AN INVESTIGATION INTO THE NATURE OF GULLY EROSION AT GOLDEN GATE HIGHLANDS NATIONAL PARK

by

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DECLARATION OF ORIGINALITY

Except where explicitly indicated to the contrary, this study is the original work of the author. This thesis has not previously been submitted in any form to any other University.

TABLE OF CONTENTS

ABSTRACT

The general aim of this study was to gain an insight into the nature of gully erosion at Golden Gate Highlands National Park. In order to achieve this the spatial and temporal characteristics of six gullies were investigated by examining their typological and morphological characteristics, the relationship between their morphometric properties and their increase in extent over a 39 year period (1952-1991). Where possible these findings and observed gully forms were related to initiating factors.

Extensive field surveys and measurements were carried out to ascertain the typological and morphological characteristics of each gully. The results of the field measurements were then statistically analyzed using linear regression analysis, principal component analysis and canonical variate analysis. These methods of analysis were used to get an indication of the relationships that exist between the morphometric properties of the gullies as well as to highlight the similarities and differences that exist between them. These results showed that the morphometric variables of the gullies are strongly interrelated. Furthermore, they revealed that the six gullies could be divided into three broad groups on the basis of their morphometric and sediment properties. The gullies within two of the three groups were found to be similar not only in terms of the above mentioned, but they also occur on same facing slopes of similar gradients and appear to have been initiated by similar processes. Differences occurring within and between the gully groups were attributed to varying combinations of initiating factors.

Aerial photographs from 1952 and 1984 were used together with field surveys to map the extent and development of five of the six gullies - the remaining gully was only initiated in 1988. The 1952 and 1984 photographs were selected as they

represent the earliest and most recent photographs to be taken of the area. The maps show the gullies to have experienced a greater amount of growth during the 1984-1991 period than during the 1952-1984 period. This finding was attributed to the sporadic nature of gully growth.

The spatial location of the gullies in relation to one another appears to have had little influence on their typological and morphological characteristics. However, their spatial location within the landscape has undoubtedly influenced these properties.

In general the research described has shown that the spatial and temporal differences of the gullies occurring in the Park are the result of various combinations of endogenous and exogenous factors that governed the initiation and development of each gully.

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LIST OF FIGURES

Page

LIST OF TABLES

CHAPTER ONE

INTRODUCTION

1.1. BRIEF HISTORICAL BACKGROUND

Man's philosophical approach to gullying has changed over time, from that of gullies being something that can be utilized for his benefit to them being regarded as "sceptic foci" (Jacks and Whyte, 1939) on the landscape. This change in approach was largely brought about by the increase in man's mobility with the onset of the age of industrialization.

Prior to the Industrial Revolution when man was less mobile and thereby more dependent on the land, gullies were not regarded as an evil in themselves, but were instead utilized - particularly in desert agriculture - for the collection of water and the cultivation of crops. Examples of such agricultural systems dating back to the Iron Age are described by Evenari *et al.* (1961), for the Negev Desert in Israel. Furthermore, Herold (1965), describes how the aborigines of the northern Sierra Madre Mountains of Chihuahua and Sonora, Mexico, were able to create agricultural and garden plots in gullies by building "trincheras" - check dams built from loose rocks. These "trincheras" served to trap sediment within the gullies thereby increasing the water storage of these trapped deposits. Besides these two examples, similar desert agriculture was also practised in Transjordan, Southern Arabia, North Africa, Syria and North America, with many of these areas supporting higher population densities than they do today (Dennis and Griffin, 1971; Evenari *et al.*, 1961; Evenari, 1974).

However, the onset of industrialization and the resulting increase in mobility led to the establishment of roads and communication networks, an increase in population densities, the fencing off of property and ultimately to the loss of man's close dependence on the land. As a consequence the environmental value of gullies changed. No longer were they seen as something that could be utilized for man's benefit, but instead were regarded as destroyers of farmland and property, and as a hinderance to rapid communication. It is thus not surprising that the first textbook on gullies, which was published in the 1860's in France, dealt only with gully control (Heede, 1976).

From the 1860's until the mid 1950's gully erosion research continued to focus mainly on control structures and management techniques (Heede, 1976). Since the 1950's, however, the scope of research has broadened to include numerous investigations into factors such as: conditions governing gully initiation and development (see for example, Palmer, 1965; Heede, 1976), general gully morphology (e.g. Heede, 1970; Veness, 1980; Hannam, 1983), flow conditions (e.g. Pickup, 1975), sediment characteristics (e.g. Schumm, 1960a; 1960b; 1961; Heede, 1971) and mechanisms and rates of gully erosion (e.g. Beer and Johnson, 1963; Bradford and Piest, 1980; Crouch, 1990a; 1990b).

Today it is generally agreed that gully erosion is of major environmental concern. This concensus is reflected in the sizeable body of literature pertaining to these erosional features, and the fact that they have been investigated by numerous researchers at various locations around the world. The worldwide occurrence of this phenomenon is also well documented in the variety of names given to gullies, many of which are colloquial to a given region (Table 1.1).

Table 1.1. **Some of the different terms used to describe a gully, and the location where the term is used.**

Name	Region of Usage
Arroyo or washes	American southwest
Barrancas	Pacific southwest
Bocorocas or carcava	South America
Coulees	Pacific northwest
Donga	Southern Africa
Gulch	North America
Lavaka or "scoop"	Madagascar
Nulla or ravination	India
Ravin	French speaking lands
Wadi	Egypt

In spite of the above and the progress that has been made in researching these phenomena, a major problem that is fundamental to discussions of gullies is that of a consistent definition. Inherent in this problem are two schools of thought. On the one hand, it is argued that a specific definition is required, because without one the term "gully" is often used intuitively, resulting in the erosion phenomena grouped as "gullies" being extremely diverse (Imeson and Kwaad, 1980). This diversity makes the interpretation of the scientific meaning of this phenomenon, and the extrapolation of data from one area to another, difficult. On the other hand, Harvey *et al.* (1985), while acknowleding the lack of a consistent definition, believe that by attempting to define gullies, researchers are imposing a more specific meaning on a term intended for general usage. After all, the term, which was first used to describe an erosional feature in 1657 (Harvey *et al.*, 1985), is probably a corruption of the term gullet, which is Middle English for a "defile gully or ravine" (Little *et al.*, 1964). Furthermore, in the glossary of the American Geological Institute (1972:318), a gully is defined as being either:

> 'a) A very small valley, such as a small ravine in a cliff face, or a long, narrow hollow or channel worn in earth or unconsolidated materials (as on a hillslope)...' or 'b) Any erosion channel so deep that it cannot be crossed by a wheeled vehicle or eliminated by ploughing,especially one excavated in soil on a bare slope.'

The question thus arises; should "gully" remain a general term, or should it be defined more specifically? While a consistent definition is desirable, it would exclude the features which are unique to each gully, and these features should not be overlooked by researchers (Firth and Whitlow, 1991). It is therefore proposed here, that instead of a consistent definition, the characteristics of gullies be highlighted as a guideline, thereby making the interpretation and extrapolation of data from one area to another easier, but at the same time allowing the incorporation of features unique to a given area or gully.

A summary of the many alternative definitions that have been proposed (Food and Agricultural Organization (FAO), 1965; Little *et al.*, 1964; Brice, 1966; Hudson, 1971; American Geological Institute, 1972; Hauge, 1977; Moss and Walker, 1978; Morgan, 1979; Bradford and Piest, 1980; Imeson and Kwaad, 1980; Graf, 1983; Graham, 1984; Harvey *et al.*, 1985; Ebisemiju, 1989), together with some personal observations, suggest the following characteristics to be intrinsic to a gully:

- a steeply incised U- or V-shaped channel, often with a sharp head scarp
- fluvially incised into unconsolidated earth materials but may sometimes develop in bedrock
- only intermittently occupied by flowing water
- forms part of a continuum of incised channels being distinguished from a rill by its size i.e. depth greater than 0.6m and shoulder width greater than 0.3m (Brice 1966, Imeson and Kwaad 1980), and from a stream channel by a width:depth ratio greater than unity
- an unstable landform which is dynamic and changing

It was according to the above criteria that the gullies in this study were recognized and defined.

1.2. THE AIM OF THIS STUDY

The general aim of this study is to gain an insight into the nature of gully erosion occurring at Golden Gate Highlands National Park. In order to achieve this the spatial and temporal characteristics of six gullies are analyzed by examining:

- their typological and morphological characteristics
- the relationship between their morphometric properties and,
- their increase in extent over a 39 year period.

Where possible these findings and observed gully forms are related to causal factors.

The scientific background to this study is set in Chapter 2. This is a theoretical chapter, but with a systematic approach aimed at summarizing the concepts and variables associated with gully erosion, as pertaining to this study. Chapter 3 describes the physical setting of the study area as well as the various techniques used for data collection and analysis. The results of the study are contained in Chapters 4 and 5, and are discussed in Chapter 6. Finally, Chapter 7 presents a summary of this study in which conclusions are drawn.

CHAPTER TWO

SCIENTIFIC BACKGROUND

2.1. CAUSES OF GULLY EROSION

A review of the literature pertaining to causes of gully erosion suggests that much controversy still surrounds many of the theories postulated, occasionally even to the point of contradiction. Part of the reason for this appears to be that gully erosion is difficult to quantify in terms of causative factors (Piest and Spomer, 1968). Furthermore, as Harvey *et al.* (1985:3) point out '... there are no commonly accepted techniques that quantify gully initiation, growth and development under varying conditions of land use.' As a result, any relationships derived from the study of gullies in a particular area, cannot be readily extrapolated to another area in which the environmental conditions are different. Consequently, there still exists a need for a better understanding of the geomorphic causes of gully erosion (cf. Patton and Schumm, 1975).

Two issues about which there is little controversy and which are particularly important when discussing the causes of gully initiation namely, the threshold phenomenon and runoff responsible for gully initiation, are reviewed below.

2.1.1. The threshold phenomenon

In attempting to describe the factors which act as catalysts triggering complex sequences of events that result in gullying, the threshold phenomenon needs first to be discussed. It is in the context of Bradford and Piest's (1980:75), description of a landscape that this phenomenon may best be described and understood. They describe a landscape as:

> 'an energy regime with a delicate balance between the form of the system and inflow and outflow of energy. The system is continuously importing energy, and an erosion threshold may be reached if the mode of energy utilization changes. The way in which this added potential energy is stored or utilized changes when a change of state threshold is reached.'

A threshold simply means 'The point at which a stimulus initiates a response' (Rao, 1978:179). Schumm (1973) recognized what he terms a "geomorphic threshold". This is a threshold of landform stability that is exceeded by changes either in external or internal variables. Inherent in this concept are two basic types of thresholds namely, extrinsic thresholds and intrinsic thresholds. The difference between the two being that, the extrinsic threshold is exceeded by the application of a force or process external to the system, such as climatic fluctuations, land use changes, overgrazing etc. (Schumm, 1980), while, in the case of intrinsic thresholds, progressive changes within the system itself, for example changes in the soils, vegetation etc, cause the crossing of the threshold (Nordström, 1988).

The significance of the concept of intrinsic thresholds is that it recognizes that changes in external variables are not always required for a geomorphic threshold to be exceeded. Instead, abrupt erosional and depositional changes can be inherent in the normal development of a landscape. This concept challenges the well-established basis of geomorphology i.e. that landform change is the result of some climatic, land use or base-level change (Harvey *et al.*, 1985).

Once a geomorphic threshold has been exceeded by either intrinsic or extrinsic variables, or both, gully erosion is initiated. A common factor in all cases of gully erosion is that the basic cause is the same i.e. the genesis of gullies usually involves an interrelationship between the erosional resistance of the soil or sediment, and the volume, speed and type of runoff (Hudson, 1971; Bocco, 1991).

2.1.2. The nature of runoff responsible for gully initiation

Studies of runoff processes reveal that water flows downslope by means of either, Horton overland flow, groundwater flow, shallow subsurface flow and saturation overland flow, or a combination of the above. Dunne (1980) argues that each of these flow types may be responsible for channel incision.

Gullies, however, principally occur when the combined effect of rainfall energy and overland flow exceed the resistance of the materials subjected to that flow (Begin and Schumm, 1984; Hadley *et al.*, 1985; Harvey *et al.*, 1985). This is what Kingsbury (1952), called the conventional pattern of gully erosion. Surface runoff often initiates gullying by a sequence of: sheetwash → rill erosion → gullying. This sequence was first outlined by Horton (1945) and later elaborated on by Strahler (1958). It does not however, constitute the norm. Bergsma (1974), describes an erosion toposequence which is made up of a sequence of inter-rill → rill → gully erosion, and Selby (1982), describes how gullies develop from the enlargement of rills. Furthermore, Nordström (1988), states that sheet eroded surfaces may be found in direct association with gullies, without any sign of rill erosion. She also describes gully headcuts found in cultivated fields in Lesotho in the absence of both rills and sheetflow.

Although surface flow is the primary source of runoff initiating gully erosion it is not necessarily the only one. In many instances the influence of subsurface flow may dominate (Rubey, 1928; Buckham and Cockfield, 1950; Heede, 1971; Jones, 1971; Löffler, 1974). The importance of this form of runoff as a cause of gullying was highlighted during the 1970's with the partial rejection of the Horton model of overland flow (cf. Dunne, 1978), and the subsequent recognition of saturation overland flow, throughflow and piping.

The dominant way in which subsurface flow initiates gullying is by linear subsurface erosion, which eventually reaches the soil surface resulting in pipe collapse and an open gully.

There are thus two basic types of runoff responsible for gully initiation viz, overland flow and subsurface flow. They may act separately or in conjunction; the influence of each varying according to the factors discussed below.

2.2. FACTORS AFFECTING GULLY EROSION

2.2.1. Morphology of a drainage basin

The most important features of a drainage basin's morphology namely, its topography, elevation, size, shape and slope geometry are all largely determined by the past erosional history of the basin.

The macrotopography of a given basin is particularly important to gully erosion as it affects the formation and development of soils, and hence influences the nature of runoff responsible for gullying and the processes operative. For example, clayey soils are more susceptible to desiccation cracking and this makes them more vulnerable to gully erosion through the process of piping.

The elevation of a basin affects the type, amount and velocity of runoff received by a gully by influencing the orographic effect of the precipitation as well as the growth of vegetation (Nordström, 1988). Higher elevations are usually associated with increased orographic activity and a decrease or change in vegetation cover.

A drainage basin's size also influences the amount of runoff received by a gully. In large drainage basins there may be differences in the precipitation received over the area, and this often results in variations in the processes and rates of erosion experienced within and between gullies in a single basin. This appears to be particularly the case in areas which receive only sparse rainfall, or rainfall in the form of intense thunderstorms (Nordström, 1988). Furthermore, the size and shape of a basin exerts an influence on the area above a gully head. This area has been reported by Jepson (1939), Thompson (1964) and Stocking (1981), to be very important in determining rates of gullying. As a gully extends upslope towards the drainage divide the slope above the head steepens and consequently, the erosivity of runoff collecting at the gully head increases. However, as the gully continues to extend upslope the amount of runoff received by the gully head decreases so too does the availability of material in which gullies can form. Thus, the potential for erosion may initially increase as the head migrates upslope but thereafter it decreases and the rate of erosion slows down as the head reaches the divide.

Another factor that plays a vital role in gullying is slope geometry (Ireland *et al.*, 1939; Proffitt, 1983). The gradient, aspect, length and profile of a slope all affect gully erosion by influencing the evolution and morphology of a gully, as well as the processes operative. Gentle slopes are more conducive to gully evolution by subsurface flow and piping (Nordström, 1986; Allison, 1991) as they allow sufficient time for the infiltration of runoff and hence the initiation of subsurface flow. Besides slope gradient, research conducted by Le Roux and Roos (1982) highlighted the importance of slope length. Gullies occurring on short slopes have been found to be formed largely by the effects of concentrated overland flow (Allison, 1991). A steep slope occurring above a gully headcut naturally increases the erosivity of flow and consequently, long, deep gullies are often found occurring on steep slopes (Beaty, 1959). Slope aspect and profile i.e. concave or convex, both affect the processes operative in a gully. The aspect of a slope determines the impact that raindrops have on the soil surface as well as the effect of solar radiation (De Ploey, 1974). Slopes having concave profiles are prone to saturation as a result of the convergence of runoff and consequently landslides and slumping dominate (Proffitt, 1983).

It thus appears that the morphology of a drainage basin has both a direct link with causes of gully initiation and an indirect effect (due to, for example, its influence over vegetation distribution and type of rainfall), and that each factor exerts its own particular control on the overall process of denudation.

2.2.2. Geology and soils

The underlying geology of an area may affect gully erosion in two ways. In the first instance, bedrock surfaces may act as impermeable layers along which interflow will be concentrated. The juxtaposition between the permeable upper layer (soil) and the impermeable lower layer (bedrock) serves to enhance the processes of seepage and piping and appears to be particularly conducive to gully erosion (van den Brink and Jungerius, 1983). Secondly, the stratigraphy in most landscapes influences the processes operative (Roloff *et al.*, 1981), particularly where gullies have eroded down onto resistant bedrock. As a result of the bedrock's resistance to further linear incision or downcutting, the processes of sidewall or lateral erosion are often accentuated. The main reason for this being the increase in the velocity and erosivity of flow as a result of the decrease in roughness of the bedrock surface.

The relationship that exists between the underlying geology and the soils of a given region has long been recognized (Weaver, 1991), and is such that during the mid-to-late nineteenth century, soil classification schemes were based on geology (Steila, 1976).

The primary effect that geology exerts on gully erosion is that it influences soil formation and soil type, and hence determines the presence or absence of erodible material (Dardis *et al.*, 1988). Berjak *et al.* (1986), and Weaver (1991), commented on the extent to which geology influences erosion. In their respective investigations they found erosion to be less severe in soils underlain by dolerite than in those underlain by sedimentary rocks.

Weathering of the underlying geology largely, but indirectly, determines the two most important soil characteristics which affect the genesis and rate of gully erosion viz, infiltration capacity and erodibility.

The infiltration capacity of a soil refers to the 'maximum rate at which the soil in a given condition can absorb water' (Dunne and Leopold, 1978:163) and is determined by the soil's texture. Soils comprised largely of sand particles have higher infiltration capacities, due to their larger grain and pore sizes, than clayey soils. Consequently, soils with a high clay content tend to generate runoff quickly during rainstorms. Although this is the case, clayey soils are relatively resistant to surface erosion, while sandy soils which favour infiltration are easily eroded if the flow is sufficiently erosive. Factors influencing the rate of infiltration are listed in Table 2.1. One fact that must be noted, is that the infiltration rate of soils decreases rapidly during a storm, reaching a relatively constant level within an hour or two after the storm has commenced (Dunne and Leopold, 1978).

Table 2.1. Factors affecting a soils infiltration capacity as indicated by Nordström (1988).

1. Soil factors:	- depth of soil profile - soil structure - pore size - grain size - clay content - compaction - permeability - soil moisture - organic matter content
2. Vegetation factors:	- root penetration - interception - density - transpiration - type and composition
3. Climatic factors:	- rain intensity - frequency of rainfall events - duration of rainfall - type of precipitation - temperature
4. Water characteristics:	- sediment composition - salt content - temperature
5. Basin characteristics:	- slope

Not only is the sand-clay content influential in determining the infiltration capacity of a soil, but also its erodibility. What is meant by erodibility is the soil's susceptibility to erosion, this being a function of the soil's physical characteristics and its management (Hudson, 1971). A soil's erodibility can be expressed as a relationship between particle size and flow velocity (Hjulström, 1935). The major underlying factor governing its erodibility is, however, its clay ratio i.e. the relation between the total sand and silt content and the total clay content (Bouyoucos, 1935). The clay ratio is smallest in soils which are considered non-erosive, and greatest in soils which are erosive. The terms erosive and non-erosive are only relative because a soil as such, cannot be erosive, but is affected by an erosive event. However, given all factors as being equal, aside from the soil factor, it will be found that some soils are more readily eroded than others and hence are termed erosive.

When considering the erodibility of soils two factors that need careful consideration are rainfall amount and intensity. High rainfall events of low intensity are prone to eroding the soil's sand and silt fractions more readily than the clay fraction. The converse applies to high intensity rainfall events (Le Roux and Roos, 1986). What this indicates is that, during high rainfall events the cohesion of the clay particles is better able to withstand erosion than the sand and silt fractions. On the other hand, during high intensity storms, the higher kinetic energy expended by the falling raindrops and surface flow is more capable of breaking the clay's cohesive bonds than in moving the sand fraction. Consequently, the erodibility of the soil depends not only on the soil's texture but also the amount and intensity of the rainfall. Dry soil particles are, however, much more readily eroded than cohesive wet ones (Wilson, 1973).

The chemical properties and nutrient variability of soils are also important factors affecting gully erosion. The chemical nature of the soil is related to its clay content (Brown, 1962), which in turn determines the amount of dispersion and therefore the soils susceptibility to piping. The interaction between a soil's chemical nature, underlying geology, rainfall, and processes, is clearly evident in the lower rainfall areas of Zimbabwe. Here rainfall is insufficient to allow throughflow to flush out the sodium released from weathering (Firth and Whitlow, 1991). As a result, the accumulation of this chemical in the soil leads to the development of impermeable, clay-rich subsoils, which in turn influence runoff rates and hence processes (Firth and Whitlow, 1991). Nutrient variability of soils indirectly affect gully erosion by affecting soil fertility and hence vegetation growth (Nordström, 1988).

