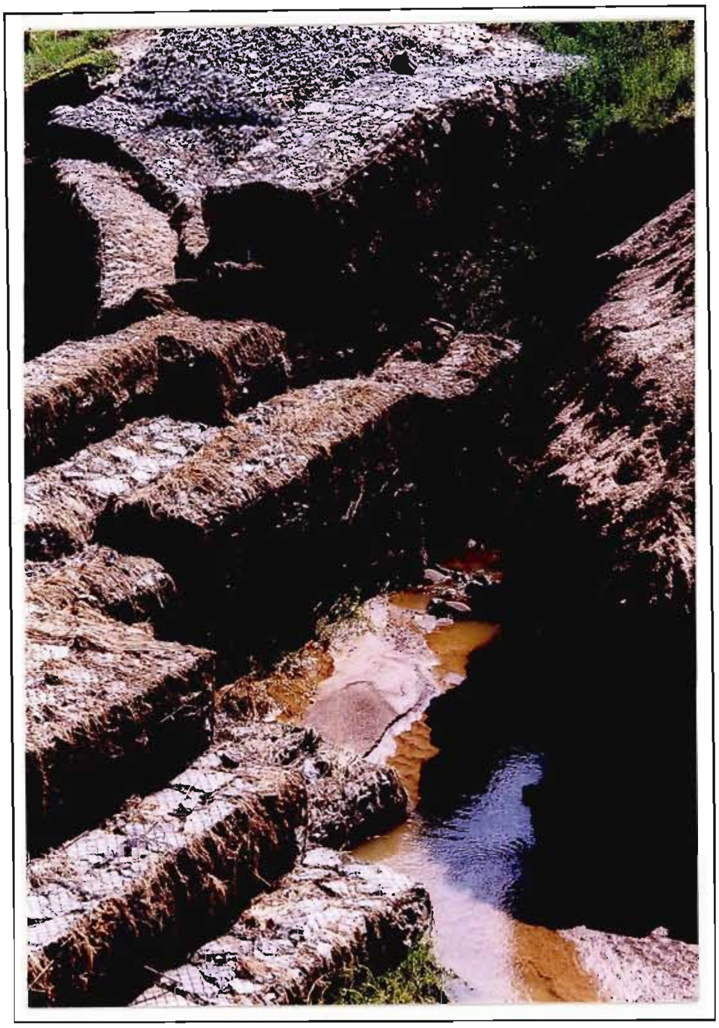


Figure 6.3.1: A failed gabion at Ncise. Dispersion has resulted in the gabion having been under-tunnelled on three successive occasions since it was constructed in 1987.

It is, however, important to maintain a realistic perspective of the nature and complexity of the problem. Although it may be feasible in some countries to alter the land - use practices radically in regions prone to subsurface erosion, for example to use them exclusively for low intensity activities such as grazing, this is not practical within the context of the present work where a large rural population is primarily dependent on the land in order to survive. Certainly, the long term (*ca.* ten to twenty year) goal needs to focus on creating a meaningful system of adequate/appropriate rural land - use planning, counterbalanced by job creation to decrease individual dependence on primary agricultural production. In the short to medium term, however, the erosion problem still needs to be addressed; all the more so in that, once piping has resulted in gullying, reclamation by conventional methods such as gabion structures is almost impossible (see Figure 6.3.1).

The Balasi site has also demonstrated the problem of soil disturbance and ponding associated with contour embankments, yet in many areas a severe surface erosion hazard exists due to the combination of slope angle and slope length. It is suggested that under these circumstances a conventional contoured grass strip is used in place
of an embankment, preferably in combination with a line of Vetiver grass (for a detailed discussion of the use of this grass in soil conservation, see UNEP, 1991). The rationale for this recommendation is as follows: The use of contoured grass strips in soil conservation is well documented for shallow slopes (see, for example, Hóly (1980) and Morgan (1986)) and is founded on the principle of decreasing the velocity of slope wash by increasing the surface roughness and infiltration, hence inducing siltation. Once established, the Vetiver acts as an efficient slope barrier resulting in ponding, infiltration and sedimentation. From the earlier discussion, the ponding and infiltration are problematic on structured soils (especially if these are also dispersive in the subsoil). Again Vetiver has an advantage - it develops a dense, near vertical roof structure to a depth of some 1.5m and is therefore likely to utilize much of the infiltration water, yet does not have a spreading root system which may lead to a significant nutrient impoverishment along the periphery of the cropland. Although Vetiver grass is considered unpalatable for livestock, it may be used as thrashing, for mulching or basket weaving.