Local soil characteristics influence not only gully genesis and erosion rates, but also gully morphology (see for example, Singh and Agnihorti, 1987). To facilitate investigations into the influence of soils on gully morphology, Schumm (1960a), introduced the "M" parameter, or weighted mean percent silt + clay, and stressed its important effect on channel shape.

2.2.3. Baselevel

There are two main types of baselevels, namely, grand baselevels and local baselevels (King, 1951). When discussing baselevels in the context of gully erosion, we essentially deal only with local baselevels.

A local baselevel is caused by the local topographical or geological conditions, and thus, may be determined by, for example, the temporary storage of sediment in a valley, or a local outcrop of bedrock (Nordström, 1988). Changes in this baselevel are commonly regarded as being important causative factors in gully initiation (Jones, 1987; Beckedahl and Dardis, 1988; Dardis and Beckedahl, 1988a; 1988b). Not only are changes important as causative factors, but they may also lead to adjustments within a gully which was previously in equilibrium with the baselevel.

Local changes may be induced by either, endogenous or exogenous agents (Heede, 1982). Endogenous events are those that result from gully development processes, while exogenous events are those involving tectonic crustal movements, sea level changes, volcanic activity or man-induced changes e.g. building of check dams or clearing of vegetation (Heede, 1982). These events may lead to either the raising or lowering of the local baselevel. Raising the baselevel results in a decrease in gradient, and in order for a gully to return to equilibrium, deposition or aggradation is required. Conversely, a lowering of the baselevel results in an increase in gradient and consequently, adjustment is brought about by erosion or degradation (Ireland *et al.*, 1939). Whatever the effect that the local baselevel exacts, Leopold and Bull (1979), found the effect to extend only a limited distance upstream, and that the effect decreased with distance. Experiments conducted by Schumm and Parker (1973), and Schumm (1977), revealed that the lowering of the baselevel initiated incision first at the mouth of the channel, and that this effect progressed upstream rejuvenating tributaries and scouring previously deposited material. What these separate findings imply is that the initial effect of baselevel change is felt only immediately upstream. However, if the initial effect initiates adjustments, these adjustments will in turn initiate new effects until ultimately the gully attains a new state of equilibrium.

2.2.4. Climate

The influence that climatic factors exert on gully erosion can be examined in two different time frames. They are the long term, which determines the rate and kind of rock weathering, and consequently, the rate and type of soil formation, or the short term, and here the important factors are temperature and precipitation.

Temperature is important as it affects factors such as vegetation, runoff and processes e.g. freeze-thaw, desiccation cracking etc. Its effect on runoff is largely indirect. What temperature actually influences is the rate of evaporation, which in turn determines, to some extent, the amount of runoff.

Annual rainfall amount, seasonality, intensity and antecedent moisture content are all important climatic variables to be considered in gully erosion research.

Annual rainfall is important when considered in conjunction with distribution. An area receiving a large amount of precipitation which is evenly distributed over the year is likely to support dense, protective vegetation cover which intercepts the rainfall, reducing the impact of the falling raindrops and encouraging infiltration. On the other hand, the same amount of precipitation concentrated over only a few days is unlikely to encourage plant growth as it generates runoff quickly causing scouring. Annual precipitation does, however, not bear any close relationship with the rate of gully erosion (Ireland *et al.*, 1939). Instead, it is the character of the individual storm that plays a greater role in gully erosion (Bailey, 1935; Ireland *et al.*, 1939).

The four seasons are often marked by differences in the type of rainfall that predominate. Consequently, the rate and manner of gully enlargement may vary during the year, with the winter and spring months being essentially times of wall caving, while the summer and autumn months are characterised by channel cleanout or clearing. In regions that experience seasonal climates, soils are highly vulnerable to erosion at the beginning of the rainy season when the vegetation cover affords little protection. It is at such times that an intense rainstorm may initiate a gully which will be further enlarged during periods of less intense rains, rains that on their own would have been incapable of generating a gully. Marked seasonality of rainfall (i.e. distinct wet and dry periods) provides favourable conditions for piping erosion (see for example, Downes, 1946; Crouch, 1976; Bryan and Yair, 1982). Although, seasonality of rainfall is not a prerequisite for piping, the reduction in vegetation and the desiccation cracking of the soils that occur during the dry months provide the optimum conditions for the initiation of pipes (Nordström, 1988). Nordström (1986), found there to be a negative correlation between seasonality of precipitation and piping erosion. Thus, the greater the seasonality the fewer but larger the pipes, the converse being true for reduced seasonality.

Although annual precipitation and seasonality of rainfall are important variables to consider, the factors of rainfall intensity and antecedent moisture content appear to be more important.

It is generally believed that high intensity rainstorms which rapidly saturate the topsoil, creating runoff, cause the most damage. Research has, however, shown that the damage caused by rainfall intensity depends on factors such as the current landuse practice and whether or not a geomorphic threshold is transgressed during the storm. An intensity of 25mm/h has been suggested as the threshold value above which rainfall becomes erosive (Hudson, 1971). Research conducted by Rydgren (1986), reveals that lower intensities may, however, also be erosive, but that this depends on landuse. He found an intensity of 15mm/h was sufficient to create surface runoff on cultivated lands, while on grazing lands an intensity of between only 3-5mm/h was sufficient. All factors being equal though, low intensity rains do not posses the same energy that high intensity storms do. Hence, high intensity rains can break up soil aggregates more readily rendering the soil particles susceptible to erosion by runoff. High magnitude events may, however, only have a minor effect on the landscape if no geomorphic threshold is exceeded (Harvey *et al.*, 1985).

The amount of runoff produced during a storm is also dependent on the antecedent moisture content of the soil. Soils which are thoroughly soaked from previous rainfalls will generate a higher percentage of runoff as opposed to soils which have had no preliminary soaking (Ireland *et al.*, 1939).

2.2.5. Vegetation

The relationship between vegetation and gully erosion involves both positive and negative feedback loops, and is so complex that the factors responsible for initiating a positive feedback are often the same as those producing a negative feedback. In other words, vegetation covers can protect the soil by dissipating the kinetic energy of raindrop impact, thereby reducing both surface sealing (Allison, 1991), and runoff, and thus inhibiting gully genesis. However, vegetation covers may, by stimulating infiltration, encourage piping (cf. Beckedahl, 1977), mass movement and ultimately gullying (Bocco, 1991).

Vegetation is, however, generally considered to protect the soil and prevent gully erosion by reducing raindrop impact, runoff velocity, peak discharge and by increasing surface roughness. The effectiveness of vegetation in achieving the above mentioned depends upon: the height and density of the canopy, the density of the ground cover, and the root density (Proffitt, 1983).

An example of the influence that the canopy has on erosion is provided by broad-leaved trees. Raindrops tend to coalesce on the leaves of these trees forming large drops. When the drops are large enough to overcome surface detention and drop off, their energy (through-fall) is often greater than that of the rain (Nordström, 1988). Consequently, the force with which they strike the soil surface is greater and hence more erosive.

Close-growing, near ground cover thus provides the most effective canopy for reducing raindrop impact and surface runoff, and it can increase a slope's resistance to erosion by between one and two orders of magnitude (cf. Carson and Kirkby, 1972).

Although increased vegetation density may reduce the possibility of gully initiation, it can in some cases increase the rate at which an already formed gully erodes. This was found to be the case by Blandford (1981). He ascribed the increased erosion rate to the increase in infiltration occurring at the gully head which resulted in high soil moisture contents, and ultimately a higher percentage of slumping and failure.

A dense litter of ground cover has the following effects: it protects the soil by intercepting raindrops, it increases the surface roughness of the soil thereby reducing the velocity of runoff, and it reduces runoff by retaining water on the soil surface for longer periods, thus encouraging infiltration. Again, not all these effects have a protective influence against gully initiation, but in some cases, may actively encourage it. The same applies to the density of root systems. Roots and rhizomes may protect the soil against erosion by binding the soil and adding extra cohesion (Thorne, 1990), but root penetration increases the porosity of the soil and thus encourages infiltration (Nordström, 1988). Increased infiltration can, in the case of Blandford (1981), increase the soil moisture content resulting in slumping and failure, or it may encourage piping erosion.

Both Goede (1971) and Graf (1979) found the spatial distribution of vegetation in watersheds to exert a strong influence on channel erosion. In determining its influence, however, the vegetation of the catchment slopes and that of the floodplains must be viewed separately (Goede, 1971). This is because a reduction in catchment vegetation is likely to cause a trend towards aggradation in the channel due to the increased delivery of sediment yield to the channel, whereas, a reduction in floodplain vegetation tends to cause degradation by promoting channel and floodplain erosion through increased flow velocities (Goede, 1971). Gully entrenchment will, however, only occur once the tractive force (flow velocity) exceeds the threshold values of resistance (vegetation) (Graf, 1979). The threshold values of resistance may be reduced by a variety of climatic, edaphic, topographical and anthropogenic factors.

2.2.6. Anthropogenic factors

It often appears in the literature that soil erosion and man are inextricably linked (see for example: Stocking, 1972; Faniran and Areola, 1974; Twidale, 1976; Toy, 1982; Whitlow, 1989). Yet, of all the factors affecting erosion, man has been the least investigated (Stocking, 1972). The reason for this can perhaps be found in the writings of Ekblaw (1936:2):

> 'Man is most difficult of all things to relate scientifically to his environment because he possesses as wide a degree of adaptability as plants and animals, greater mobility as a genus than either plants or animals, and, in addition, has his peculiar power of volition, of choosing for himself his own course ...'

The role played by anthropogenic factors in initiating gully erosion is, however, known to consist primarily of disruptions of the natural processes and/or disturbances of the steady states that exist (Graf, 1977). Changes in either, or both, are brought about in different ways by different landuses, the most common of which are: cultivation, overgrazing, controlled or uncontrolled burning of vegetation, animal tracks, roads and ditches.

Soil erosion on cultivated lands depends on the length of cultivation, the type of crop being cultivated, and the method of tillage used.

The length of cultivation is important in terms of the times during which harvesting and planting occur. It is during these times, when the soil is bare of vegetation and thus unprotected that rainstorms can cause untold damage. An example of this is provided by Zimbabwe where peak soil losses from cultivated lands were recorded during December. This month marks the beginning of the rainfall season, but is also the time of year at which the crop cover is lowest (Elwell and Stocking, 1976).

Contour ploughing which is used to reduce erosion, particularly on slopes, can actually promote gullying if the furrows are not ploughed exactly along the slope contour, if they do not run exactly on a level or are not well maintained. These factors may result in the concentration of runoff and the initiation of gully erosion through surface erosion. Furthermore, the reduction of surficial runoff caused by this form of ploughing, has been found to increase the rate of gullying by encouraging interflow and piping erosion (cf. Nir and Klein, 1974). The method of tillage used may also result in the impoverishment of the soil, particularly where repeated tillage is practiced. Under normal conditions bare soil may, to some extent, protect itself against erosion by the development of protective bedload linings or erosional lag depositions (Nordström, 1988). Tillage, however, destroys these layers leaving the soil much more susceptible to erosion.

Grazing animals reduce the soil's resistance to erosion by: depleting the vegetation cover, disturbing the soil, weakening the soil structure by breaking down the surface soil aggregates through trampling, and by concentrating overland flow (Pickup, 1985). A distinction must, however, be drawn between grazing and overgrazing. This distinction is commonly based on the carrying capacity of the land i.e. the number of livestock an area is able to support without a decline in the productivity of the soil and vegetation resources (Sandford, 1983). The carrying capacity depends on factors such as: food supply, water availability, type of animal, and kind of livestock management (Denevan, 1967). The two former factors being dependent mainly on climate. The carrying capacity of the veld may vary from year to year, particularly in areas which experience variable rainfall, and unless stock numbers are adjusted accordingly, overgrazing may result.

Overgrazing reduces the infiltration capacity of the soil as well as surface roughness by depleting the vegetation cover, thereby leaving the soil exposed. On exposure to the sun and wind, the soil dries out and shrinks often resulting in deep desiccation cracks which can then encourage infiltration and hence piping erosion. Some secondary effects of overgrazing which are not well documented in the literature are: reduction in rainfall and reduced seeding and germination of the surviving plants. The way in which overgrazing can ultimately lead to the reduction in rainfall is as follows: reduction in vegetation caused by overgrazing results in increased albedo which leads to radiative cooling, increased subsidence and ultimately a reduction in rainfall (Sellers, 1977). Furthermore, a decrease in vegetation hinders the natural process of seeding and germination among the surviving plants, thus further reducing the vegetation cover (Walls, 1980).

Roads, drains, animal tracks, and veld burning have the effect of concentrating runoff (in the case of the first three) and increasing runoff due to reduced vegetation cover and surface roughness. Fire also serves to destroy the soil structure (Osuji, 1984).

Thus, human modification of the environment, whatever form it may take, is capable of either initiating gullying or enhancing gully erosion rates. It, however, is neither the sole instigator nor a prerequisite to gully initiation (Smith, 1982). Instead increasing emphasis is being placed on the interaction between anthropogenic and physical factors in the initiation and subsequent growth of gullies (Whitlow, 1989). This interaction involves numerous variables which influence and interact with one another forming a complex network. Nordström (1988), produced a hypothetical model which attempts to summarize and tie together the various factors that affect gully erosion (Fig. 2.1).

The flow chart highlights two important points previously observed by Stocking (1980a) i.e. that gully erosion is the end result of a complex set of interactive forces, and that these interactive forces are in turn the result of complex sets of interacting variables.

Consequently, when investigating the causes of gully initiation or the factors affecting gully erosion, both the above and what Schumm (1973, 1977), summarized as the essence of a geomorphic approach to understanding incised channel development, need to be borne in mind. He stated that:

- the land surface is complex and dynamic
- the land surface may respond dramatically during a short time to the exceeding of a geomorphic threshold
- the response of a complex landform to change is itself complex i.e. secondary responses will complicate the primary adjustment of a system to change

In summary it can be concluded that, despite almost a century of gully erosion research, it is not surprising that there still exists a need for a better understanding of the geomorphic causes of gully erosion. The need perhaps, is not so much for a better understanding of the causes, but more, an understanding of the interaction between the complex sets of forces and variables. What is known for certain though is that gullies are a reaction to a general imbalance in erosion forces (Stocking, 1980a), and that none of the above mentioned forces and variables would have any effect without the availability of erodible material (Bradford *et al.*, 1978; Imeson and Kwaad, 1980).

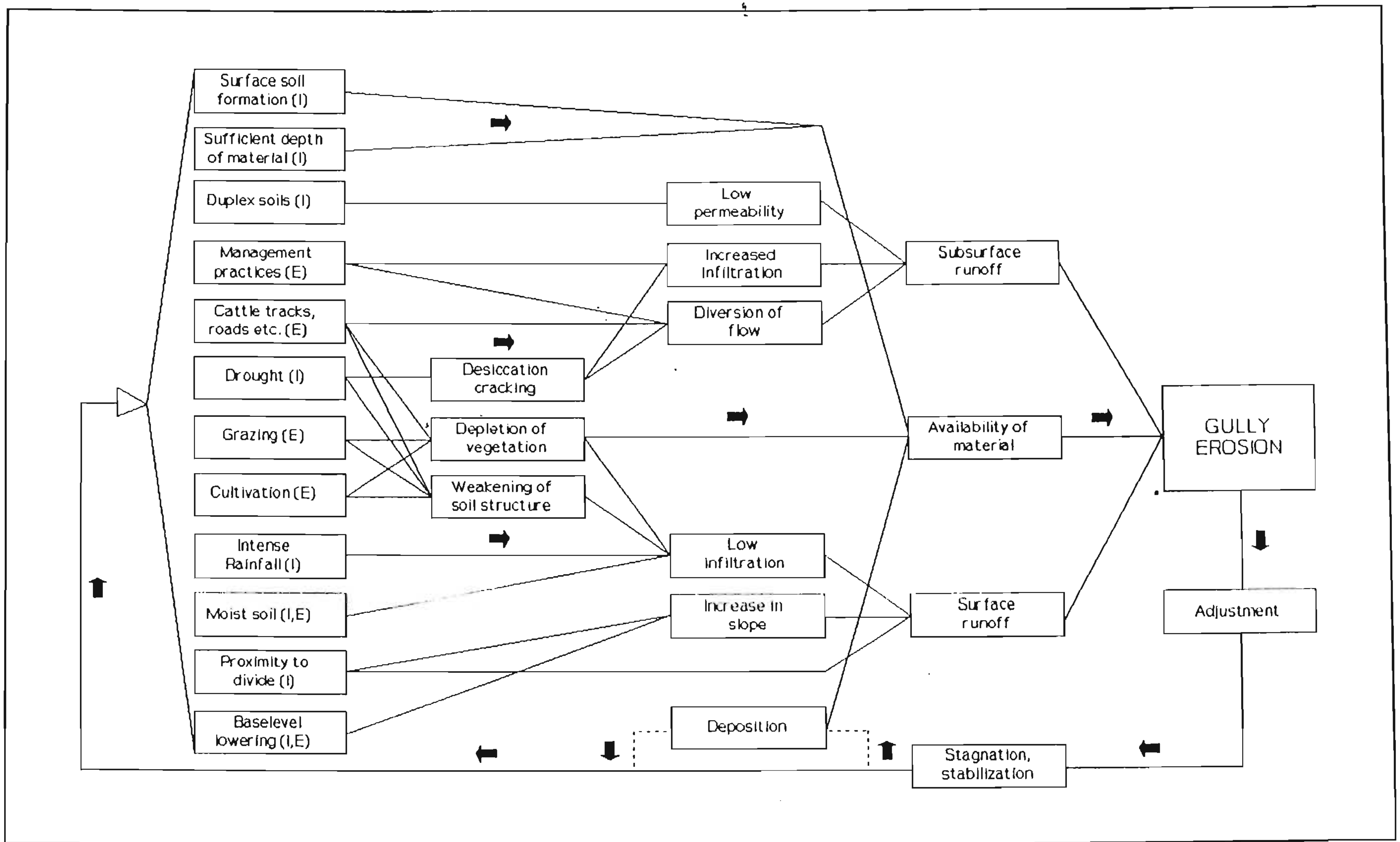

Fig. 2.1. Schematic figure showing the interaction between the factors initiating gullying and the intrinsic (I) and extrinsic (E) variables affecting these factors (from Nordström, 1988).

2.3. PROCESSES OPERATIVE IN GULLY GROWTH

Despite the sizeable body of literature pertaining to gully erosion that has been generated over the years, there is still no clear understanding of the processes involved in gully growth (Imeson and Kwaad, 1980; Bocco, 1991). The lack of understanding can perhaps be attributed to the fact that (as with causes), several processes can co-operate to achieve a single outcome. Furthermore, the relative importance of the processes operative often changes as the landform evolves (Mosley, 1972). The mechanisms of gully erosion have, however, been narrowed down to two main processes, namely: headcutting, which extends the channel into ungullied headwaters and increases the stream net and its density by developing tributaries, and downcutting, which leads to gully deepening and widening (Heede, 1976).

Processes responsible for headcutting and downcutting depend primarily on the source of the eroding water i.e. overland flow, within-gully flow, direct rainfall, and subsurface flow.

The two sources of flow particularly responsible for gully headcutting are overland flow and subsurface flow. A gully headcut which is fed by overland flow from an approach channel from the upland area recedes by any one, or a combination, of the following processes: slumping, caving, spalling, creep, abrasion, dripping, trickling, puddling, washing, or sloughing (see for example, Ireland *et al.*, 1939; Ologe, 1972; Nir and Klein, 1974; Heede, 1976; Bradford and Piest, 1980). Many of these processes operate in association with overfall erosion which encompasses, plunge pool erosion and erosion due to back trickling down the face of the headcut (Ireland *et al.*, 1939). Enlargement and upstream migration of the plunge head may be caused by lip scour, plunge pool cutting, caving, and slumping (Ireland *et al.*, 1939; Piest and Spomer, 1968; De Ploey, 1974; Bradford *et* *al.*, 1978). When undercutting of the headcut, caused by the action of the plunge pool, is deep enough, tension cracks may appear in the overhang. The end result being the slumping of the overhang into the channel.

Many headcuts also retreat through the action of subsurface water flow (Gibbs, 1945; Fletcher and Carroll, 1948; Leopold *et al.*, 1964; Stocking, 1976; 1978; Harvey, 1982; Graham, 1984). The processes involved here are piping (see for example, Berry, 1970; Chakela, 1974; Löffler, 1974; Stocking, 1980b; Crouch, 1983; 1987), and seepage water in the lower horizons. The latter process removes the soil in the wall resulting in undercutting and slumping (Leopold and Miller, 1956).

Overland flow, direct rainfall, within gully flow, and subsurface flow are all important eroding water sources in downcutting. Overland flow causes wetting and sometimes saturation of the soil, thereby providing a criterion necessary for the occurrence of processes such as freeze-thaw, wetting and drying, and slumping. What alternate freeze-thaw cycles serve to do, is to comminute surface material and lever it from the sidewalls, thereby making it readily available for removal. This process, which is more effective on sidewalls facing the sun, has been recorded as being responsible for gully widening by numerous researchers, among whom are: Ireland *et al.* (1939); Jepson (1939); Tuckfield (1964); Palmer (1965); Blong (1966; 1970); Daniels (1966); Piest and Spomer (1968); Piest *et al.* (1975); Gregory and Park (1976); Blong *et al.* (1982).

Sidewalls are more exposed to temperature changes, and therefore to wetting and drying, than the soils further in from the walls (Chakela, 1974). The repeated action of wetting and drying which causes alternate swelling and contraction of the soil, weakens the soil structure making it more susceptible to erosion by other processes. Furthermore, the drying and shrinking of the soil often results in either, soil crumbling or the formation of desiccation cracks. In addition to reducing the overall stability of the soil, the desiccation cracks collect and concentrate runoff water which increases the pore water pressure in the soil, as well as setting up the potential for piping erosion. Like freeze-thaw, this process tends to be more effective on walls facing the sun due to the more intense shrinkage effects (De Ploey, 1974). Wetting and drying has been noted as a process responsible for sidewall retreat by among others, Tuckfield (1964); Piest and Spomer (1968); Blong (1970); Chakela (1974); De Ploey (1974); Piest *et al.* (1975); Crouch (1990b).

Slumping of gully sidewalls due to reduced soil cohesion and increased instability caused by wetting during overland flow is another process observed to cause lateral gully growth (see for example, Schumm, 1961; Gregory and Park, 1976; Bradford and Piest, 1977; Little *et al.*, 1980).

Processes occurring as a result of direct rainfall include: sloughing (Piest and Spomer, 1968; Piest *et al.*, 1975), spalling, sheetwash, and creep (Ireland *et al.*, 1939; Ebisemiju, 1989), rainsplash and rilling (Blong *et al.*, 1982; Graham, 1984; Blong, 1985; Crouch, 1987) and fluting (Hudson, 1971; Charman, 1978; Veness, 1980; Graham, 1984).

Within-gully flow serves the dual purpose of deepening and widening a gully as it is responsible for both bed and bank scour by virtue of the tractive force it exerts (Piest and Spomer, 1968). Bank scouring undermines the sidewalls (Chakela, 1974; Blong *et al.*, 1982; Graham, 1984; Osuji, 1984) which in turn leads to the development of vertical tension cracks (Crouch, 1987), and ultimately the collapse of the overhanging material. Another cause of slumping, initiated by within-gully flow, is saturation of the soil at the base of the sidewall (Piest *et al.*, 1975). Minor rilling on the floor and floor washing (Beaty, 1959), are processes, other than bed scouring, responsible for gully deepening.

Gully walls give rise to hydraulic gradients, making them susceptible to subsurface erosion by piping. This process is encouraged by desiccation cracks which collect and concentrate runoff. Seepage from ground water is another process responsible for lateral gully growth. Both these subsurface erosion process may enhance the process of slumping along gully sidewalls.

A process operating in gully widening, but one which is not determined by the source of eroding water, is wind erosion. This process serves to loosen soil particles from sidewalls (Blong, 1970; Blong *et al.*, 1982), but is probably only of minor importance, being more a supplementary process.

In conclusion it can be seen that gullies are complex geomorphic systems, in which a multitude of forces, variables and processes interact to trigger a complex sequence of events resulting in their genesis and growth.

2.4. VARIOUS GULLY CLASSIFICATION SCHEMES

Numerous classifications of gullies, based on a wide range of criteria, have been proposed over the years, but as yet, there is still no "universally" accepted classification scheme. Some classification schemes are, however, more commonly used than others and these will be discussed.

Ireland *et al.* (1939) proposed the first classification of gullies. They based their scheme on gully outline and proposed six characteristic gully forms namely:

- Linear: Long and narrow with a narrow head and few important tributaries along its side.
- Bulbous: Broad and spatulate at the upper end, but may be linear in the downstream portion.

Dendritic:	Formed by many branching tributaries.
Trellis:	Tributaries or branches enter the main channel at angles approaching 90°
Parallel:	Composed of two or more parallel tributaries which empty into a main gully.
Compound:	Combinations of two or more of the above mentioned forms.

As with Ireland *et al.* (1939), Leopold and Miller (1956) also based their classification scheme on surface morphology but suggested that gullies be classified as being either continuous or discontinuous. Continuous gullies, which are regarded as being more stable and permanent features on the landscape, begin their development as rills in the headwater areas. These rills coalesce to form the main gully which maintains an almost constant depth down towards the mouth where it rapidly decreases. Discontinuous gullies, on the other hand, may have their origin anywhere on the slope, but usually consist of a series of headcuts advancing uphill along the same route. They decrease rapidly in depth in the downstream direction and have a bottom gradient which is much gentler than that of the valley floor. The distinction between discontinuous and continuous gullies was seen by Heede (1970), to give an indication of a gully's stage of development i.e. continuous gullies representing more advanced stages of development. A gully need not be classified as either, or, but may be a combination of both. In such cases the continuous gully forms the main channel with the discontinuous gullies being in various stages of fusion with the network (Heede, 1978).

Imeson and Kwaad (1980) realized the value of classifying gullies on the basis of morphology, but recognized the danger of using this as the sole criterion. The reason being that gullies are convergent forms i.e. that different processes operating under varying conditions may produce features that are morphologically similar (Imeson and Kwaad, 1980). An example of this is provided by the work of Lam (1977) and Yair *et al.* (1980). The gullies described by Lam are remarkably similar to those described by Yair *et al.*, the difference being that those studied by Lam occurred in Hong Kong which receives an annual rainfall of 2100mm per annum, while those studied by Yair *et al.*, occurred in the Negev desert which receives a scant 100mm of rainfall per annum. Consequently, Imeson and Kwaad (1980) proposed that gullies be classified according to their cross-sections, type of runoff received, and position in the landscape. They recognized four types of gullies viz:

Type 1: V-shaped; overland flow; anywhere in the landscape except valley bottoms.
Type 2: U-shaped; overland flow; anywhere in the landscape except valley bottoms.
Type 3: U-shaped; subsurface flow; anywhere in the landscape.
Type 4: U-shaped; overland and subsurface flow; exclusively in valley bottom positions.

They also recognized the fact that transitional types do occur and that various gully types may occur within a single gully system.

The criterion select by Brice (1966) for gully classification was the topographic location of the gullies in the landscape. In his investigations of gullies he recognized that the depth of a gully, its aerial position and its rate of growth, are more closely related to the topographic position of the gully head than to any other single factor. Thus, on the basis of location, he classified gullies as: valley-head; valley-side; and valley-floor. Valley-floor gullies may become valley-head gullies by the migration of their headscarps into the valley head. Valley-side gullies are independent of valley-head gullies and result from less concentrated flow from different sources.

De Ploey (1974), based his classification on the different soils in which gullies form and the effect this has on the process of formation. He recognized three types of gullying namely:

Axial gullying: occurs in gravelly deposits, is characterised by V- or U- shaped cross-sections and a single headcut which retreats upslope by plunge pool erosion

Digitate gullying: occurs in clay loams, is a complex gully form with several headcuts which extend in the direction of tributary swales

Frontal gullying with pedimentation: found on loamy sands with a columnar structure, starts from river banks and vertically stabilized gullies, retreats parallel to the slope and scarp and is associated with piping.

Although this is not a commonly adopted gully classification scheme, it is nonetheless, one of the few based on soil type and processes.

One of the more recent classification schemes is that proposed by Oliveira and Meis (in, Oliveira, 1989). They recognized three major types of gullies based on morphological variations and processes viz: seepage erosion type, concentrated overland flow type, and a combination of the two with concentrated overland flow upslope and seepage erosion downslope. In the case of the seepage erosion type, the channel is connected to the main drainage system and develops by headward expansion. Concentrated overland flow gullies are triggered by a complex combination of concentrated overland flow and mass movements, and extend by the process of concentrated overland flow. Finally, the combination type represents the oldest channels in which only the upper portions are still active. These gullies are in the final stage of evolution.

The classification scheme selected by a researcher to characterize the gullies that he/she is investigating will depend on many factors among which are the temporal and spatial dimensions of the study.

2.5. THE DIMENSIONS OF TIME AND SPACE IN STUDIES OF GULLY EROSION

The importance of the spatial and temporal scale adopted by a researcher studying gully erosion needs careful consideration because it influences the researcher's whole approach to the study. Schumm and Lichty (1965); Schumm (1985); and Higgitt (1991), pointed out that it influences:

- the researcher's definition of the erosion problem and his/her assessment of the erosion risk
- whether the landscape is to be considered as a whole or in terms of components
- whether the landscape is considered as either the result of past erosional events or modern erosive agents
- whether the landform is to be considered as either, a system in dynamic equilibrium, or as a stage of an erosion cycle
- the way in which the system is described i.e. changes in time and space can obscure or even reverse the relationship between cause and effect
- causality

It is also important because the status of gullying in the general context of geomorphic change becomes progressively less significant the longer the time period under consideration (Schumm, 1985) (Table 2.2).

Table 2.2. The status of gullying in relation to geomorphic changes in the landscape (modified after Schumm, 1985).

Relative importance of the event	TIME PERIOD				
	One day	One year	Ten years	Hundred years	Thousand years
Mega-event	GULLYING - - - - - local soil slip or flow	GULLYING	meander cutoff	volcanic eruption	terrace formation
Meso-event	rilling	local soil slip or flow	GULLYING	meander cutoff	volcanic eruption
Micro-event	sand grain movement	rilling	local soil slip or flow	GULLYING	meander cutoff
Non-event	-	sand grain movement	rilling	local soil slip or flow	GULLYING

Not only is time important in influencing the above mentioned, but the confusion and needless controversy which arises when it is neglected in the study of geomorphic processes, can also be avoided (Schumm and Lichty, 1965).

Schumm and Lichty (1965), recognized three different time scales in geomorphology, namely:

- steady or present time (day)
- graded or modern time (100-1000 years)
- cyclic or geologic time

Gully erosion is, however, best considered in terms of the time frame set out by Elwell and Stocking (1975) viz:

- short term (storm basis)
- medium term (1-20 years)
- long term (> 20 years)

A combination of the above three, actually provides the optimum time framework for studying gully erosion, as it offers a more balanced view of the erosion problem (Shakesby and Whitlow, 1991).

In terms of the spatial aspects of erosion research, Schumm and Lichty (1965), pointed out that the researcher must make a choice on two issues. On the one hand, it must be decided whether only the components of a landscape are to be considered, or whether the system is to be viewed as a whole. Furthermore, a choice must be made as to whether the relations between the landforms and modern erosion processes are to be considered, or if the origin and subsequent erosional history of the system will be considered.

The above discussion of the concepts and variables associated with gully erosion provides the scientific background to this study. The physical setting of the study area together with the actual methodology adopted for data collection and analysis are described below.

CHAPTER THREE

GULLY EROSION AT GOLDEN GATE HIGHLANDS NATIONAL PARK

3.1. GEOGRAPHICAL BACKGROUND

3.1.1. The physical setting

Golden Gate Highlands National Park (GGHNP), situated in the northeastern Orange Free State (between 28°27'S - 28°37'S and 28°33'E - 28°42'E), was proclaimed a National Park in 1963 primarily for its scenic beauty. Lying at the foothills of the Maluti Mountains in the Rooiberge mountain range, the Park comprises an area of about 11 000 hectares. It is located some 35-40 km inland from the Great Escarpment and occupies a transitional position between the Lesotho Plateau and the Highveld. The Park is bordered by Lesotho to the south and Qwa-Qwa to the southeast (Fig. 3.1).

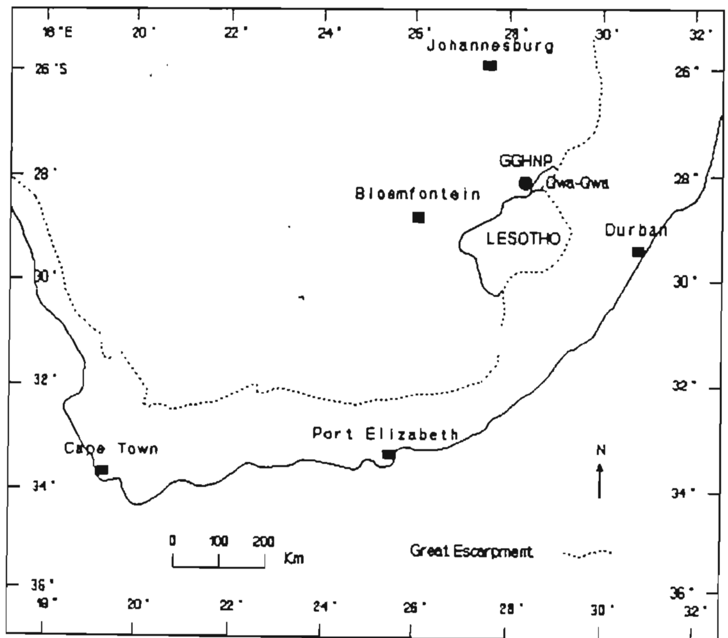

Fig. 3.1. The location of Golden Gate Highlands National Park within southern Africa.

Topographically the Park constitutes the upper catchment area of the Little Caledon River and ranges in altitude from 1892m in the Little Caledon valley to 2836m on Ribbokkop, the highest peak in the Park. The undulating landscape of the Park has been attributed to the headward erosion by streams rising on the Escarpment and to the incising of the Little Caledon River and its tributaries into the basalt, sandstone and mudstone members of the upper Karoo Sequence (see Table 3.1), (Moon and Munro-Perry, 1988; Marker, 1989). The slopes which have developed as a result of this downwearing and backwearing are characterized by steeper gradients on the south facing slopes than on those facing north. This has given rise to asymmetric east-west trending valleys (Marker, 1989).

In general the drainage system of the Park is dendritic with most of the streams and springs being non-perennial.

3.1.2. Geology, morphology and soils

The bedrock geology of the Park is characterized by rock formations representing the upper parts of the Karoo Sequence (Table 3.1), into which geologically recent dolerite dykes and sills have intruded (van Eeden, 1937; Visser and van Riet Lowe, 1956; Spies, 1969; Groenewald, 1986). The geology is essentially very simple (Marker, 1990), with mudstone, sandstone and siltstone constituting the underlying geology of the low lying reaches of the Park, Clarens Formation Sandstone, forming the conspicuous cliffs and plateau's for which the Park is so well known, and numerous superimposed outflows of basaltic lava constituting the underlying geology of the steep high lying slopes.

Table 3.1. Summary of stratigraphic units (modified after Groenewald, 1986).

Period	Sequence	Group	Formation	Lithology	Origin
Jurassic	Karoo		Drakensberg	Basalt	Volcanic
Triassic			Clarens•	Sandstone	Aeolian
			Elliot	Mudstone, Siltstone	Fluvial
			Molteno	Sandstone, Mudstone	Fluvial
		Beaufort		Mudstone, Sandstone	Fluvial

Moon and Munro-Perry (1988), found the sandstone slopes which descend from the plateau region to be characterized by two different types viz: cliff-talus slope combinations and rectilinear bedrock slopes. They also found that there exists a difference in the nature and distribution of debris on these two slope types. What they found was that the debris at the base of the larger cliffs is comprised of large sandstone boulders and smaller sandstone blocks set in a sandy-clay matrix. The thickness of this matrix is difficult to ascertain, but is believed to increase in depth downslope to where it exceeds three metres. The rectilinear bedrock slopes, on the other hand, are thinly veneered by a discontinuous debris mantle of sandy-clay colluvium, the depth of which also increases downslope. As a result of the shallow sandy texture of their soils, these rectilinear bedrock slopes are particularly susceptible to erosion (Roberts, 1969).

The most common soil form occurring on the sandstone slopes is Glenrosa, while Hutton and Clovelly soils are more commonly found on the sandstone plateaus (Groenewald and Groenewald, 1989). Soil deposits covering the basalt slopes have been found to be among the most fertile soils in Southern Africa (Staples and Hudson, 1938). Thus, despite the steep gradient of these slopes they are able to support a dense cover of temperate grassland which helps to stabilize them against erosion (Roberts, 1969). The dominant soil types found on these slopes include the Bonheim form on the south facing slopes, and Mayo and red Shortlands on the north facing slopes (Groenewald and Groenewald, 1989).

Other dominant soil forms occurring in the Park include Oakleaf and Inhoek which are common along the Little Caledon River and its tributaries (Groenewald and Groenewald, 1989).

3.1.3. Climate

The climate of the study area can be described as Cw (temperate climate with summer rainfall) according to Köppens' classification system (Schulze, 1947). It is characterised by summer rainfall, temperate summers and cold winters. The average maximum and minimum air temperatures, over a period of ten years extending from 1980 to 1990, ranged from 14.9°C to 25.5°C and -1.3°C to 13°C respectively (Fig. 3.2) (De Villiers, 1991, pers. comm.). Subzero minimum air temperatures may occur between May and September with grass temperatures as low as -19°C being recorded at Gladstone Weather Station in the Park (Groenewald, 1991, pers. comm.). Snowfalls and severe frosts are often recorded during the winter months.

The rainy season extends from September to April (Fig. 3.2). The average annual rainfall of 659.6mm falls in the form of low-intensity frontal drizzle or high-intensity thunderstorms. These thunderstorms occur either as squall line storms which approach from the south and are associated with orographically induced convergence over the Maluti/Drakensberg massif, or as convection thunderstorms which are brought in from the northwest by the plateau airflow which dominates during this period. It can be seen from Fig. 3.2 that there are no dry months in the Park. About 9% of the total annual precipitation occurs during the winter months of May to August. This winter precipitation takes the form of steady drizzle or snowfall and is induced by the inflow of cold unstable air from the south and southeast, associated with the movements of depressions around the coast (Nicol, 1976).

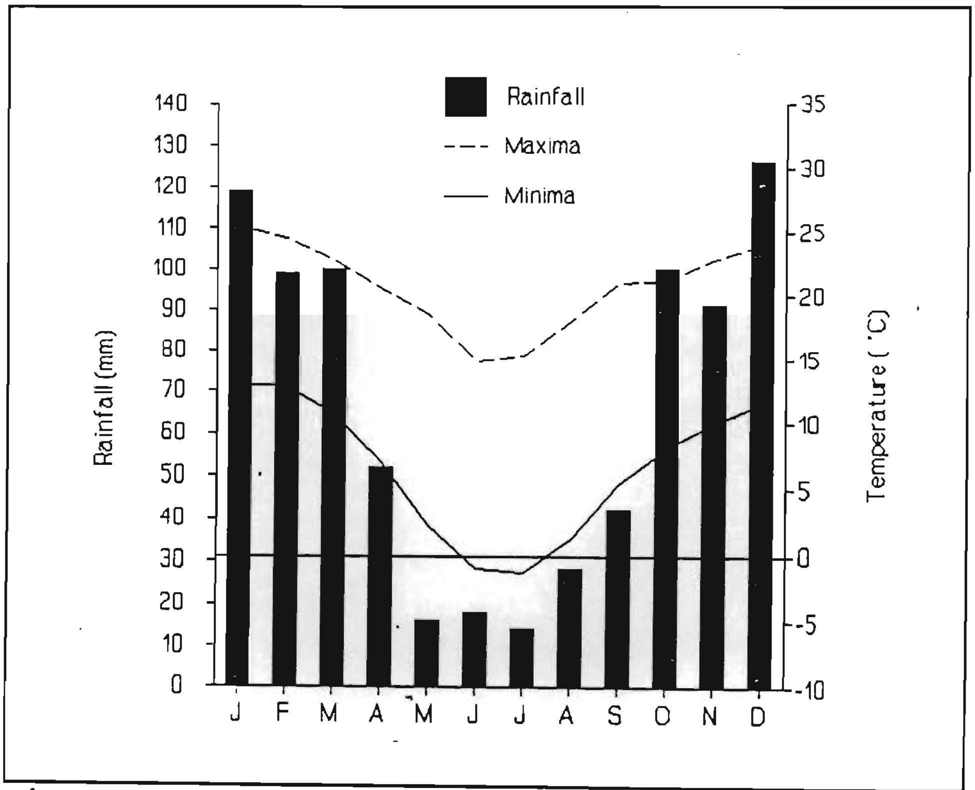

Fig. 3.2. Mean monthly rainfall and temperature data recorded at Gladstone weather station, Golden Gate Highlands National Park over the period 1980 to 1990.

Light winds are common throughout the year, except for a short spell in September when conditions can be described as gusty. These gusty conditions are related to the onset of the summer circulation pattern (Nicol, 1976). The winds in this area prevail from a northwest to westerly direction during the summer. Occasionally, however, this summer wind pattern is disrupted by high pressure cells ridging in off the east coast. These high pressure cells feed in moist easterly to northeasterly air which by virtue of adiabatic cooling result in a decrease in temperature. During winter the temperature is strongly affected by outbreaks of cold polar air which periodically move northwards from the Southern Cape coast (Preston-Whyte and Tyson, 1988). This cold polar air which is further cooled as it rises over the Lesotho plateau sweeps in from the southwest and generally lasts for two to four days (Nicol, 1976).

3.1.4. Vegetation

Virtually the entire Park is covered by grassland, the types of which are influenced by the underlying geology, soils, climate and microclimate. On account of the influence of these factors the grassland vegetation can be divided into two broad groups viz:

- Highland Sourveld (veld type no. 44a, Acocks, 1975), which occurs in the lower reaches of the Park and is currently undergoing a transition to *Cymbopogon-Themeda* grassland, and
- *Themeda-Festuca Alpine* grassland (veld type no. 58, Acocks, 1975), common at higher altitudes where the sandstone and basalt lava come into contact (Nicol, 1976).

A noticeable feature of the grass types in the Park is that they become more temperate as altitude increases. This is particularly evident at altitudes above 2500m where the short stemmed broad leaved grasses of the *Fescue* type grow, while other species are virtually absent (Nicol, 1976). The increase in temperate affinities of the grasses with increase in altitude is not unique to Golden Gate, but has been reported for other plant species by writers throughout South

Africa, for example: Acocks (1953); Edwards (1967); Killick (1963); and Roberts (1963 and 1966).