6.3.3 Construction in Relation to Subsurface Erosion

The interactions between construction and subsurface erosion centre around the key issues of ponded surface water, and alterations to the soil hydrology by changes in effective local base level. Although these problems have been reviewed in detail in

Chapter 5, no potential solutions were considered. Also, no mention has been made of the implication of soils susceptible to subsurface erosion in relation to water storage within the context of the present study.

In the rural areas of KwaZulu-Natal - Transkei, an important source of water storage both for domestic use and for subsistence agriculture is by means of relatively small earth dams, constructed by scraping the soil from the storage area into a retaining berm. During the dry winters common throughout the region as indicated in Chapter 3, appreciable lowering of the water level will occur. The consequence is that the earth berm is subjected to periodic desiccation. In the following wet season, water will again be stored in the dam, resulting in an hydrological gradient across the berm or earth wall. The situation is now akin to the problem of contour embankments, with the difference that there is a greater hydrological pressure potentially forcing water into the berm. On well structured soils, particularly if these are in addition also dispersive, piping is initiated in or beneath the earth wall in a situation analogous to what has been documented extensively elsewhere (see, for example, Terzaghi and Peck, 1963). The consequence is that a pipe develops through the retaining wall, causing spontaneous failure of the dam and the associated risk of loss/damage to life and property consequent to failure as well as near total loss of storage capacity of the dam (see Figure 6.3.2).

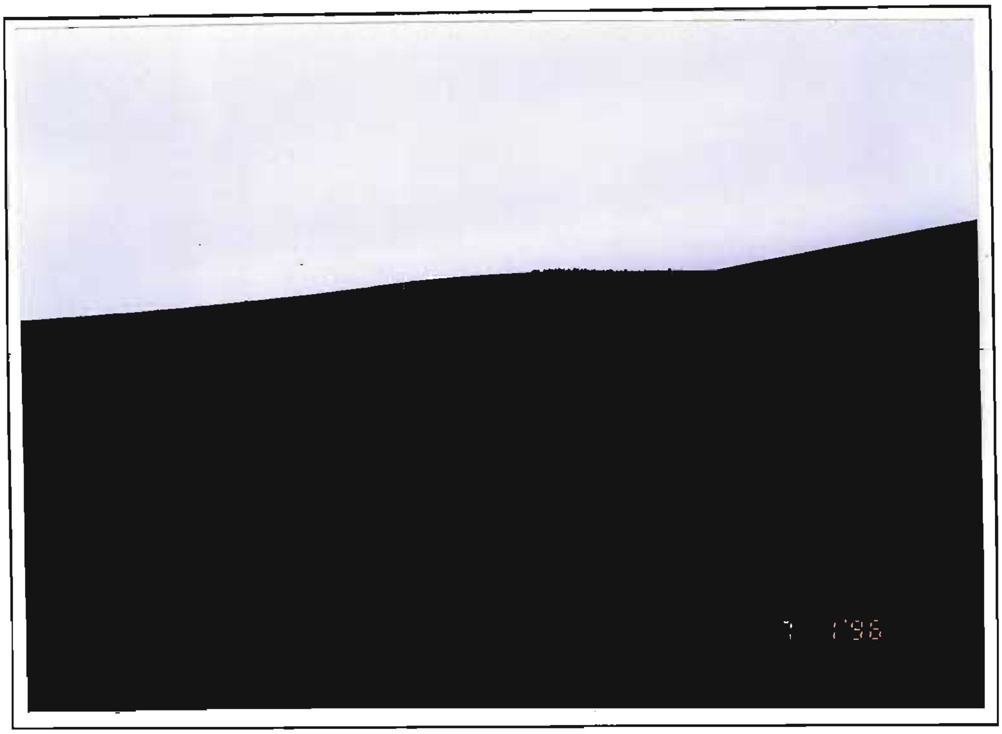


Figure 6.3.2: Failure of an earth dam due to piping near Tsolo

The problem associated with subsurface erosion in relation to infrastructural development can generally be overcome fairly readily by engineering solutions. The back slopes of cut embankments can be dewatered by use of either concrete - lined channels or porous pipes, while the runoff from road drainage can be channelled directly into existing natural drainage. Although such solutions are expensive, the likely costs represent only a small fraction of the total cost of an engineering contract, and should therefore form an integral part of the engineering specifications, as is the practice elsewhere (see for example the directives of the *Bundesanstallt für Straßenwesen,* 1985; and *Forschungsgesellschaft für Straßen- und Verkehrswesen,* 1991).