A clear example of how the underlying geology influences the growth of grass types through the nutrients and minerals of the parent materials of the soil, is exhibited by the dominance of *Themeda triandra* on or near dolerite intrusions (Carroll and Bascomb 1967; Mulder 1970). Furthermore, the geology also influences the growth of shrubs, trees and bushes in the Park. The shrubs, particularly *Lantana sp.*, *Buddleia salvifolia*, and *Rhus dendara* (Nicol, 1973), tend to favour the steeper south-facing slopes, growing predominantly in the dark, mountain clay colluvial soils which are the product of the weathered basalt above (Nicol, 1976). Isolated indigenous bushes and trees, the most common of which is the well known *Leucosidea sericea*, vernacularly known as "ouhout", occur mainly along the watercourses and in the deep valleys, protected gorges and crevices of the Clarens Formation Sandstone.

Exotic tree species found in the Park include *Eucalyptus globulus* (bluegum), *Acacia mearnsii* (black wattle) and *Salix babylonica* (willow), as well as fruit trees which are common in the vicinity of the old farm houses. A management strategy exists to try and rid the Park of the invasive *Eucalyptus globulus* and *Acacia mearnsii* trees. However, the *Salix babylonica* trees, particularly those growing along the Little Caledon River and at the camp sites are to remain for aesthetic appeal (Beukus, 1991, pers. comm.).

Besides the planting of these alien tree species, which took place prior to the area being declared a National Park, other changes have occurred in the Park's natural vegetation. These changes are particularly evident in areas where palatable grasses have been overgrazed and are being replaced by invaders such as *Harpechloa falx* and unpalatable shrubs eg *Chrysocoma tenuifolia*. A particular problem regarding overgrazing is created by the preference that black wildebeest and blesbok have for shorter grasses (Groenewald, 1988). It was noted by Groenewald (1988), that these animals shun the longer grasses in favour of shorter varieties, eventually denuding these areas of vegetation. The problem is further enhanced by these overgrazed areas serving as territoria which are demarcated and defended by single bulls and rams (Groenewald, 1988). Another problem regarding overgrazing, is that the *Cymbopogon-Themeda* grass type, which is particularly vulnerable to overgrazing (Acocks, 1975), grows in the lower reaches of the Park where the majority of the animals graze.

Acocks (1975), highlighted the impact that overgrazing has had on the veld types of South Africa. According to him, veld degradation of this sort is responsible for the reversal of the historical migration of tropical veld types from the north. As a consequence, the vegetation pattern over the entire country is undergoing a change. Instead of the usual southward migration of tropical veld, the westerly semi-arid Karoo veld type is rapidly encroaching on the east and north-east. The invasion of this bitter vegetation, which leaves in its wake "desert-like" soil conditions, is believed to be primarily the result of veld mismanagement (Christopher, 1982). An example is provided by Butzer (1971). He described how overgrazing and burning resulted in the change in vegetation from grassland to open shrub vegetation in the Orange and Vaal drainage basins. This change resulted in active gully-incision and soil stripping, which in turn, has had an affect on the drainage of the upper Orange and Vaal rivers. Veld decline of this nature is rapidly becoming an increasing threat in South Africa (Snyman and van Rensburg, 1987).

It is a combination of the above, together with other anthropogenic and natural factors that have resulted in the erosion problem experienced at GGHNP. The Park's management committee, who's strategy it is to be aware of the long and short term changes occurring within this area (Groenewald, 1988), have recognized that the erosion occurring viz: mass movement (Marker, 1990, Moon and Munro-Perry, 1988), gullying and sheetwash, is due, not only to natural processes, but is occurring at an accelerated rate. It is as a result of their awareness and realization that greater insight, based on quantitative analysis of the existing erosion problems is needed that the present study was undertaken.

3.2. STUDY SITES

In attempting to gain insight into the nature of gully erosion occurring at GGHNP, six gullies were selected for detailed investigation. These gullies, the locations of which are shown in Fig. 3.3, will be referred to throughout as, from east to west, Ribbok, Oorbietjie, Car, Glen Reenen, Camp, and Noord Brabant. After careful examination of the aerial photographs covering the Golden Gate Reserve together with field checking it was concluded that these gullies are representative of the range of gullying occurring in the Park. Criteria for selection of the gullies were that they:

- occur on slopes of different aspect
- occur on slopes of varying gradients
- vary in age
- have different gully dimensions
- developed on different farms at locations that were under a range of land uses i.e. crop production and animal husbandry, prior to the farms being acquired by the Park.

An additional factor influencing their selection was that they were readily accessible for field data collection.

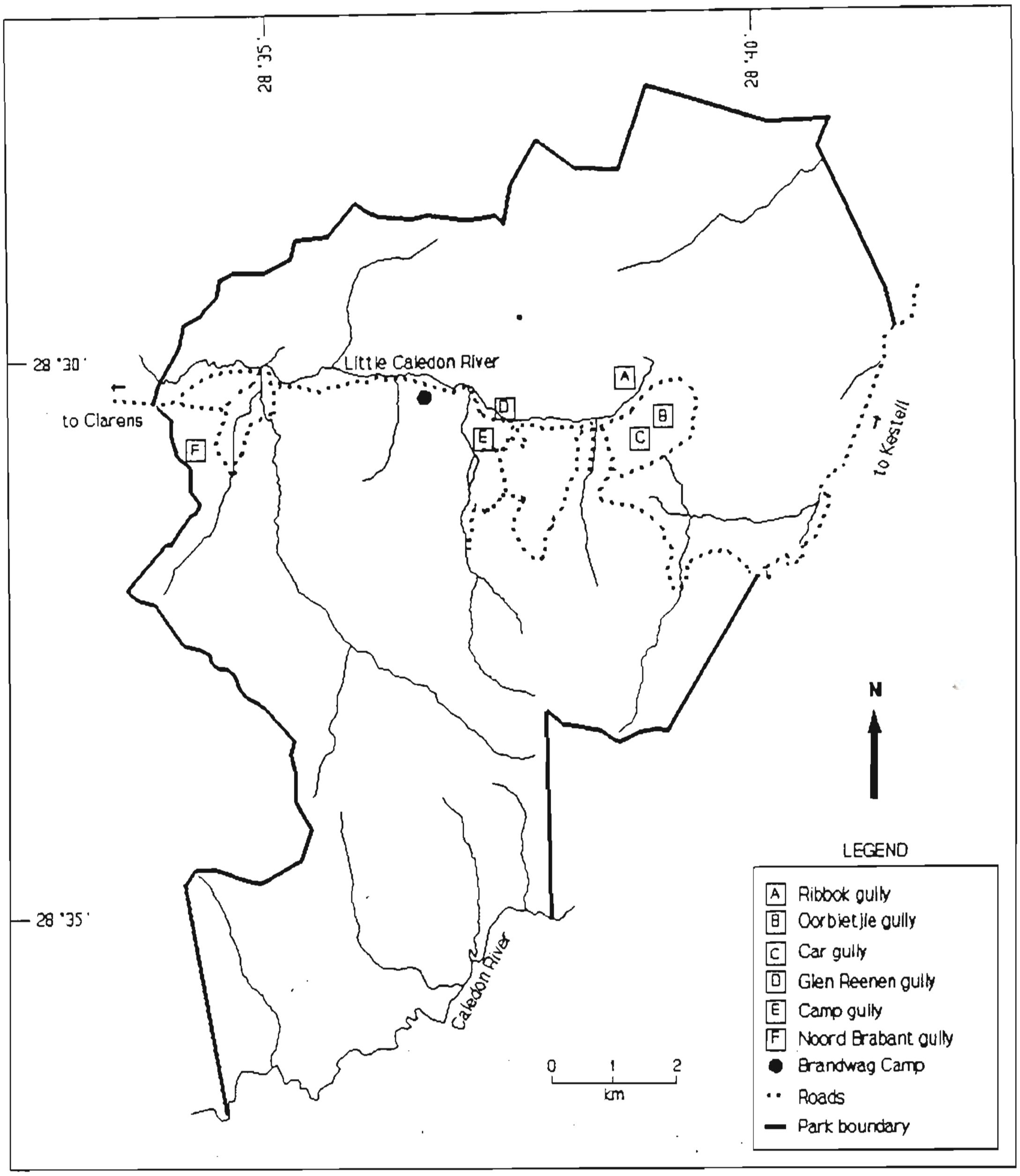

Fig. 3.3. **Sketch map of Golden Gate Highlands National Park showing the location of the study sites.**

3.3. METHODOLOGY

The methodology adopted is discussed in three sections. First the methodology and the inventory used for field data collection are reviewed. The methods used for data processing and statistical analyses are then discussed, followed by a discussion on the methods adopted for interpretation of the aerial photographs.

3.3.1. Field methodology and inventory

The typology, morphology and temporal changes of the gullies were determined from field surveys and measurements, and from aerial photographs.

Lueder (1959), suggested that when attempting to analyze gullies, the characteristics of gully shape (cross section, plan, long profile), gully dimensions (length, width, depth) and supplementary features (typology, trees, bedrock, animal tracks) be considered. Each of these gully characteristics have been investigated in this study.

When determining the typology of the gullies a scheme of strictly empirical field classification was used. In selecting the schemes which best classify the typology of the six gullies, the advice of Imeson and Kwaad (1980), was heeded i.e. that the diagnostic criteria used to classify gullies be such that they allow for quick and easy determination in the field. On the basis of this, it was decided to classify the gullies according to: position in the landscape (Brice, 1966); form (Ireland *et al.*, 1939 and Imeson and Kwaad, 1980), and stage of development (Leopold and Miller, 1956).

Ireland *et al's* (1939) classification of gully form was selected as it provides a simple means of describing their form as well as giving some indication of the physical and land use factors influencing the drainage of the gullies. This classification is, however, used in conjuction with Brice's (1966) and Imeson and Kwaad's (1980) classifications for, although form is easy to distinguish in the field, morphologically similar gullies do occur under a wide variety of conditions (cf. Imeson and Kwaad, 1980; Hanvey *et al.*, 1991). Thus, by classifying the gullies according to form as well as processes operative (or inferred), the possibility that the gullies be incorrectly identified is largely eradicated. Finally, the continuous-discontinuous scheme was selected as it provides an indication of the stage of gully development (Heede, 1967; 1974).

From the above it can be seen that both of the main perspectives regarding gully form viz: form as related to an evolutionary sequence from rejuvenation to maturity to stability (Heede, 1974; Schumm *et al.*, 1984), and form as related to the interaction of host materials and erosion processes (Imeson and Kwaad, 1980) are examined.

Detailed field surveys of the morphology of the six gullies were then carried out during which plan views, cross-sections and longitudinal profiles were recorded and plotted. Gully parameters were measured and indices derived from these plotted profiles.

The longitudinal profile of each gully was surveyed with an Abney level, while a theodolite was used for surveying the plan views and transverse profiles. The respective profiles were then digitized using the computer package MicroStation. These digitized plots serve as a basis for evaluating the relationship between the morphometric variables measured (Table 3.2). Furthermore, for each of the cross-sections surveyed in the individual gullies, a value was calculated for the cross-sectional parameters indicated in Table 3.3. These values were used to characterise the morphology of the individual gullies, as well as to evaluate the relationship between the dimensional parameters measured and the soil properties analyzed. It must be noted that the positions of the cross-sections in each gully were determined by pacing the length of the gully floor and dividing it into roughly equal sections. As a consequence the distances between the cross-sections along the gully shoulders are not necessarily constant for a given gully system.

Table 3.2. Gully morphometric variables measured.

Variables	Comment
Length (L)	total length of the gully
Mean bed width (Wb)	average width of the channel floor
Mean bank width (Ws)	average width of the bank, measured from the edge of the first bank to the corresponding elevation on the opposite side of the channel
Mean maximum depth (Dmax)	average depth measured from the lowest point on the channel floor to the height corresponding to the height of the first bank above the floor
Mean depth (Dm)	average cross-sectional area divided by average bank width
Mean width:depth ratio (W/Dm)	average width divided by average depth
Mean bank width:mean bed width (Ws/Wb)	average bank width divided by average bed width
Mean shape factor (Sf)	average maximum depth divided by average mean depth
Mean cross-sectional area (A)	mean area of material removed by downcutting and sidewall retreat

Table 3.3. Data recorded at each gully cross-section.

Variables	Comment
Bed slope	slope (degrees) calculated between each cross-section
Bed width	width of the channel floor
Bank width	measured from the edge of the first surface or bank above the channel floor
Maximum depth	measured from the lowest part of the channel floor to the depth corresponding to the height of the first bank above the floor
Mean depth	cross-sectional area divided by the bank width
Width:depth ratio	width divided by depth
Bank width:bed width ratio	bank width divided by bed width
Shape factor	maximum depth divided by mean depth where mean depth is the cross-sectional area divided by the bank width (Heede, 1970)
Bed silt + clay % (Sc)	samples of channel sediment taken across the cross-section and combined to give a composite sample. The percent silt + clay was taken as that part of each sample passing through the 0.074mm mesh sieve
Bank silt + clay % (Sb)	combined sample from bank and sieved
"M" (weighted mean % silt + clay)	expression of the sediment comprising the perimeter of each channel section where $M = \frac{Sc \times W + Sb \times 2D}{W + 2D}$ (after Schumm, 1960a)
Cross-sectional area	area of material removed by downcutting and sidewall retreat

The shape of each channel was determined by calculating both the width:depth ratio and shape factor of each cross-section. A cross-section with a shape factor of 1.5, usually has a parabolic shape and is regarded as the most efficient channel shape, while shape factors of 2.0 and 1.0 are indicative of triangular shaped and rectangular shaped channels respectively (Heede, 1970). The shape factor is not only an expression of channel morphology but also gives some indication of whether a gully is in equilibrium or not (Heede, 1970). The condition of equilibrium does, however, not represent a true balance between the opposing forces, but instead gives an indication of the capability of a system to adjust to changes in short timespans, and thus regain equilibrium (Heede, 1976). As was recognized by Heede (1970), one value may not necessarily be related to only one cross-sectional shape, but to a variety of unusual gully cross-sections. Consequently, when applying the shape factor the results were examined together with the profiles before conclusions were drawn.

Any discussion of cross-sectional shape which does not take into account the material into which the gully is incised, the processes operative and flow regime, is incomplete, for it is commonly agreed that the shape of a cross-section is influenced by these three factors (see for example, Leopold and Maddock, 1953; Lueder, 1959; Schumm, 1960a, 1960b, 1961; Tuckfield, 1964; Stocking, 1980a; Knighton, 1981; Nordström, 1986; Singh and Agnihotri, 1987; Ebisemiju, 1989; Rowntree, 1991). In investigating the influence of the *in situ* material on channel morphology, the weighted mean percent silt + clay or "M" was selected as the parameter representing sediment type. In order to determine "M", which is an expression of the soil texture comprising the perimeter of the gully (Schumm, 1960b), soil samples were collected from the channel floor and sidewalls at each cross-section. The positions of the sample points along each cross-section were determined by the various soil horizons along each sidewall, while three soil samples were collected from the floor of each cross-section. These were then subjected to mechanical analysis in the laboratory to determine the silt-clay percent of each sample. The silt-clay percent being taken as that part of the sample which passed through the 0.074mm sieve (following the standard set by Schumm, 1960a). "M" was then calculated according to Schumm's (1960a) equation (see Table 3.3). The reason for selecting "M" as the parameter representative of sediment type is that the erosivity of soil has been found to be related to the silt-clay content (Brown, 1962), such that the greater the silt-clay percentage the more resistant is the soil to erosion and thus the narrower will be the channel.

Linear regression analysis was then used to illustrate the extent to which "M" influences the shape of each channel cross-section, as well as the correlation between "M" and the width:depth ratio's of all the cross-sections investigated. In so doing it was taken into account that it is simplistic to relate only one aspect of gully morphology to one other variable, but as Schumm (1960b:17) said: 'this may be proper as long as both the writer and reader are aware that other factors may be important...'

The area removed by downcutting and sidewall retreat was calculated for each of the cross-sections using the method illustrated in Fig. 3.4. The total volume of sediment eroded by each gully was also calculated by multiplying the average depth of the gully by the gully area measured. It must, however, be borne in mind that these calculations present only rough estimates.

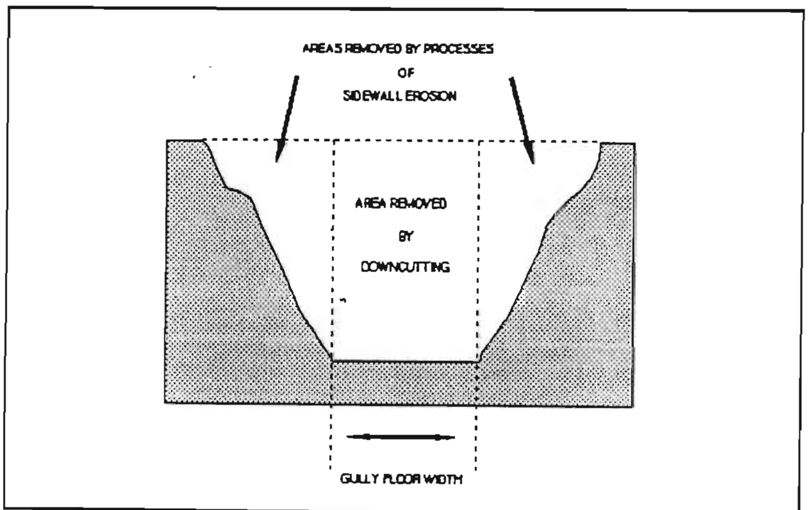

Fig. 3.4. Method used to determine the area removed by downcutting and sidewall retreat at each cross-section (after Veness, 1980).

In addition to the above, a detailed inventory of the head and sidewall characteristics was compiled for each gully.

The following were noted at each gully head:

- if the gully head had extended onto bedrock (i.e. reached its ultimate extension)
- if the head was found in association with an animal track or path
- headward extension by waterfall erosion
- headcutting with the presence of piping erosion

The following were recorded along the sidewalls:

- occurrence of piping
- if and where animal tracks entered/exited the gully
- if the gully had cut down onto bedrock
- the location of trees on the gully floor
- the category of sidewall erosional activity
- morphology of the sidewalls
- dominant sidewall processes

Sidewall morphology and erosional activity were categorized according to the classification scheme presented by Crouch and Blong (1989). Three categories of erosional activity were recognized with the degree of activity being determined by the percentage vegetation cover (Table 3.4). Percentages of ground cover were visually estimated using the chart presented by Folk (1951).

Table 3.4. Categories of sidewall erosional activity as defined by Crouch and Blong (1989).

Symbol	Classification	Criterion
A	active	< 20% ground cover
SA	semi-active	20-70% ground cover
S	stable	> 70% ground cover

Gully sidewall morphology was categorized according to the slope profiles shown in Fig. 3.5. Dominant sidewall processes were inferred from observations during erosion events, and from the morphology of the sidewalls, as the shapes of sidewalls are often important indicators of the processes that have formed them (Imeson and Kwaad, 1980; Stocking, 1980a). The occurrence of piping, which is often very difficult to discover in the field, was only noted if it could be clearly detected i.e. showing a visible inlet or outlet.

Furthermore, a record was made of where game tracks entered/ exited the gullies and whether expansion or extension of the gullies could be directly attributed to them, or if they were merely contributing factors.

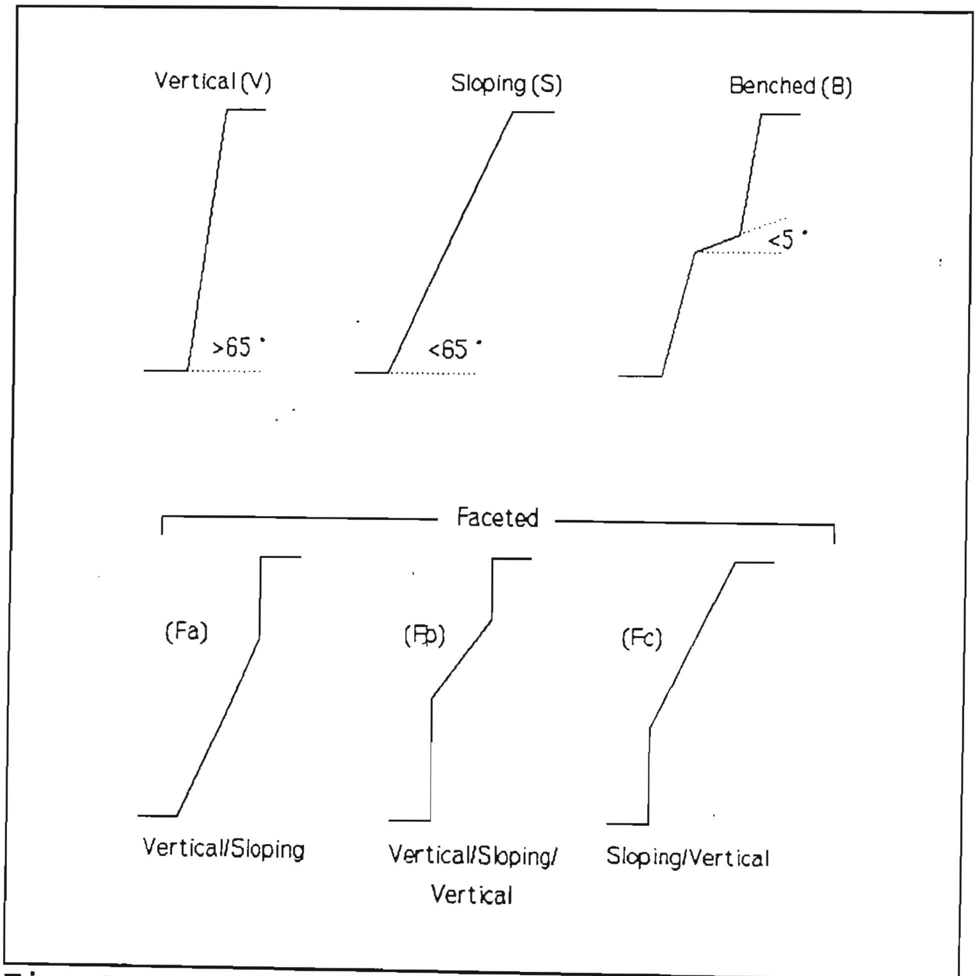

Fig. 3.5. Categories of gully sidewall morphology as defined by Crouch and Blong (1989).