A potential difficulty arises where a rural village is situated on a moderately steep slope, such that house construction on `cut and fill' - type platforms is necessary. Here too the backslope is conventionally drained as is the case with a cut road embankment. Again this situation is potentially conducive to pipe development; the difference being that the individual householder is unlikely to have the financial resources to make an engineered solution viable. Under these conditions, effective liaison with extension personnel should enable the community to monitor the situation effectively and largely to circumvent problems by preventing water from ponding by ensuring that it is led off to irrigate nearby fields.

The focus thus far has been largely on the negative effects of subsurface water movement and the associated erosion. As was indicated in Chapter 5, many of the subsurface systems continue flowing for significant periods after the past precipitation event. In the absence of a reticulated water supply, many of the rural communities use the water from particularly the Type 5 systems (for example, Gungululu) for domestic purposes, as the water has been effectively filtered through the soil profile. Water is generally taken out of the macro-pore section before it reaches the surface, largely for ease of collection, but the water is also simultaneously protected from livestock. Although subsurface systems other than the Type 5 are utilized by communities, there is a strong tendency to use sites where little or no clay dispersion is present. It is of great importance that soil conservation schemes focused on reducing subsurface erosion should be sensitive to this second facet of soil moisture movement for, in the absence of reticulated water, much effort is expended by the community when the subsurface seepage dries up. Alternately, water is purchased at a high price from entrepreneurs who bring water in by truck, much like the water carriers of Europe during the Middle Ages.

On the basis of the results presented, it is evident that notwithstanding the present lack of understanding on several aspects of subsurface erosion phenomena, a consideration of the potential for subsurface erosion should be incorporated into all aspects of particularly rural land-use planning in much the same way as has been done concerning surficial erosion processes.

Chapter 7

7. Conclusions

The analysis of subsurface erosion phenomena in the foregoing work has facilitated an explanation of landscape morphology based on the interaction between denudational process, structure and parent material; according to Sparks (1972) the ultimate aim of geomorphology.

The results of the present study suggest that subsurface erosion forms, and soil pipes in particular, occur considerably more frequently than has hitherto been acknowledged - the literature in many respects still regards these erosional phenomena as freak occurrences. The evidence presented has shown that, although rates of subsurface erosion generally range between the two extremes of 0.7 and 14.2 t/ha/a, under suitable environmental conditions piping may account for an additional 77% of the sediment losses sustained as a consequence of surficial processes. Current mathematical soil erosion models do not, as a rule, take cognisance of subsurface erosion - a fact which may account for the poor correlation between observed and predicted values of soil loss in some areas.

It has further been shown that there is a causal relationship between the geological structure and the macro-structure reflected by the inter-ped surfaces within the soils of the region. The statistical correspondence which has been shown to exist between soil pipe segments, gully segments, inter-ped surfaces and bedrock joint systems has, for the first time, facilitated the quantitative explanation which details the mechanisms by which the structural characteristics of the underlying bedrock may be imprinted onto drainage systems of landscapes to produce the 'structurally controlled drainage basins' often cited in the literature.

The analysis of 148 soil pipes has shown that, contrary to current belief, subsurface erosion does not necessarily develop only as a direct consequence of soil chemistry, but may also be associated with soil-physical and/or soil hydrological conditions in strongly structured soils. Soil chemistry, -physics and -hydrology may individually or in concert with one-another cause piping. It was therefore possible to identify five distinct types of subsurface erosion system, namely:

- scree slope systems;
- gully sidewall systems;
- human-induced systems (which can potentially be subdivided further);
- systems in highly dispersive soils; and
- seepage systems.

It was further found that the occurrence of these subsurface erosion systems was spatially well defined, and that particular types of system only occur on particular landscape units of the Nine Unit Landscape Model (NULM), as indicated in Table 7.1:

Table 7.1: The occurrence of subsurface erosion systems relative to landscape units off the NULM of Conacher and Blong (1977).