3.3.2. Data processing and statistical analyses

To aid in interpreting the quantitative data obtained for each gully, linear regression analysis, principal component analysis and canonical variate analysis were undertaken.

Following the work of Heede (1970), linear regression analysis was undertaken to illustrate if certain gully dimensions within each gully followed any particular trends. The six gullies were not grouped together in order to retain the characteristics of the single channel. This analysis related the following parameters to distance along the thalweg: maximum depth, mean depth, bank width, width:depth ratio, and shape factor. Bank width was measured from the top of the highest bank to the corresponding height on the opposite bank and maximum depth was measured from this point to the lowest reach of the cross-section.

Principal component analysis was selected to interpret the relationships that exist between the morphometric parameters. Here the combined effect of all the parameters are examined. In all, nine parameters were measured and derived for quantifying gully morphology. The advantage of this analysis is that it reduces the data set by highlighting the most important principal components and in so doing it makes the interpretation of the relationships that exist between the parameters easier (Manly, 1986). Canonical variate analysis of the twelve variables listed in Table 3.3 was undertaken to get an indication of the similarities or differences that exist between the gullies. Unlike principal component analysis, canonical variate analysis takes into account the fact that the observations are grouped i.e. that the measurements of the 12 variables were obtained from six individual gullies. This analysis then serves to maximize the differences between the observations (Manly, 1986) and, on the basis of this, it separates the gullies.

3.3.3. Air photo interpretation

Good coverage of panchromatic aerial photographs exists for Golden Gate. The earliest of these were taken in August 1952 and the most recent in May 1984, although additional sequences were flown in 1962/63, 1969/70 and 1978.

Aerial photographs were selected in order to cover as long a period as possible to facilitate investigating the temporal changes which have occurred within the gullies (with the exception of Glen Reenen, which was only formed in 1988). Examination of the photo sequences revealed that insufficient gully growth had occurred between the successive sequences to merit the use of all the available sequences in measuring gully development. Instead, only the 1952 and 1984 images were used as these provided an optimal time period for sufficient growth to have occurred (cf. Bocco, 1991 and Nir and Klein, 1974).

Diapositives of the 1952 and 1984 photographs were obtained at a scale of 1:30 000, and by means of photogrammetry, using a Wild Heerbrugg A8-522 stereoplotter, maps at a scale of 1:10 000 were drawn delineating the gully boundaries. The accuracy of the photogrammetric measurements is difficult to determine precisely due to the many sources of error (American Society of Photogrammetry, 1980), for example, the subjectivity of the researcher in delineating the gully boundaries (Nordström, 1988). Notwithstanding these difficulties, the estimated accuracy of these maps is some 5m in the horizontal (Eekhout, 1992, pers. comm.). The control used to determine the limit of error was obtained by identifying a number of points on the 1:50 000 topographical map that could be fixed on both sets of aerial photographs, thus providing an approximate scale. Using this scale a model was constructed whereby the common points were transferred from the 1952 aerial photographs onto the 1984 photographs. Based on the repeatability of the observations the limit of error was found to be 5m in the horizontal.

These maps serve to show the increase in gully area (expansion) and length (extension) during the period 1952 to 1984. Furthermore, they form the basis for calculating the expansion (m^2) and extension (m^2) rates of the gullies over this period. In order to get an indication of which of the two gully development parameters i.e. extension or expansion, dominated during the above mentioned period an extension: expansion ratio was calculated for each gully.

The method of using aerial photographs to show the temporal changes of gully morphometry has previously been employed by a range of researchers, including: Beer and Johnson (1963); Thompson (1964); Brice (1966); Seginer (1966); Nir and Klein (1974); Blong (1985); Strömquist *et al.* (1985); Nordström (1986) and Thomas and Welch (1988).

In addition to aerial photographic interpretation further historical evidence was obtained by conducting interviews with the farmers who had previously owned the land. These two means of historical data collection are important methods of trying to recreate the past in order to predict the future (Crouch, 1991, pers. comm.), because although geomorphology is primarily concerned with present-day landscapes, it attains its maximum usefulness by historical extension (Thornbury, 1969).

CHAPTER FOUR

FIELD SURVEY AND INVENTORY DATA

In presenting the results of the field survey and inventory, each gully is dealt with individually so that its particular typological and morphological characteristics may be highlighted.

4.1. Ribbok gully

Ribbok gully is a 355 metre long, second order gully which typologically can be classified as shown in Table 4.1:

Table 4.1. Typological classification of Ribbok gully.

Form	Location	Type	Surface morphology
Bulbous	Valley-side	Type 2	Continuous

In form, this valley-side gully is broad and spatulate at the headwall tending towards linear downslope (Fig. 4.1). It can be deduced from Fig. 4.1 that essentially the cross-sectional shape of Ribbok gully is U-shaped although a few cross-sections tend to be V-shaped. Furthermore, this Figure shows that the longitudinal profile, which is essentially concave in the downslope direction, is broken by a "channel scarp" in the lower reaches. A channel scarp being defined as: 'a scarp that forms a break in the long profile of a well-defined channel' (Brice, 1966:291).

Results of the morphometric parameters recorded at each of Ribbok gully's cross-sections (Table 4.2), show that from a depth of about 2m at cross-section seven, the gully is cut progressively deeper in an upslope direction. This progressive increase in depth is not accompanied by a

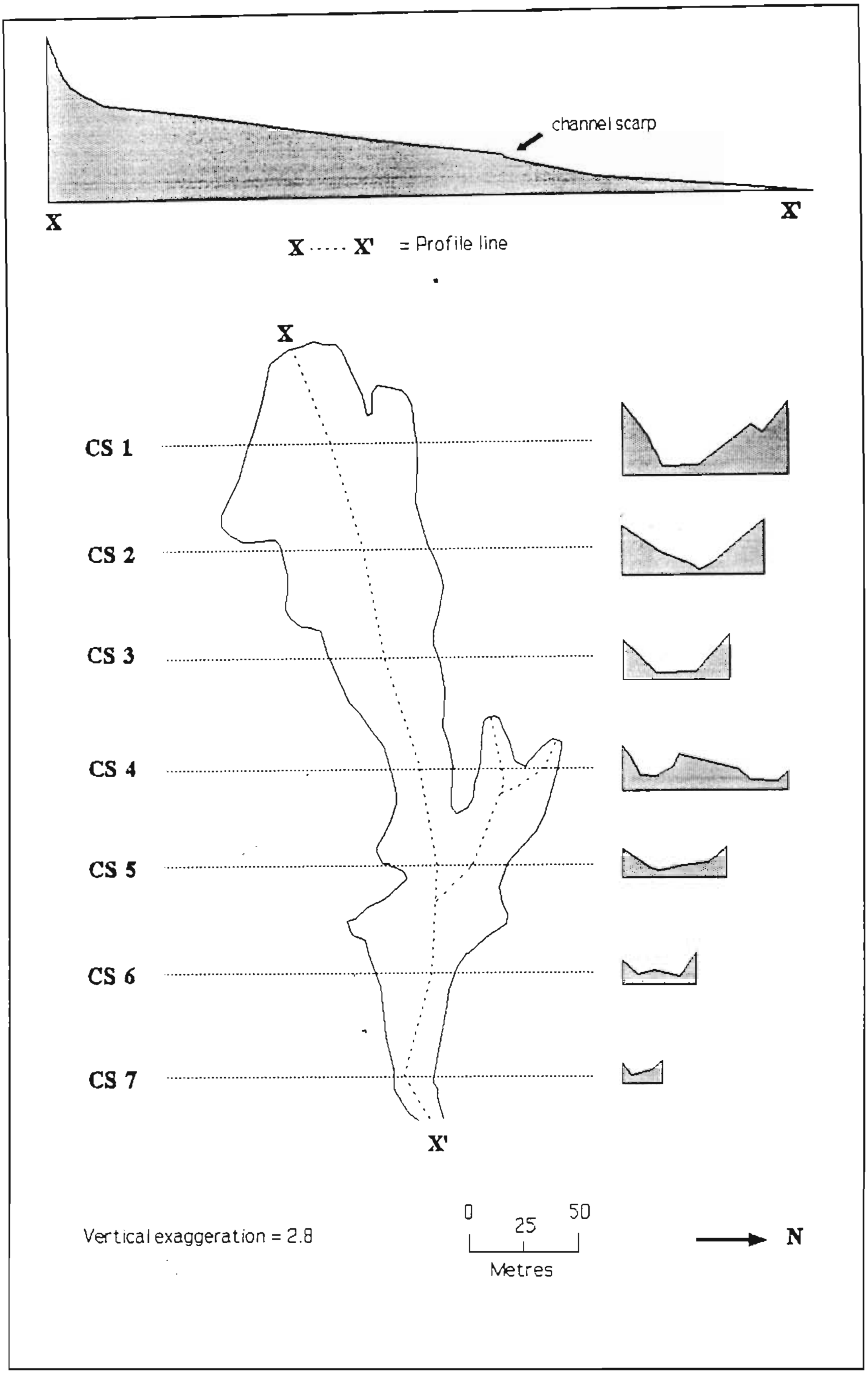

Fig. 4.1. Plan view, cross-sections and longitudinal profile of Ribbok gully.

progressive increase in width. The relatively high width:depth ratio's which range from 6.1 to 13.5 with a mean of 9.4 indicate that changes in the width of the gully were not always accompanied by similar changes in depth. Furthermore, following the work of Schumm (1960a), the changes in the width:depth ratio suggest that Ribbok gully is an unstable channel. The bed width values are high (7.5m to 23.8m), with a mean value of 13.5m. These high values together with the low values for bank width:bed width ratio (2.1 to 6.8, mean 3.8), and a mean shape factor value of 1.7 are evidence that essentially the shape of the cross-sections is U-shape.

Table 4.2. Morphometric parameters recorded at each of Ribbok gully's cross-sections.

Cross-section	Bed width (m)	Bank width (m)	Maximum depth (m)	Mean depth	Width:depth ratio	Bank width: bed width ratio	Shape factor
1	17.8	78.8	10.4	6.5	7.6	4.4	1.6
2	10.0	67.5	8.0	4.0	8.4	6.8	2.0
3	18.8	51.3	6.1	3.6	8.4	2.7	1.7
4	7.5	27.3	4.5	2.8	6.1	3.6	1.6
5	23.8	53.8	4.0	2.2	13.5	2.3	1.8
6	7.5	36.3	3.1	1.7	11.7	4.8	1.8
7	8.8	18.8	1.8	1.2	10.4	2.1	1.5
MEANS	13.5	47.7	5.4	3.1	9.4	3.8	1.7

In relating maximum depth, mean depth, bank width, width: depth ratio and shape factor to distance along the thalweg using linear regression analysis, it was revealed that the first three cross-sectional variables are strongly correlated with distance along the thalweg while the remaining two are poorly correlated (Table 4.3). These r^2 values are not surprising since the maximum depth, mean depth and bank width values show a general decrease in the downslope direction while the width:depth ratio and shape factor values show no particular trend (Table 4.2). The r^2 values presented in Table 4.3 provide some indication that the cross-sectional and longitudinal variables of Ribbok gully are not orthogonal dimensions but that some interdependence exists between them.

Table 4.3. Results of the linear regression analysis, Ribbok gully.

Parameters	r^2
Maximum depth	0.95
Mean depth	0.89
Bank width	0.73
Width:depth ratio	0.36
Shape factor	0.07

Results of the textural analysis of the soil samples collected at each cross-section together with the morphometric parameters used to calculate "M" are presented in Table 4.4 and shown in Fig. 4.2. Inspection of Fig. 4.2 shows that an increase or decrease of the width:depth ratio is accompanied by an increase or decrease in the silt-clay percentage respectively. This finding is contrary to that of Schumm (1960a; 1960b) who found an increase in the width:depth ratio to be accompanied by a decrease in the silt-clay percentage and vice versa.

Table 4.4. Gully morphometric and sediment data, Ribbok gully.

Cross-section	Bank width (m)	Maximum depth (m)	Width: depth ratio	% silt-clay in bank	% silt-clay in bed	"M"
1	78.8	10.4	7.6	18.5	bedrock	-
2	67.5	8.0	8.4	17.8	18.0	17.9
3	51.3	6.1	8.4	16.0	18.0	17.6
4	27.3	4.5	6.1	16.0	16.0	16.0
5	53.8	4.0	13.5	16.0	16.0	16.0
6	36.3	3.1	11.7	16.0	20.0	19.4
7	18.8	1.8	10.4	15.9	20.0	19.3

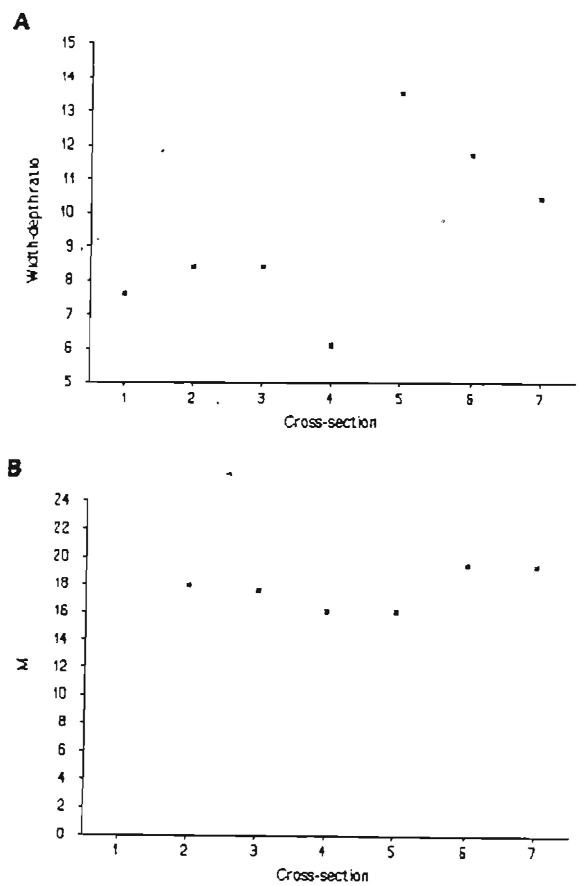

Fig. 4.2. Graphs showing A: variations in the width:depth ratio and B: M or weighted mean percent silt-clay along Ribbok gully.

Linear regression analysis shows that there is no correlation between the width:depth ratio and "M" (r^2 = 0.04, where r^2 is the coefficient of determination or the percentage of variance explained by fitting a straight line to the data). This result is in agreement with the earlier finding that a weak correlation exits between the width:depth ratio and distance along the thalweg (r^2 = 0.36). Consequently, it can be stated that the influence of "M" on channel shape is negligible for Ribbok gully and that other factors, for example, vegetation (Fig. 4.3), must be seen to play a more important part in determining channel shape.

Several studies (see for example, Zimmerman *et al.*, 1967; Heede, 1976; Thorne, 1990) have highlighted the effect that bank vegetation has on bank stability and width adjustment. The role played by vegetation in binding the soil, thereby increasing bank stability, is seen in Fig. 4.3, where the roots of this tree prevented the collapse of the sidewall until recently. These collapsed blocks will remain intact until they are disintegrated by either rainsplash or by the velocity of the gully flow which will entrain the sediment. Where the water flow in the channel is not sufficient to transport the fallen debris the channel takes on a trapezoidal shape.

Fig. 4.3. The influence exerted by bank vegetation on sidewall stability and morphology.

Sidewall erosional activity and sidewall morphology are presented in Fig. 4.4 and Fig. 4.5 respectively. As was found by Blong (1985) in his investigations of gully sidewall development in New South Wales, Australia, the geomorphically active sidewalls (as defined by Crouch and Blong, 1989, refer to Table 3.4:51) of Ribbok gully are generally found towards the gully headwall, and the stable sidewalls near the mouth of the gully (Fig. 4.4). Figure 4.5 indicates, among other things, that this gully has a large amount of trees or bushes growing along the sidewalls and on the floor. Furthermore, it indicates where animal tracks enter/exit the gully. These tracks are seen to be important in that they tend to compact the soil rendering it impermeable and unable to support vegetation growth. Consequently, they make ideal channels for concentrating water during runoff events thereby influencing the shape of the sidewalls and the rate of sidewall extension. An interesting feature to note is that these points of entry/exit generally correspond with

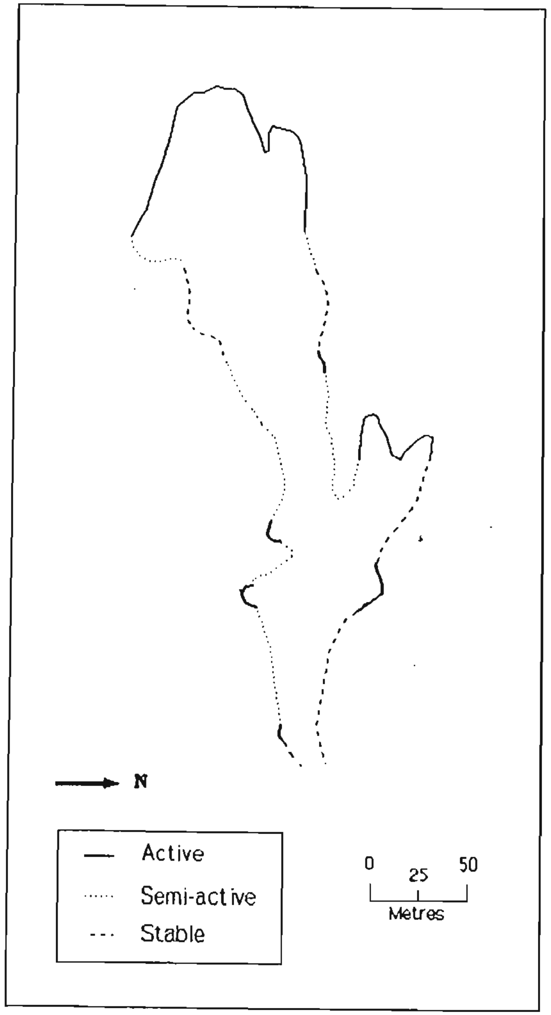

Fig. 4.4. Sidewall erosional activity in Ribbok gully.

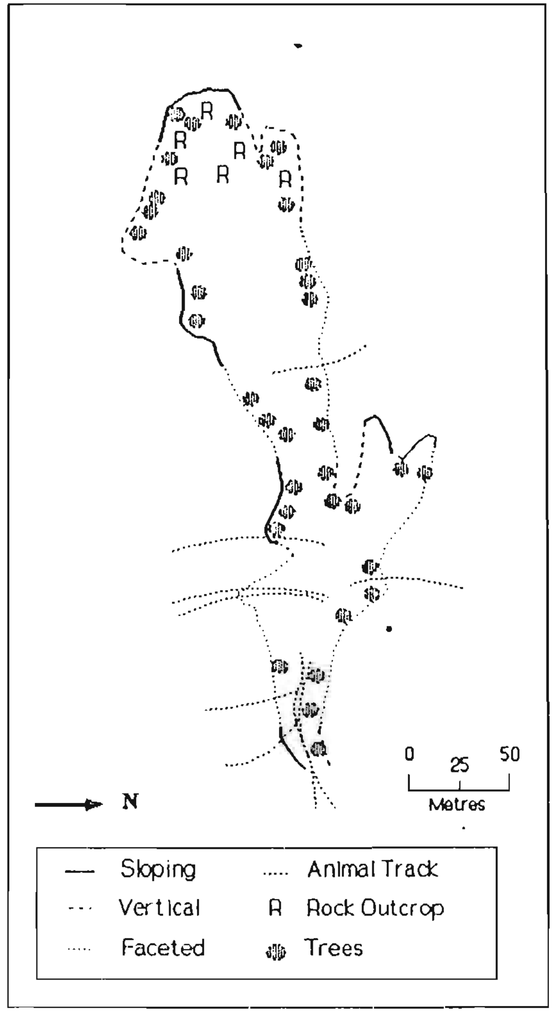

Fig. 4.5. Sidewall morphology and special features in Ribbok gully.

geomorphically active areas (Fig. 4.4) as well as with areas that have experienced considerable lateral extension (see Fig. 4.8). Several studies (for example, Bishop, 1962; Twidale, 1964; Blong, 1970; Graham, 1984; Whitlow, 1988; Shakesby and Whitlow, 1991) have shown animal tracks to have similar effects on the sidewalls of gullies.

Dominant sidewall processes occurring in Ribbok gully are spalling i.e. the separation and falling of relatively thin sheets from gully walls (Ireland *et al.*, 1939) and slumping. Slumping of the sidewalls was found to dominate in the upper section of the gully while downgully spalling appeared to be more important. These sidewall processes are seen to be very important in contributing to the total amount of sediment being derived from this gully.

The significant role played by sidewall erosion in the growth of gullies was first recognized by Piest *et al.* (1975) and later by Blong *et al.* (1982). In their investigations of four gullies in Razorback, New South Wales, Australia, Blong *et al.* (1982) found sidewall erosion to be responsible for more than half the sediment derived from these gullies. A similar finding was made in the present study of Ribbok gully where, on average, the sidewalls contribute about 57% of the total sediment produced. The largest proportion of this is derived from the upper section of the gully where sidewall erosion dominates (Table 4.5 and Fig. 4.6). The ratio of sidewall erosion to downcutting, which was calculated (as set out in section 3.3) for each cross-section, varies between 0.6m^3 and 2.5m^3 with a mean value of 1.2m^3. This dominance of sidewall erosion over downcutting is also evidenced by the high width:depth ratio's calculated for Ribbok gully i.e. mean value of 9.4.

Table 4.5. The ratio of sidewall cutting to downcutting, Ribbok gully.

Cross-section	Sidewall cutting (m^3)	Downcutting (m^3)	Sidewall cutting: downcutting ratio
1	299	212	1.4
2	192	76	2.5
3	91	94	0.9
4	43	33	1.3
5	45	76	0.6
6	29	34	0.9
7	9	13	0.7
MEANS	101.1	76.9	1.2

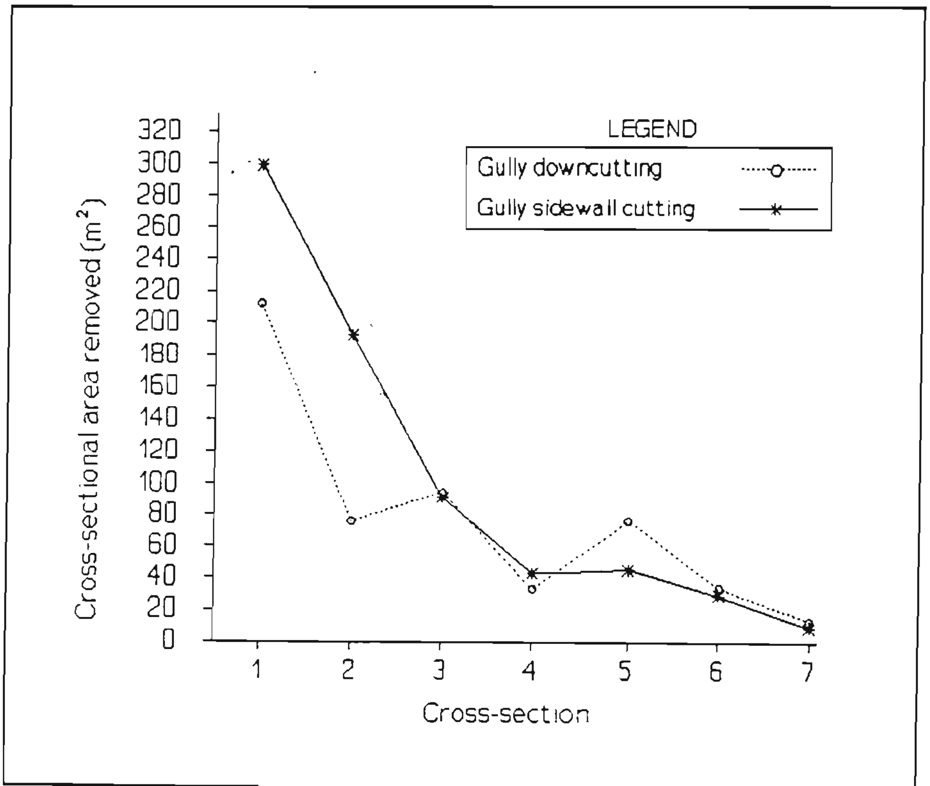

Fig. 4.6. Gully sidewall cutting compared with gully downcutting at each cross-section, Ribbok gully.

It is interesting to note that the lowest sidewall erosion versus downcutting ratio recorded for Ribbok gully occurs at cross-section five, and that it is in vicinity of this cross-section that the channel scarp is located. This scarp, which corresponds with what De Ploey (1989) describes as an "hydraulic jump", is seen to be the result of the increase in flow velocity at the junction of the main and tributary channels. The action of the plunge pool at the base of the scarp (Fig. 4.7) appears to have the same effect on this section of Ribbok gully as was observed by Leopold and Miller (1956) in their investigation of ephemeral streams i.e. it is deepening the channel faster than it can be widened. Similar changes in the geometry of river channels at tributary junctions were noted by Richards (1980), and he too attributed the changes induced in channel variables at tributary junctions to the increase in discharge and introduced load.

The low sidewall erosion versus downcutting ratio together with the presence of the scarp clearly suggest the dominance of linear incision in this section of Ribbok gully. Furthermore, they indicate that this section is still actively eroding. Headward advance of the knickpoint will lead to the deepening of the gully in an upslope direction.

Fig. 4.7. Channel scarp with a plunge pool at its base.

Sheetflow was observed to be the dominant process occurring at the headwall. This process is seen to have played a major role in the expansion and extension of Ribbok gully. Figure 4.8 shows the headwall of the main channel to have experienced a large increase in area during the 1984 to 1991 period. The shape of the headwall as it occurred in 1952 and 1984 was notched and according to Ireland *et al.* (1939), this shaped headwall often indicates that the gully rim has incised into resistant B-horizon material, while the channel has cut into weaker material. Bearing this in mind, it is argued that the rapid extension that the headwall experienced during the 1984-1991 period, was caused when the depth of the soil decreased as the headwall migrated upslope under normal processes, and thereby exposed the underlying bedrock.

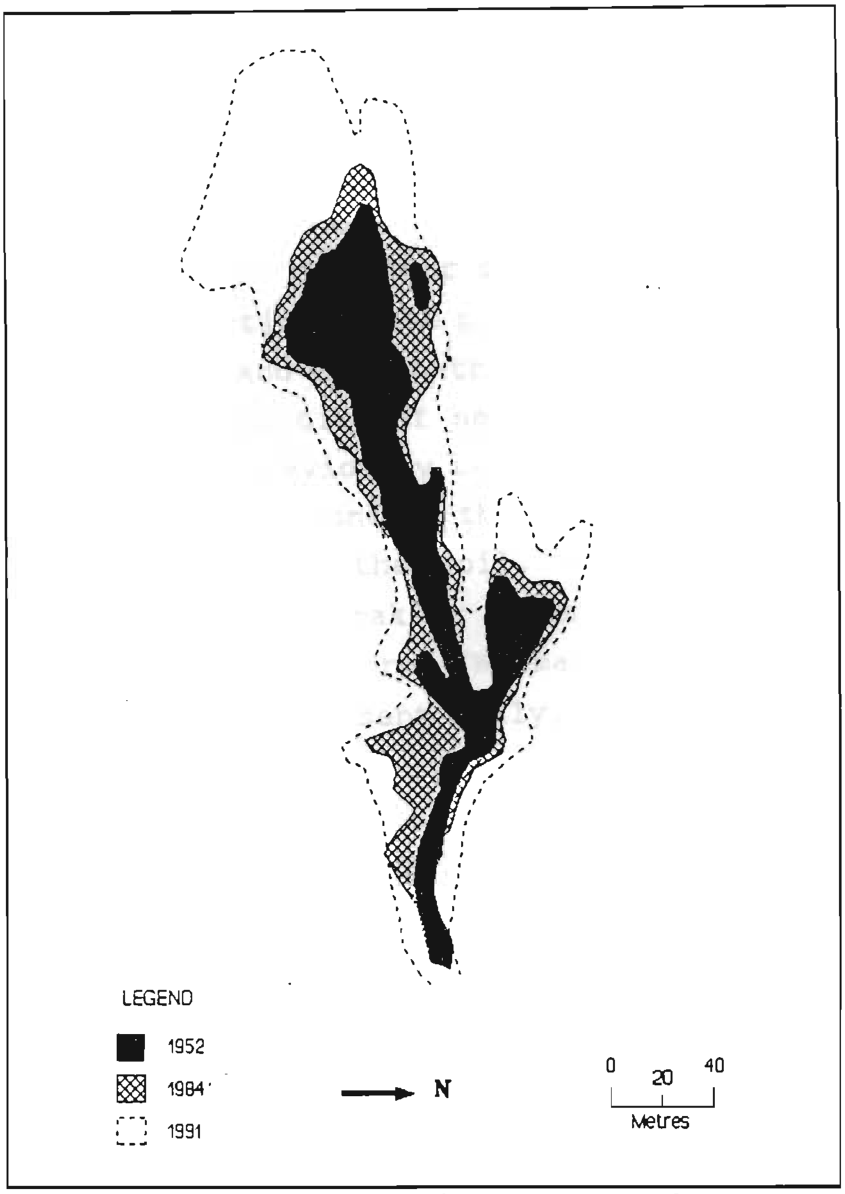

Fig. 4.8. Extent of Ribbok gully in 1952, 1984 and 1991.

Once the bedrock had been exposed, the velocity of the water entering the channel increased, causing rapid erosion of the weaker material, and the consequent widening of the channel at the headwall. As widening occurred, so more bedrock was exposed. With more bedrock being exposed, the headwall broadened and in so doing was able to drain larger quantities of water which, flowing rapidly off the bedrock, caused widening of the channel. Consequently, the headwall has now assumed a rounded shape in plan view, and has reached its ultimate extension.

sheet of water flows downslope towards cross-section five. This entire aggrading section of gully floor supports dense grass vegetation. Downslope from cross-section five where flow velocity increases, the channel, which narrows due to incision, is degrading. Beyond the channel scarp where the bedslope gradient decreases the width between the sidewalls is such that the discharge begins to meander. Where the meandering channel touches the slumped debris at the base of the sidewalls, scouring occurs. The sediment which is entrained as a result of the scouring is transported downslope to cross-section seven. Here the well vegetated floor results in the decrease of flow velocity and the deposition of the bedload. Cross-section seven is thus aggrading. The flow was found to only meander in this downslope section of the gully, for the sinuosity index calculated for the entire length of the gully is only 1.3. A stream is said to meander when the sinuosity ratio i.e. amount of meandering exhibited by a stream channel expressed as a ratio between channel length and length of the axis, is greater than 1.5 (Blong *et al.*, 1982).

Thorne's (1990), concept of basal endpoint control is used to describe the conditions occurring in Ribbok gully. This concept which explains the balance between the sediment received by the channel and that being removed from the channel has three possible states of balance, namely:

1. input greater than output (impeded removal)
2. input equal to output (unimpeded removal)
3. input less than output (excess basal capacity)

According to Thorne the rate at which bank retreat occurs is largely determined by the state of basal endpoint control, such that impeded removal induces bank stability, unimpeded removal exhibits zero bank retreat and excess basal capacity initiates bank instability.

Two of the three stages are evident in Ribbok gully. Cross-sections one, three, four, five and seven exhibit a state of balance where the input is greater than the output and hence bank stability is occurring. Between cross-sections one and two, and five and six, the input of sediment is less than the output and consequently basal scouring occurs. Basal scouring, which was witnessed occurring between cross-sections five and six was not severe enough to induce bank instability. Bank instability could perhaps be induced in this section during runoff events of greater magnitude.

In summarizing Ribbok gully it can be said that it is unstable on the basis of the change in width:depth ratio downslope but that it does have some degree of hydraulic efficiency. The fact that the headwall has reached its ultimate extension, i.e. extended back onto bedrock, and that the gully is essentially characterized by U-shaped cross-sections along with the relatively large amount of vegetation growing along the sidewalls and floor suggests that this gully may have entered a period of stabilization. The occurrence of the channel scarp may in instances of high velocity flow, rapidly retreat upslope and in so doing rejuvenate linear incision and sidewall instability and return this section to a cycle of gully cutting. Consequently, this knickpoint is regarded as a critical location within Ribbok gully.

4.2. Oorbietjie gully

Oorbietjie is a long and narrow second order gully (Fig. 4.9 and Fig. 4.10) which is classified as shown in Table 4.6:

Table 4.6. Typological classification of Oorbietjie gully.

Form	Location	Type	Surface morphology
Linear	Valley-bottom	Type 4	Continuous

This 500 metre long valley-bottom gully has developed on a gentle convex slope and receives much of its water supply from diverse directions. On the basis of its position in the landscape (i.e. valley bottom) and the principal source of runoff received being overland flow it is classified as a Type 4 gully (cf. Imeson and Kwaad, 1980) even though the typical shape of the cross-sections is V-shaped (Fig. 4.9).

Oorbietjie begins its course with an abrupt headcut and is terminated where the mouth intersects the main valley floor in the form of a sediment fan. The longitudinal profile is essentially concave with a slight convexity in the lower reaches (Fig. 4.9). This convexity is seen to be the result of a channel scarp which is situated between cross-sections seven and eight (Fig. 4.11). It is inferred from field observations that the channel scarp originated when the sediment fan became overly steepened, thereby passing the threshold value for the safe convergence of flow. This led to the development of a secondary gully in its steep forward edge.

An interesting feature to note about Oorbietjie is that it has developed along the major valley depression and where it has reached a junction of depressions independent headscarps have developed. These independent headscarps are continuing their headward advance along their respective depressions in a similar manner to the gullies described by Seginer (1966) in Israel. As a result of the above, the headwall of Oorbietjie is classified as being in the initial stages of becoming complexly branching. The planar morphology of the headcuts may be classified as rounded (Fig. 4.9), having approximately vertical faces. According to Handy (1973), the existence of vertical headwalls implies tension failure of the soil which is caused by the soil at the base of the headwall being sufficiently wet to collapse. Although the gullies on which Handy (1973), conducted his research were formed in loess, the vertical headwalls of Oorbietjie are also seen to be largely the result of tension failure.

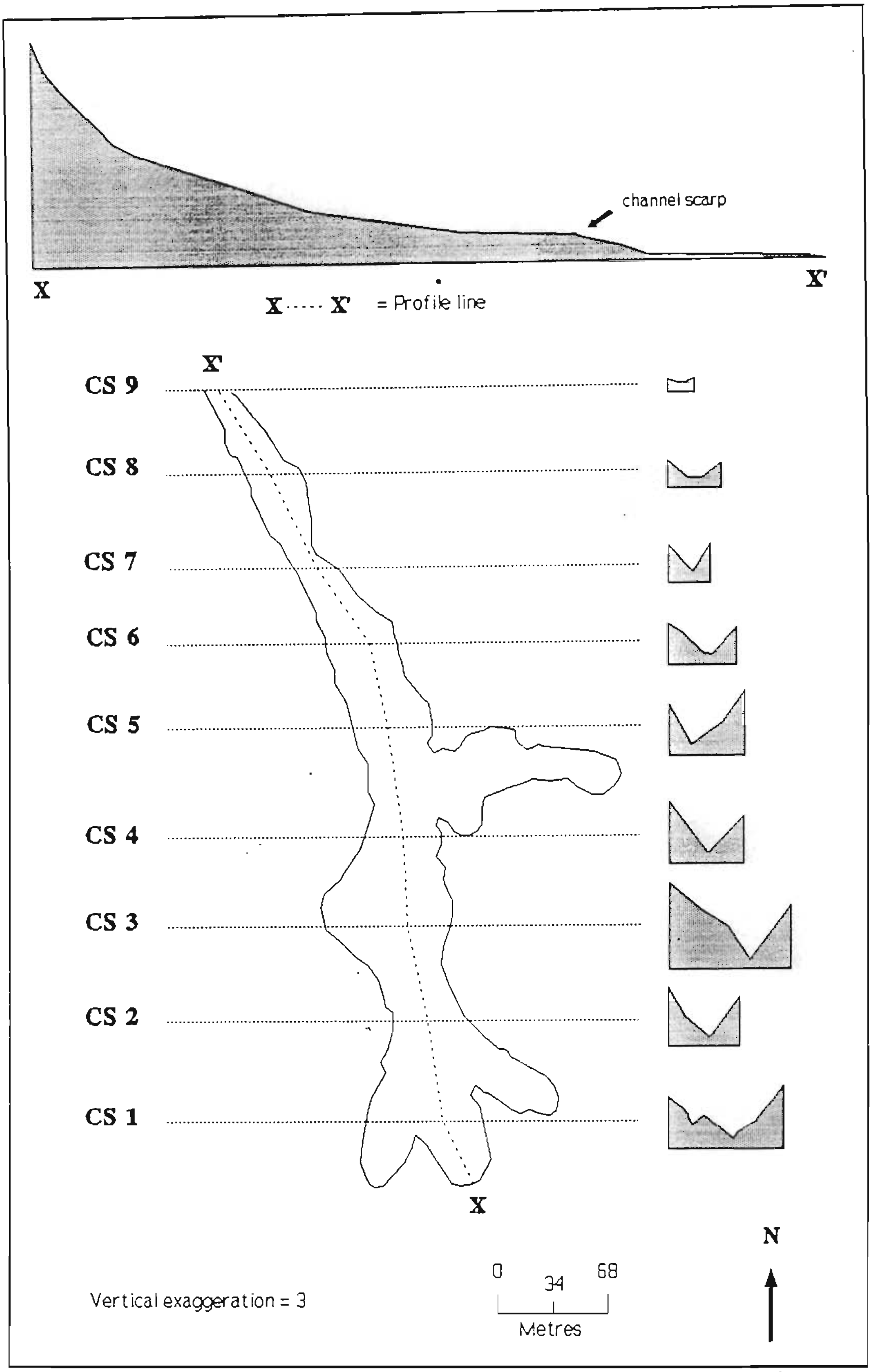

Fig. 4.9. Plan view, cross-sections and longitudinal profile of Oorbietjie gully.

Fig. 4.10. Oblique view of Oorbietjie gully taken in 1988, showing its long linear form, the major tributary and the branching of the headscarp (Source: G.Groenewald).

Fig. 4.11. Channel scarp situated between cross-sections seven and eight.

Retreat of the centre and left headcuts (looking from the gully mouth up) (Fig. 4.10), takes place largely through the combined effect of surface runoff and slumping of large and, in many instances, vegetated blocks (Fig. 4.12). The volume of slumped material generated by these two processes is often in excess of that which can be removed by the gully flow. Consequently, the slumped material collects on the gully floor creating what Daniels (1966) described as "false floors" under which runoff entering the gully flows (Fig. 4.13). The collapsed material will remain on the gully floor until such time as the velocity of flow is great enough to remove it.

Fig. 4.12. Slumping of large vegetated blocks onto the floor of the left headcut.

Fig. 4.13. Accumulation of slumped debris on the floor of the middle headcut creating a "false floor". Note the disappearance of the flow under the collapsed debris.

Despite the fact that visible pipe inlets/outlets were not observed in the field it is probable that piping erosion also plays an active role in the retreat of the centre and left headcuts. The occurrence of this process is indicated by the change in vegetation colour (i.e. lighter green) and the linear depressions in the turf mat above these headcuts (Fig. 4.14). In their investigations of tunnel gully erosion in New Zealand, Lynn and Eyles (1984) also found that often the only surface expression of the process of piping is in the form of depressions in the turf mat.

Fig. 4.14. Depression in the turf mat above the centre headcut and the lighter vegetation colour above the left headcut indicate piping erosion.

A visible pipe outlet was, however, noted along the right headwall (Fig. 4.15). Slumping occurring at this point is promoted by the pipe which has developed along a diagonal line almost midway between the general surface and the gully floor. The flow of water down the face of the wall causes spalling and slab failure of the soil below the pipe exit. This material slumps onto the gully floor leaving the A-horizon material unsupported. When the lateral retreat has undermined the wall of the B-horizon to such an extent that the A-horizon material can no longer support itself, the overhang collapses onto the gully floor (Fig. 4.15). Headward retreat of this headcut is not caused by piping alone, but instead is operating in conjunction with surface runoff. The runoff has much the same effect as the water exiting the pipe i.e. it causes spalling and lateral retreat of the B-horizon until such time as the A-horizon material can no longer support itself and slumping occurs.

Fig. 4.15. Figure showing the pipe exit, spalling, and slumping of the vegetated A-horizon.

Thus, the major processes seen to be responsible for the advance of these three headcuts are surface runoff, slumping, spalling and piping.

The headcut of the tributary along the left sidewall was also found to be retreating along its independent depression as a result of surface runoff and piping (Fig. 4.16 and Fig. 4.17).

Fig. 4.16. Surface runoff and discharge from two pipes. The jet of water from the larger pipe landed one metre clear of the base (March, 1991).

Fig. 4.17. Collapse of portion of the pipe in the upslope direction. Note the constant trickle of water down the vertical face (July, 1991).

Figure 4.18 shows the extent to which the right, left, middle and tributary headcuts have extended and expanded in their respective upslope directions over the 39 years from 1952-1991. The occurrence of a discontinuous gully above the left headwall in 1952 appeared, from the aerial photographs, to be the result of a collapsed drainage channel. This discontinuous gully, which by 1984 had been incorporated into the main gully, adds further weight to the argument that piping is, or has been an operative process in the upslope retreat of this headcut.