SYSTEM TYPE	SYSTEM NUMBER	LANDSCAPE UNIT
SCREE	1	5
GULLY SIDEWALL	2	5; 6; 7
HUMAN INDUCED	3	2; 5; 6
DISPERSIVE SYSTEMS	4	2; 4
SEEPAGE SYSTEMS	5	4; 5

Conclusions which may be drawn from the study pertain to the social and economic significance of subsurface erosion, the potential implications for the rehabilitation of degraded land associated with subsurface erosion processes, and the avenues for future research.

7.1 Social and Economic Implications

The socio-economic implications of subsurface erosion centre around the primary community concerns of food and water. All forms of erosion pose a threat to the agricultural potential in a region by diminishing the soil reserves and particularly by lowering the available soil nutrients.

It has been shown that the risk associated with subsurface erosion in this regard is relatively low as the topsoil is often unaffected, especially in the early stages of subsurface erosion. The threat to food production is primarily a structural one - the productivity and potential of cropland are affected in that access routes are disrupted, or that fields are dissected by the sudden appearance of gullies as a pipe roof collapses. Alternatively, what should have been soil conservation works (eg. contour embankments) actually enhance an erosion problem and in turn trigger forms of surface erosion further down slope.

The effect of subsurface erosion on the supply of potable water has been shown to be complex: The subsurface erosion frequently concentrates the soil water at the soil-rock interface, and thus protects it from surface contamination by pollutants and from evaporation. As a result rural communities often rely on the water from such systems to meet their domestic water needs. At a larger scale, however, the problem is more severe - subsurface erosion and particularly piping is the main cause of failure of earth dams. The realisation that piping may stem from causes other than the dispersive nature of soils is thus of particular relevance in this context.

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7.2 Rehabilitation of Areas Affected by Subsurface Erosion

It has been shown that the rehabilitation of degraded areas associated with subsurface erosion is particularly problematical, as many of the conventional conservation structures such as gabions, exacerbate the erosion problem under these conditions. Although the scope of the present research did not allow extensive investigation into suitable methods of rehabilitation, it is clear that the most effective manner of rehabilitation will be, where possible, to remove the cause of the problem. The most effective conservation measures are likely to be those which keep the soil moisture within a profile as constant as possible without creating any steep hydrological gradients within the soil. The use of vegetation in combatting erosion appears to be effective, but considerably more research is needed in order to validate these early indications.

7.3 The Need for Further Research

The research presented here has facilitated the explanation of many of the erosion phenomena observed in southern KwaZulu-Natal and Transkei and, through the recognition of the five types of subsurface erosion, shed light on many of the apparent contradictions which existed regarding thee genesis of soil pipes. It has, however, also raised new questions requiring further research. Pertinent among these are the following:

- The *critical* values of soil chemistry appear to be ill suited to the southern African environment, and need to be recalibrated for the conditions in this region;
- An acceptable methodology needs to be developed to measure the rate of development of subsurface erosion, including the rates of discharge of these systems, rather than measurement by inference as was of necessity the case in the present study; and

- the importance of the causal parameters relative to one another needs to be quantified so that due consideration of subsurface erosion phenomena can be given in mathematical erosion models.

Once such research results are available, the information can be integrated back into the soil conservation and rehabilitation practices through applications-based research.