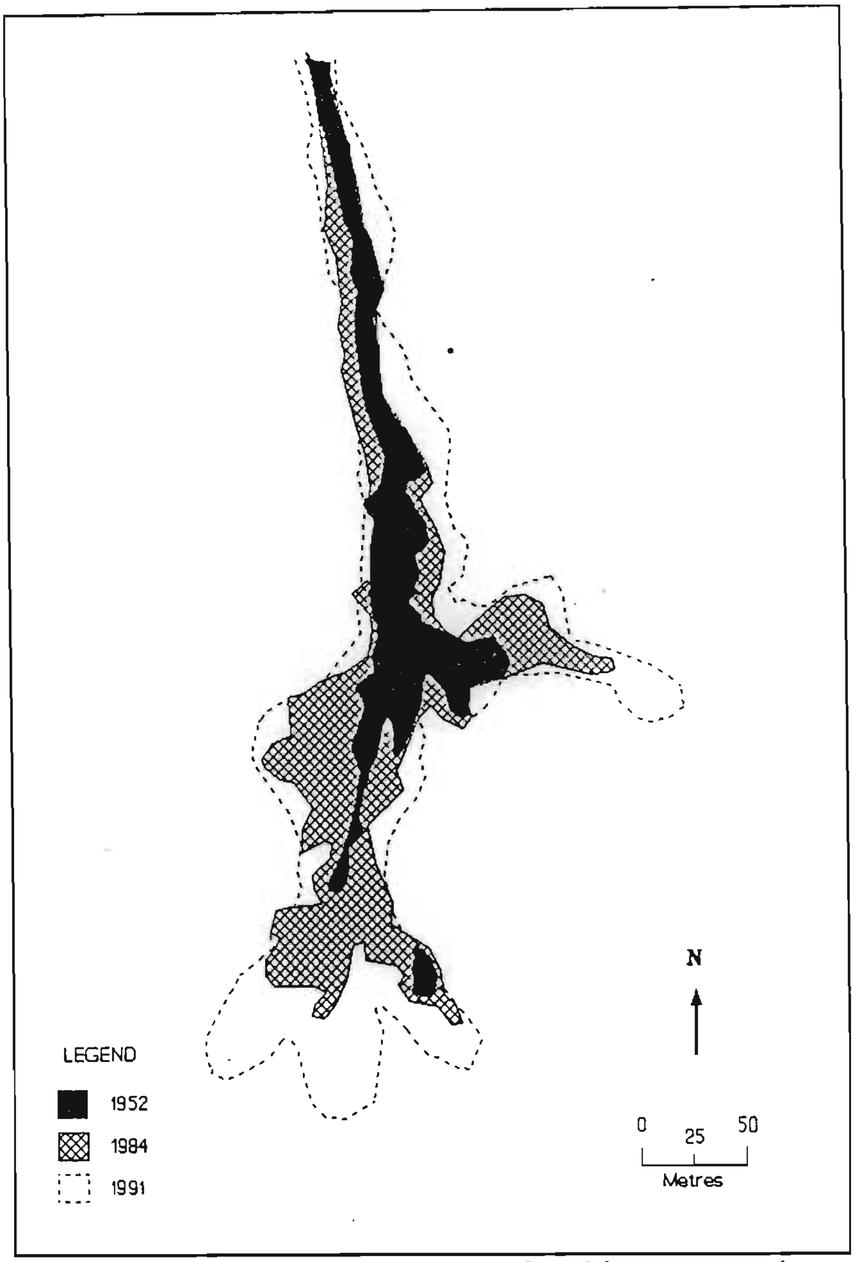

Fig. 4.18. Extent of Oorbietjie gully in 1952, 1984 and 1991.

The results of the morphometric parameters recorded at each of Oorbietjie's nine cross-sections are shown in Table 4.7. From this Table it can be seen that the bed width values are limited, ranging from 3.4m to 13.6m, with a mean value of 9.1m. The bank width values, on the other hand, are high varying between 18.7m and 80.0m, with a mean of 47.1. The relatively high bank width:bed width ratio's, which range from 1.8 to 11.0 (mean = 5.8), together with the mean shape factor value of 2.0, indicate that the gully cross-sections are essentially V-shaped (Fig. 4.9), and are thus hydraulically inefficient. Maximum gully depth varies between 1.3m, where the gully mouth intersects the main valley floor and 13.6m, near the headwall. The width:depth ratio's are relatively high (4.8 to 14.4, mean 7.3), indicating that as the channel width increases the depth does not increase at a similar rate. Changes in the width:depth ratio down the length of the gully signifies that Oorbietjie is an unstable channel (cf. Schumm, 1960a).

Table 4.7. Morphometric parameters recorded at each of Oorbietjie gully's cross-sections.

Cross-section	Bed width (m)	Bank width (m)	Maximum depth (m)	Mean depth	Width: depth ratio	Bank width: bed width ratio	Shape factor
1	6.8	74.5	10.2	5.6	7.3	11.0	1.8
2	6.8	44.0	9.0	4.6	4.9	6.5	1.9
3	10.5	80.0	13.6	5.3	5.9	7.6	2.6
4	13.6	47.6	9.0	4.6	5.3	3.5	2.0
5	13.3	49.3	10.2	5.2	4.8	3.7	2.0
6	6.8	45.9	6.2	3.0	7.4	6.8	2.1
7	3.4	27.2	5.6	2.4	4.9	8.0	2.3
8	10.2	36.7	3.4	1.9	10.8	3.6	1.8
9	10.2	18.7	1.3	0.8	14.4	1.8	1.6
MEANS	9.1	47.1	7.6	3.7	7.3	5.8	2.0

Linear regression analysis used to illustrate the correlation between the cross-sectional parameters listed in Table 4.8 and distance along the thalweg reveals that the longitudinal characteristics of Oorbietjie gully have some bearing on the cross-sectional parameters. Thus, there exists some inter-dependence between the longitudinal and cross-sectional variables.

Table 4.8. Results of the linear regression analysis, Oorbietjie gully.

Parameters	r^2
Maximum depth	0.72
Mean depth	0.83
Bank width	0.65
Width:depth ratio	0.43
Shape factor	0.06

Results of the textural analysis of the soil samples collected at each cross-section are presented in Table 4.9 and shown in Fig. 4.19.

Table 4.9. Gully morphometric and sediment data, Oorbietjie gully.

Cross-section	Bank width (m)	Maximum depth (m)	Width: depth ratio	% silt-clay in bank	% silt-clay in bed	"M"
1	74.5	10.2	7.3	49.0	38.0	40.4
2	44.0	9.0	4.9	42.0	bedrock	-
3	80.0	13.6	5.9	48.3	bedrock	-
4	47.6	9.0	5.3	33.8	bedrock	-
5	49.3	10.2	4.8	41.8	36.0	37.7
6	45.9	6.2	7.4	34.1	42.0	40.3
7	27.2	5.6	4.9	50.0	39.0	42.2
8	36.7	3.4	10.8	55.3	42.0	44.1
9	18.7	1.3	14.4	36.4	28.0	29.0

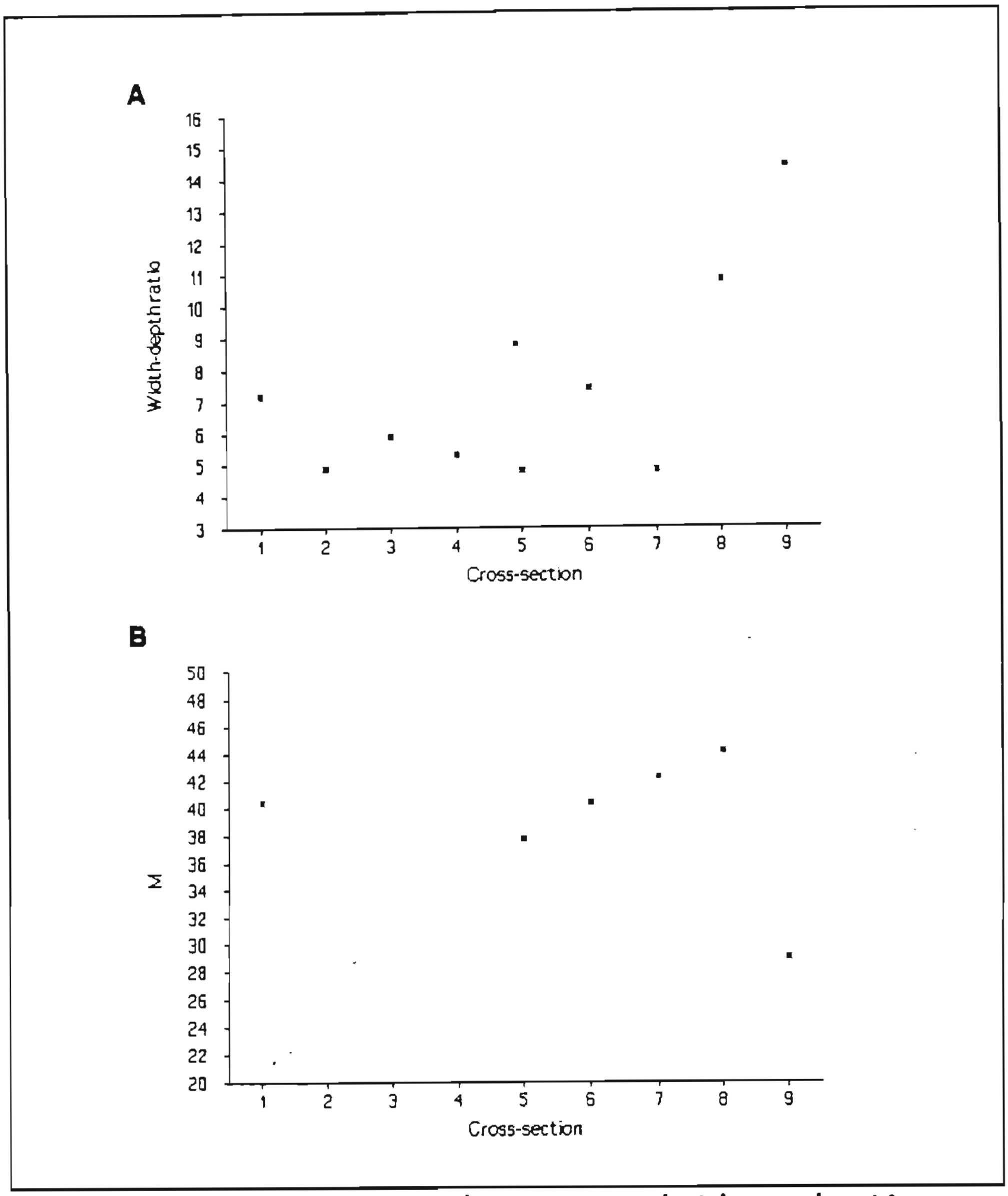

Fig. 4.19. Graphs showing A: variations in the width:depth ratio and B: M or weighted mean silt-clay percent along Oorbietjie gully.

The lack of a strong correlation between "M" and width:depth ratio (i.e. $r^2 = 0.34$) shows that factors other than "M" exert a stronger influence on the morphology of Oorbietjie gully. Furthermore, the fact that the gully has cut down onto bedrock along almost half of its length (Fig. 4.21), is likely to have further influenced the results.

Results of the classification of Oorbietjie's sidewalls according to erosional activity and morphology are presented in Fig. 4.20 and Fig. 4.21 respectively. As found for Ribbok gully, the geomorphically active sidewalls are predominantly found in the region of the headwalls, and the stable sidewalls towards the mouth of the gully.

Recession of the gully sidewalls is influenced by the interaction of several factors, such as soil type, topographic properties, and processes. Surface runoff and mass movement in the form of slumps and flows appear to be the dominant processes responsible for gully wall failure, which together with rilling and fluting have been and still are responsible for gully widening.

The scalloped appearance of the sidewalls (Fig. 4.10:74) provides evidence of the occurrence of what Charman (1978) called the "phenomenon of cathedralism", whereby the gully sides are cut back predominantly by the action of running water leaving behind residual wall masses or "cathedrals" which extend into the gully. Fluting is, however, not only indicated by these remnants but it was observed to be currently active in the gully, particularly at cross-section six.

The process of slumping, which in Oorbietjie gully takes the form of slab-type or toppling failure has been described by Varnes (1958) as, a slide phenomenon, made up of one or only a few moving units, each of which displays little or no internal deformation. Toppling failure which occurs on the unstable sidewalls involves the downward and outward movement of slabs of soil along almost planar surfaces. The upper half of the potential failure blocks are separated from the intact bank by near-vertical tension cracks. These tension cracks, which develop as a result of the tensile stress that exists in the upper part of the bank adjacent to the slope, can be seen to be initiated in Oorbietjie by, among other things, animal tracks along the gully walls. These tracks,

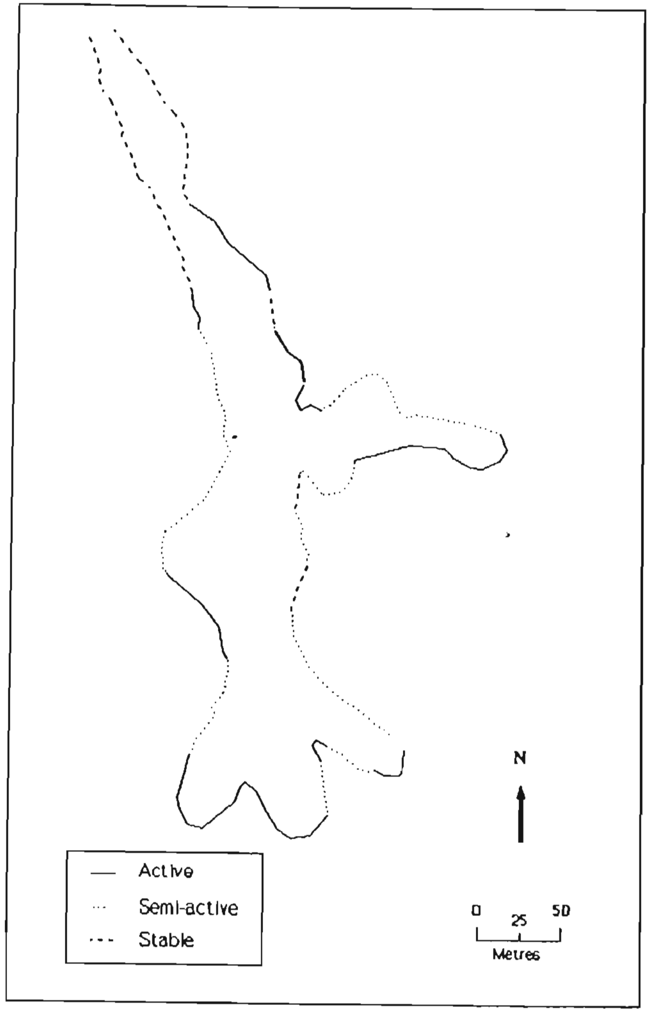

Fig. 4.20. Sidewall erosional activity in Oorbietjie gully.

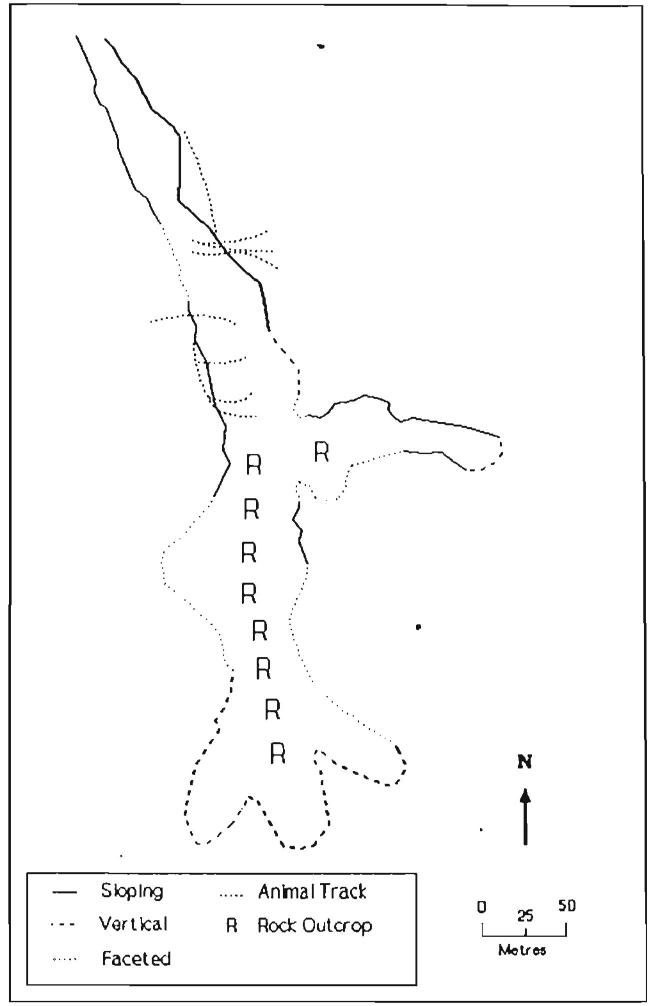

Fig. 4.21. Sidewall morphology and special features in Oorbietjie gully.

which compress the topsoil thereby rendering it impermeable and unable to support vegetation growth, dry out and form small cracks. Water infiltrating from the soil surface into the cracks increases the pore water pressure acting on the failure surface (Bradford and Piest, 1977), thus initiating slumping. Slumping induced by animal tracks has previously also been noted by Gregory and Park (1976). When the failure of the vegetated blocks finally occurs i.e. when the driving forces of the soil (weight of the soil, the weight of the water added to the soil and seepage forces of percolating water) equal or exceed the resisting forces (shear strength of the soil) the still vegetated blocks topple forward into the channel, usually remaining in tact. In most instances the rotation of the toppled blocks is not great and the vegetation on the blocks and that occurring on the banks prior to collapse continue to grow. The growth of this vegetation can in future promote stabilization of the sidewalls, as was found by Schumm (1961).

The dominant sidewall processes occurring in Oorbietjie gully i.e. surface runoff, slumping and fluting must not be seen to be operating in isolation but to be interdependent, such that surface runoff may initiate slumping and/or fluting. Similarly, slumping can either aid in the initiate the process of fluting by exposing a rill-free face or destroy it by drowning the fluted surface.

Entering and exiting of animal tracks were noted along the sidewalls (Fig. 4.21). The effect that these tracks have on the sidewalls of Oorbietjie gully can be seen to be similar to those described for Ribbok gully.

It was calculated that on average the gully sidewalls contribute about 64% of the total sediment production. Consequently, the role played by the above mentioned sidewall processes in the growth of the gully are important. In order to see how important these processes are, the contribution of sidewall erosion as opposed to downcutting was calculated. The results of these calculations are presented in Table 4.10 and shown in Fig. 4.22.

Table 4.10. Ratio of sidewall cutting to downcutting, Oorbietjie gully.

Cross-section	Sidewall cutting (m^3)	Downcutting (m^3)	Sidewall cutting: downcutting ratio
1	274	103	2.7
2	143	61	2.3
3	276	150	1.8
4	115	104	1.1
5	150	104	1.4
6	100	38	2.6
7	40	25	1.6
8	35	34	1.0
9	3	12	0.3
MEANS	126.2	70.1	1.6

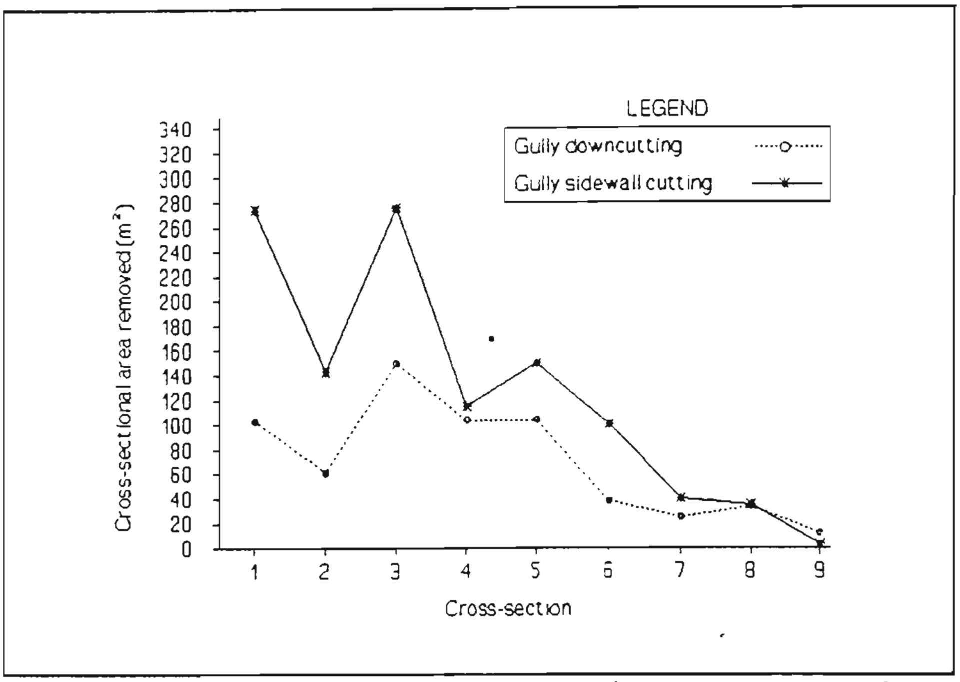

Fig. 4.22. Gully sidewall cutting compared with gully downcutting at each cross-section, Oorbietjie gully.

As found for Ribbok gully, sidewall cutting dominates in the upper channel reaches with its influence decreasing downslope as the floor of the cross-sections become broader and the sidewalls more stable. The ratio of sidewall cutting to downcutting varies between 0.3 and 2.7 with a mean value of 1.6. The second highest value i.e. 2.6 was that calculated for cross-section six. This is not surprising given the fact that the process of fluting, which is indicative of active sidewall erosion (Graham, 1984; Crouch, 1990a), was found to be particularly active in this section of the gully. On the other hand, in the vicinity of the channel scarp i.e. between cross-sections seven and eight, there is a decrease in the importance of sidewall cutting. Although this decrease is in keeping with the general decreasing of sidewall cutting in the downslope direction, it can perhaps also be attributed to the increase in linear incision downslope from the scarp. Seen together with the channel scarp this decrease implies that this section of gully is potentially unstable and that renewed backcutting could occur during a period of intense discharge, thereby upsetting any state of equilibrium which may have been reached.