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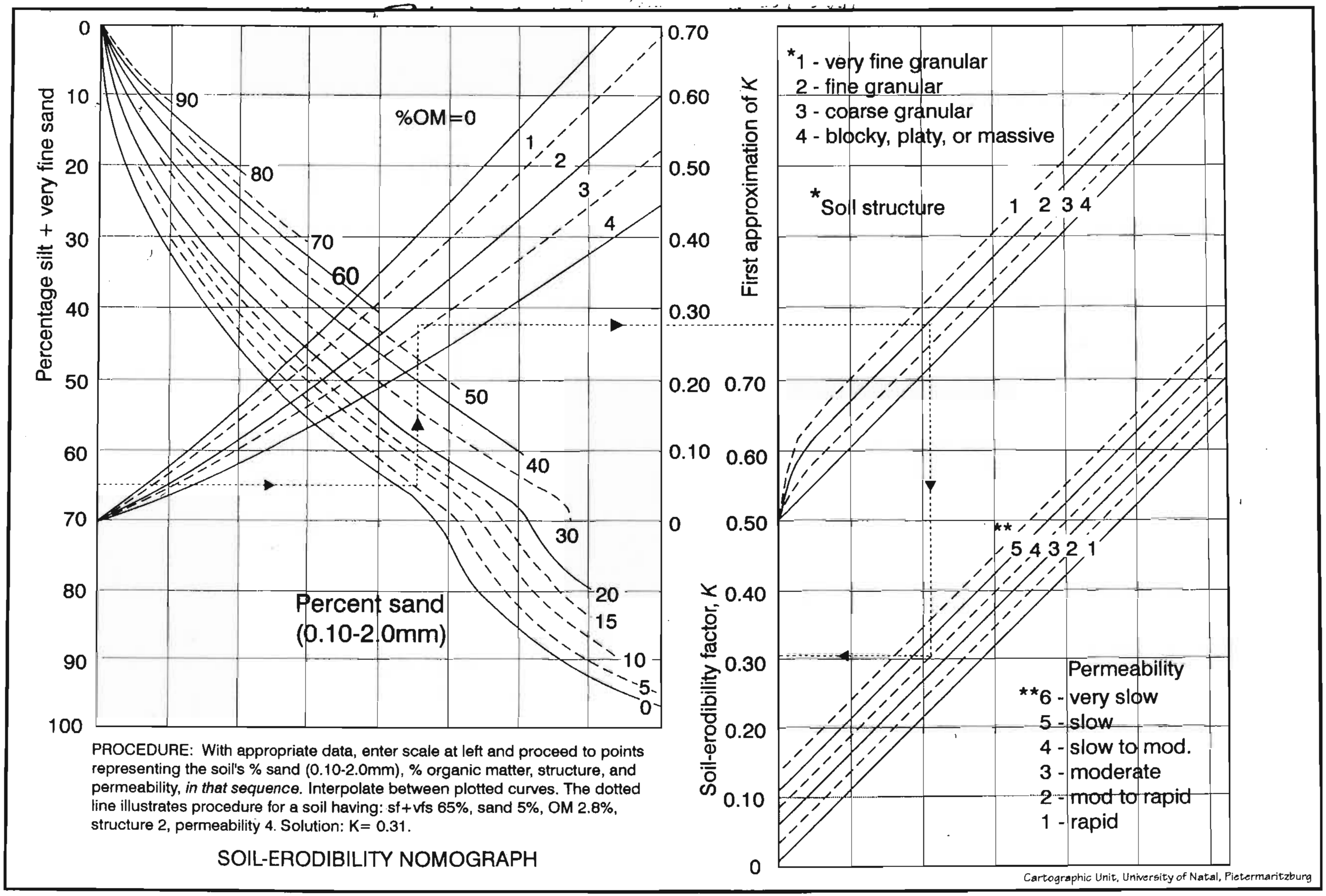

The soil-erodibility nomograph (after Wischmeier *et al.*, 1971).

APPENDIX 2

LOC. NO.	LOCATION	LAT	LONG	RAINDAYTOT	PPTTOT.	RDI-RAINFALL	RDI-RAINDAY	RAINDAYDIST
1	KEI BRIDGE	**32 30**	27 58	51	502.2	60.35	66.67	13.97
2	KENTANI	**32 30**	28 19	91	961.2	58.45	61.90	24.93
3	MANUBIE	**32 26**	28 37	111	1168.2	46.07	50.00	30.41
4	NDABAKAZI	**32 23**	28 02	82	741.8	64.35	45.95	22.47
5	BOLO	**32 22**	27 39	90	984	64.95	55.00	24.66
6	HOPEWELL	**32 22**	27 42	85	622.2	66.30	55.00	23.29
7	GCUWA	**32 20**	28 08	80	709.9	59.52	60.00	21.92
8	WILLOWVALE	**32 16**	28 30	94	897	62.75	57.14	25.75
9	BASHEE MOUTH	**32 14**	28 55	114	1114.2	41.37	44.44	31.23
10	NQAMAKWE	**32 12**	27 56	91	681.1	60.56	57.14	24.93
11	CWEBE	**32 12**	28 56	87	699.3	45.28	51.22	23.84
12	KEILANDS	**32 12**	27 32	58	501.4	69.16	53.85	15.89
13	MBULU	**32 09**	27 43	83	674.4	68.57	58.97	22.74
14	IDUTYWA	**32 06**	28 18	72	723.3	64.52	62.50	19.73
15	TUBENI	**32 03**	28 45	81	779.9	70.51	68.42	22.19
16	TSOMO	**32 02**	27 49	59	542.1	67.20	55.56	16.16
17	ELLIOTDALE	**31 58**	28 40	73	711	61.26	64.71	20.00
18	QUEENSTOWN	**31 53**	26 53	86	559.8	68.42	50.00	23.56
19	ENGCOBO	**31 52**	28 03	101	1037.8	75.44	62.50	27.67
20	MQANDULI	**31 48**	28 45	89	966.3	65.66	66.67	24.38
21	CLARKEBURY	**31 48**	28 18	83	875.5	68.12	56.76	22.74
22	QUNU	**31 47**	28 37	59	681.9	64.75	58.62	16.16
23	CESU	**31 46**	28 44	94	1038.4	64.43	60.00	25.76
24	LADY FRERE	**31 42**	27 14	59	591.1	71.83	55.56	16.16
25	NGQELENI	**31 40**	29 02	81	978.4	59.11	58.97	22.19
26	PT ST JOHNS	**31 37**	29 31	106	1354.3	50.33	53.85	29.04
27	UMTATA	**31 35**	28 47	96	648	66.41	56.52	26.30
28	BAZIYA	**31 34**	28 25	106	1090.5	75.48	68.00	29.04
29	LIBODE	**31 32**	29 02	83	756.3	62.39	58.97	22.74
30	CALA	**31 31**	27 42	68	618.5	68.80	54.84	18.63
31	LANGENI	**31 29**	28 28	99	1020	78.73	82.98	27.12
32	KAMBI	**31 28**	28 37	94	932.8	75.32	67.44	25.75
33	INDWE	**31 28**	27 20	63	598.6	73.77	58.62	17.26
34	NQADU	**31 26**	28 45	103	968.9	71.16	62.50	28.22
35	IDA	**31 25**	27 33	78	703.4	71.63	55.56	21.37
36	NTSUBANE	**31 24**	29 42	112	1463.5	56.71	54.72	30.68
37	SASSUN	**31 24**	27 45	45	526	73.06	60.00	12.33
38	LUSIKISIKI	**31 22**	29 35	94	799.9	57.41	60.00	25.75
39	ELLIOT	**31 20**	27 51	73	781.6	74.77	64.71	20.00
40	TSOLO	**31 18**	28 46	62	587.8	69.60	71.43	16.99
41	MKAMBATI	**31 16**	29 57	96	1184.1	48.83	47.83	26.30
42	BARKLY PASS	**31 11**	27 50	75	754.9	61.96	47.06	20.55
43	QUMBU	**31 10**	28 52	76	783.6	78.84	61.11	20.82
44	FLAGSTAFF	**31 05**	29 30	92	864.8	65.21	67.44	25.21
45	MACLEAR	**31 04**	28 21	88	803.3	78.13	66.67	24.11
46	CENGCANE	**31 02**	28 47	93	976.5	76.97	68.89	25.48
47	TABANKULU	**31 01**	29 22	119	1198	70.41	64.91	32.60

48	PAPANE	**31 00**	29 01	80	690.6	70.38	64.10	21.92
49	KROMHOEK	**30 57**	28 27	55	716.2	80.05	69.23	15.07
50	TABANKULU	**30 57**	29 18	76	746.6	62.46	61.11	20.82
51	BUSHY VALES	**30 55**	30 18	66	1061.6	53.78	53.33	18.08
52	N LYNNDALE	**30 54**	28 19	94	1035.7	74.58	64.44	25.75
53	MT FRERE	**30 54**	28 59	84	893.1	72.75	65.85	23.01
54	AMANZAMNYAMA	**30 53**	28 54	107	1133.5	74.58	64.71	29.32
55	ETWA	**30 53**	28 42	78	686	74.78	64.10	21.37
56	TONTI	**30 52**	29 24	116	1082.6	66.48	60.00	31.78
57	BIZANA	**30 51**	29 49	102	826.6	63.49	64.00	27.95
58	BALLYCLARE	**30 49**	30 15	90	622.9	62.48	63.64	24.66
59	INSIZWA	**30 49**	29 15	99	1237.1	70.07	62.50	27.12
60	LUDEKE	**30 49**	29 43	88	779.7	63.61	55.00	24.11
61	ELANDS HTS	**30 48**	28 13	90	1206.5	78.67	66.67	24.66
62	MT AYLIFF	**30 48**	29 22	84	675	64.33	58.97	23.01
63	BLOEGOMHOF	**30 46**	28 20	54	693.2	77.25	68.00	14.79
64	DELVILLEBOS	**30 46**	28 21	89	693.5	76.47	67.44	24.38
65	COLWANA	**30 44**	28 42	99	967.7	75.44	66.67	27.12
66	PT SHEPSTONE	**30 44**	30 27	96	1113.5	54.83	52.17	26.30
67	EUREKA	**30 43**	30 01	87	1050.2	72.22	76.74	23.84
68	FT DONALD	**30 43**	29 33	123	954.6	69.75	62.71	33.70
69	MT FLETCHER	**30 41**	28 30	82	751.4	77.57	68.42	22.47
70	TSHATSHENI	**30 40**	28 57	91	956.7	76.55	64.44	24.93
71	IMPETYNE	**30 37**	29 40	132	1393.8	77.14	69.23	36.16
72	WEZA	**30 36**	29 43	129	1122.2	75.28	68.25	35.34
73	HARDING	**30 34**	29 53	88	788.3	71.63	68.18	24.11
74	MVENYANE	**30 32**	20 02	117	835.2	73.34	65.52	32.05
75	WILLOWDALE	**30 32**	29 32	87	693.6	70.76	65.85	23.84
76	KOKSTAD	**30 32**	29 25	72	784.2	76.19	70.59	19.73
77	SEVENFONTEIN	**30 30**	29 28	75	736.4	77.57	77.78	20.55
78	CEDARVILLE	**30 23**	29 03	80	624.6	70.26	70.00	21.92
79	MATATIELE	**30 20**	28 49	78	970.7	78.83	68.42	21.37
80	SCOTTBURGH	**30 17**	30 45	99	1115.7	46.07	54.17	27.12
81	THE MEADOWS	**30 16**	29 14	72	750.2	78.76	76.47	19.73
82	UMZIMKULU	**30 16**	29 56	84	696.8	73.13	65.85	23.01
83	IXOPO	**30 09**	30 04	105	824.9	67.65	73.58	28.77
84	QACHASNEK	**30 07**	28 42	97	928.1	80.24	69.57	26.58
85	SEHLABATHEBE	**29 53**	29 04	81	749	79.69	74.36	22.19
86	BUSHMAN'S NEK	**29 50**	29 13	89	819.5	92.08	77.78	24.38
87	BULWER	**29 48**	29 46	106	1267.9	79.12	76.92	29.04
88	HIMEVILLE	**29 46**	29 32	94	1013.1	85.16	81.40	25.75
89	IMPENDLE	**29 36**	29 52	99	944.5	77.75	70.83	27.12
90	SANI PASS	**29 34**	29 18	120	1171.8	78.30	68.97	32.88
91	CEDARA	**29 32**	30 17	149	880	73.66	61.11	40.82
92	KAMBERG	**29 22**	29 42	109	1087.6	89.77	76.92	29.86
93	GIANT'S CASTLE	**29 17**	29 30	101	1045	85.26	79.59	27.67
94	MOKHOTLONG	**29 17**	29 05	92	575.1	80.50	77.27	25.21
95	CATHKIN PEAK	**29 00**	29 25	101	1255.6	76.23	73.08	27.67

96	ESTCOURT	**29 00**	29 53	82	770.8	82.38	75.61	22.47
97	CATHEDRAL PEAK	**28 57**	29 12	105	1268.7	80.14	76.00	28.77
98	FICKSBURG	**28 52**	27 53	77	752.9	81.39	66.67	21.10
99	WEENEN	**28 51**	30 05	69	672.8	82.14	77.14	18.90
100	BERGVILLE	**28 44**	29 21	69	768	79.71	75.76	18.90
101	ROYAL NATAL	**28 41**	28 57	122	1320.9	83.72	71.93	33.42
102	FOURIESBURG	**28 37**	28 12	72	597.2	79.31	70.59	19.73
103	LADYSMITH	**28 33**	29 47	91	789.4	79.77	76.74	24.93
104	WITSIESHOEK	**28 32**	28 48	67	696.4	76.27	76.47	18.36
105	CLARENS	**28 31**	28 25	55	724	78.23	76.00	15.07
106	GROENLAND (GG)	**28 30**	28 34	72	674.9	78.04	71.43	19.73
107	VAN REENEN	**28 22**	29 23	86	986.8	82.94	76.74	23.56
108	KESTEL	**28 19**	28 42	67	829.8	77.92	69.70	18.36
109	HARRISMITH	**28 16**	29 08	67	631.4	77.67	75.76	18.36