The contribution made by sidewall erosion to the general expansion of Oorbietjie over the 39 year period is evident in Fig. 4.18. What is clear is that sidewall erosion was far more active during the period 1984-1991, than during the period 1952-1984. This can perhaps be explained by Oorbietjie following the same pattern of development as described by Blong *et al.* (1982) for Dead Cow gully in Razorback, Australia. The pattern is one of initial incision with headward retreat, followed by gully widening, with the rate of widening tending to decrease with time. Oorbietjie can thus be seen to be in the widening stage, this being indicated by the high sidewall erosion versus downcutting ratios.

Basal scour and bank undercutting were found to be the dominant processes operating on the floor of the gully. The process of freeze-thaw which was observed during the winter months is, as in Ribbok, seen to play a supplementary role rather than a dominant one.

The theory that gullies do not erode their beds along the entire length but instead have reaches of aggradation alternating with sections of degradation is again borne out in Oorbietjie gully. The input of material into the gully between the headwall and cross-section one is far greater than that removed by the discharge. Consequently a condition of impeded removal exists in this section of the gully. Between cross-sections one and four where the gully has eroded down onto bedrock a condition of excess basal capacity exists. From what could be ascertained in the field the effect that the exposed bedrock is exerting on gully floor processes is that it is retarding any further linear incision/basal scour, but in so doing is leading to lateral erosion of the gully walls by bank undercutting. Exposed bedrock on the floor of the arroyos investigated by Schumm and Hadley (1957) was found to exert a similar effect. Downslope from cross-section four a general condition of unimpeded removal exists, except in the vicinity of the channel scarp where excess basal capacity is resulting in linear incision. A condition has been reached in this lower section of the gully (i.e. between cross-sections six and seven) where the total width between the gully walls is sufficient to allow the flow to meander between the walls. The amount of meandering exhibited by the whole channel is, however, negligible, as indicated by a sinuosity ratio of only 1.2.

In summarizing Oorbietjie gully it can be said that it is characterized by V-shaped cross-sections and rounded headscarps which are in the initial stages of becoming complexly branching. The gully is still enlarging as indicated by the active headcuts at the upslope terminals of the individual branches. Although headward extension is actively occurring the contribution of the sidewalls to general increase in gully area is also of great importance. Sidewall erosion occurs predominantly by surface runoff and sidewall fracturing, and is essentially more dominant than downcutting in the erosion of material from the gully. Generally this gully, which has two main critical locations i.e. headscarps and channel scarp, is still unstable and hydraulically inefficient.

4.3. Car gully

Like Ribbok and Oorbietjie, Car gully is a second order gully which is typologically classified as shown in Table 4.11:

Table 4.11. Typological classification of Car gully.

Form	Location	Type	Surface morphology
Linear	Valley-bottom	Type 4	Continuous

This 400m long valley-bottom gully is characterised by a long and narrow form which has two narrow heads and no tributaries along its sides (Fig. 4.23 and Fig. 4.24). The cross profiles are essentially V-shaped in the upper reaches of the gully (i.e. headwalls to cross-section 4) while in the lower reaches (i.e. between cross-sections five and eight) they tend towards being U-shaped. The longitudinal profile exhibits a weak convexity in the downslope direction where it flattens out before intersecting with the valley slope (Fig. 23). Like Oorbietjie, this gully has developed on a gentle convex slope along a depression. Where this depression has reached a junction, the gully has divided into two headcuts which are developing independently along their respective depressions.

Both gully heads can be classified as pointed (cf. Ireland *et al.* 1939). Headwall A, which in vertical profile is vegetated (cf. Ireland *et al.* 1939), began retreating upslope sometime between 1952 and 1984 (see Fig. 4.28). It is currently retreating upslope by means spalling, surface wash, slumping and piping. The outlet of a small pipe was found almost midway between the floor of the gully and the general surface of this headwall. Water flowing from the pipe causes spalling of the material below its exit. The wearing back of the B-horizon material as a result of this process, leaves the A-horizon material unsupported. This material remains as an overhang until such time as it can no longer support its own weight and slumps onto the gully floor. Another process causing undermining of the vegetated lip is surface wash. Overland flow entering the gully, flows over the overhanging A-horizon and back underneath it. This back trickle effect sloughs off material as it flows down the sidewall, thereby undermining the overhang. The dominant processes found to be responsible for the retreat of headwall B are also surface runoff and slumping. No pipe inlet or outlet was observed at this headwall.

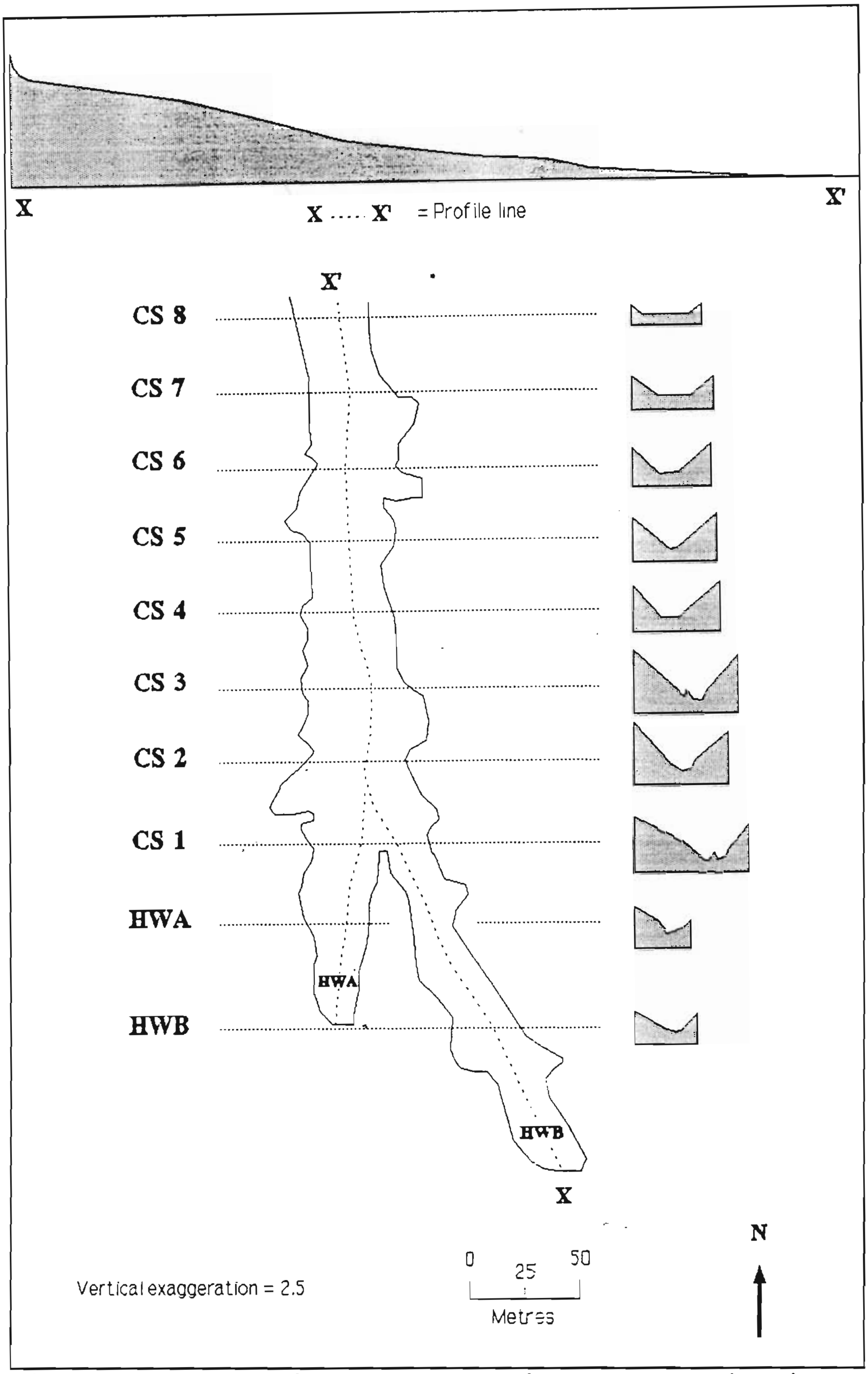

Fig. 4.23. Plan view, cross-sections and longitudinal profile of Car gully. HWA refers to headwall A and HWB refers to headwall B.

Fig. 4.24. Oblique view of Car gully taken in 1988 showing its long and narrow form and the two head-cuts (Source: G. Groenewald).

Animal tracks and waterfall erosion were not found in association with either of the headwalls.

The results of the morphometric parameters recorded at each of Car gully's cross-sections are presented in Table 4.12. The mean bank width:bed width ratio (5.3) together with the mean shape factor value of 1.8, support field observations that the shape of the cross-sections vary between being V- and U-shaped.

Table 4.12. Morphometric parameters recorded at each of Car gully's cross-sections.

Cross-section	Bed width (m)	Bank width (m)	Maximum depth (m)	Mean depth	Width:depth ratio	Bank width: bed width ratio	Shape factor
HWA	3.8	28.8	4.0	1.6	7.2	7.6	2.6
HWB	5.0	31.3	4.0	2.3	7.8	6.3	1.7
1	9.0	55.0	7.0	3.6	7.9	6.1	2.0
2	7.5	46.3	9.0	5.3	5.1	6.2	1.7
3	8.8	50.0	9.5	4.5	5.3	5.7	2.1
4	7.5	42.5	6.0	3.2	7.1	5.7	1.8
5	5.0	40.0	5.5	3.6	7.3	8.0	1.5
6	11.0	38.8	5.2	3.5	7.5	3.5	1.5
7	15.0	37.5	3.5	2.5	10.7	2.5	1.4
8	21.8	35.0	2.0	1.6	17.5	1.6	1.3
MEANS	9.4	40.5	5.6	3.2	8.3	5.3	1.8

On the basis of maximum depth, Car gully can be divided into three sections namely: headwalls, upper channel (cross-sections 1-3), and middle and lower channel (cross-sections 4-8). The upper channel section exhibits an increase in depth in the downgully direction while the middle and lower sections are characterized by a steady decrease in depth. Variations in width:depth ratio along the length of the gully indicate that this gully is still an unstable channel.

Relating the cross-sectional variables listed in Table 4.13 to the longitudinal variable of distance along the thalweg by means of linear regression analysis, revealed that with the exception of shape factor the correlations were very weak. These weak correlations were attributed to the inclusion of the two headwalls in the analysis, for when they were excluded and the variables of the main channel only (viz cross-sections one to eight) were correlated, the correlations proved to be strong (Table 4.14). A reason for this is that the headwalls are seen to in an earlier stage of development than the rest of the channel. Consequently, their width, maximum depth and mean depth values are much smaller in relation to what is usually the case at that thalweg distance.

Table 4.13. Results of the linear regression analysis, Car gully.

Parameters	r^2
Maximum depth	0.10
Mean depth	0.003
Bank width	0.00
Width:depth ratio	0.36
Shape factor	0.65

Table 4.14. Results of the linear regression analysis of the main channel only, Car gully.

Parameters	r^2
Maximum depth	0.74
Mean depth	0.61
Bank width	0.89
Width:depth ratio	0.54
Shape factor	0.71

Results of the variations in width:depth ratio and silt-clay percentage along the length of Car gully are presented in Table 4.15 and shown in Fig. 4.25. Linear regression analysis showed that no meaningful correlation exists between the width:depth ratio and "M" ($r^2 = 0.35$). This is not surprising for when one examines the values obtained for "M" (Table 4.15) it is seen that the mean silt-clay percent varies only slightly despite the changes in width:depth ratio. These results conform with Heede's (1970) observations of the morphology of gullies in the Colorado Rocky Mountains where he found no significance difference in the texture of the soil along Alkali Creek despite changes in the width:depth ratio.

Table 4.15. Gully morphometric and sediment data, Car gully.

Cross-section	Bank width (m)	Maximum depth (m)	Width:depth ratio	% silt-clay in bank	% silt-clay in bed	"M"
HWA	28.8	4.0	7.2	45.3	46.0	45.8
HWB	31.3	4.0	7.8	43.0	bedrock	-
1	55.0	7.0	7.9	39.9	48.0	46.4
2	46.3	9.0	5.1	39.9	40.0	40.0
3	50.0	9.5	5.3	51.4	48.0	48.9
4	42.5	6.0	7.1	46.2	40.0	41.4
5	40.0	5.5	7.3	31.3	bedrock	-
6	38.8	5.2	7.5	31.5	bedrock	-
7	37.5	3.5	10.7	47.1	38.0	39.4
8	35.0	2.0	17.5	40.0	38.0	38.2

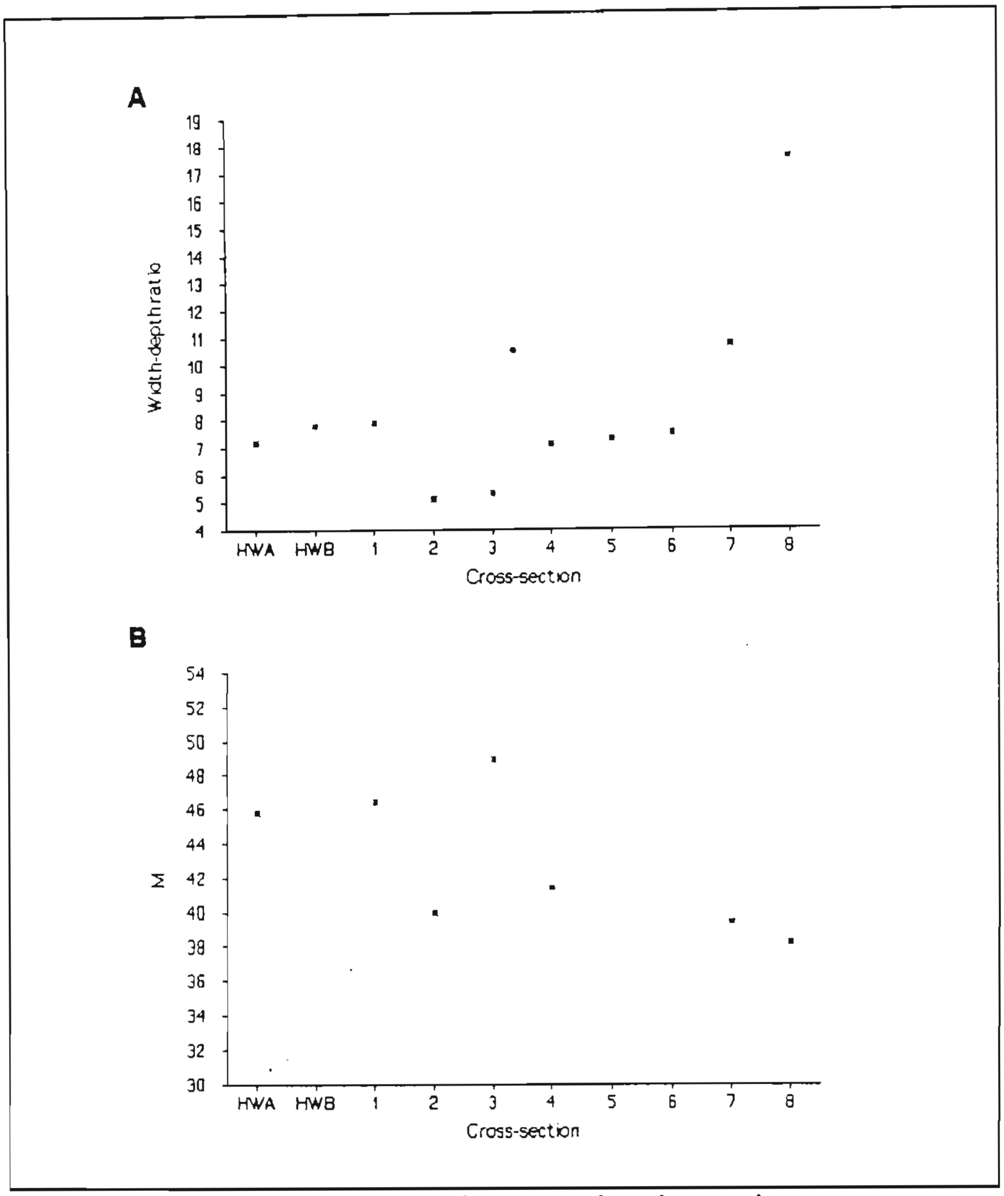

Fig. 4.25. Graphs showing variations in A: the width:depth ratio and B: M or weighted mean silt-clay percent along Car gully.

Classifications of the sidewall erosional activity and morphology of Car gully are presented in Fig's 4.26 and 4.27 respectively. Figure 4.26 shows that the geomorphically active sidewalls occur near the headwalls and along the upper reaches of the left sidewall. The right sidewall is predominantly stable and sloping.

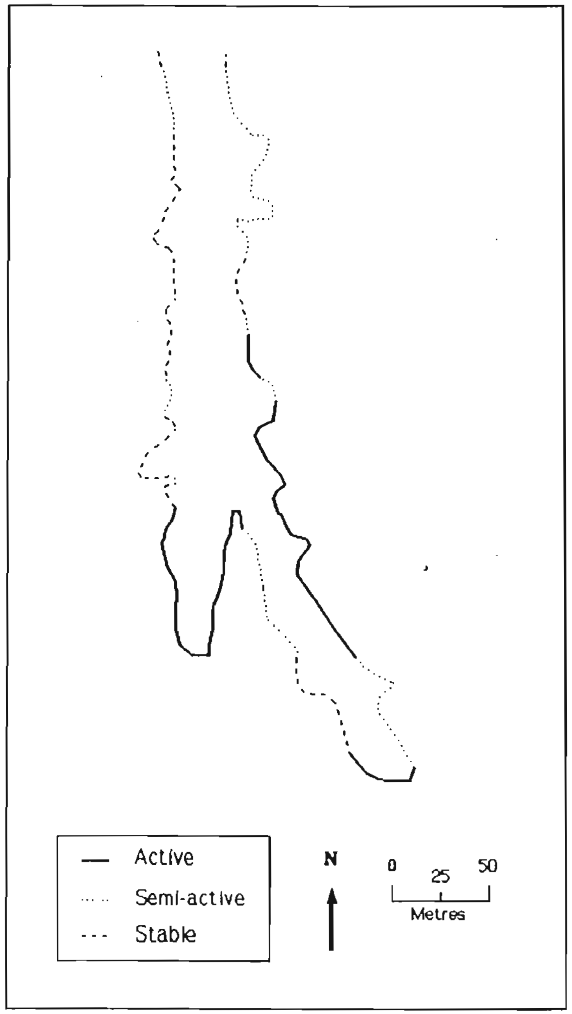

Fig. 4.26. Sidewall erosional activity in Car gully.

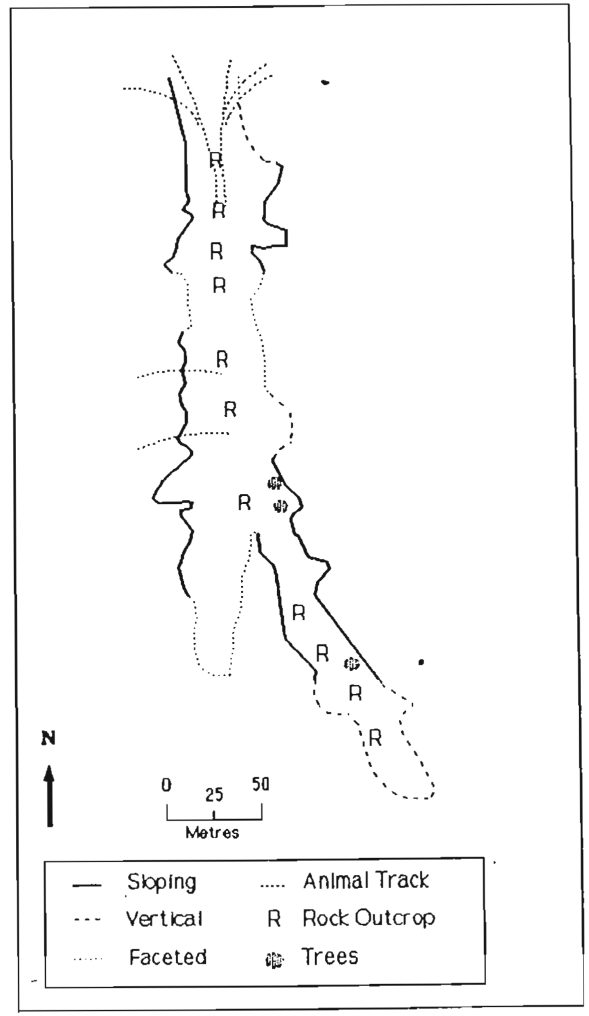

Fig. 4.27. Sidewall morphology and special features in Car gully.

The dominant processes occurring along the sidewalls are surface runoff, slumping of vegetated blocks, and rilling. These processes are currently reducing the angle of sidewall slope to more stable values which are then able to support vegetation growth. Evidence of fluting having been a dominant process along most of the gully, but particularly the left wall, was found in the form of cathedrals left extending into the gully. These fluted sidewalls have, however, subsequently stabilized or are in the process of stabilizing i.e. are semi-active, and thus, are not great sources of sediment production. This statement is supported by Fig. 4.28 which indicates the extent of expansion and extension of Car gully. What is evident from this figure is that a large portion of the left sidewall has not undergone any significant increase in area over the 39 year period. The right sidewall shows a greater degree of expansion, particularly in the 1984-1991 period.

Another interesting point to note in Fig. 4.28 is that, where the two animal tracks enter/exit the gully, sidewall expansion has increased remarkably.

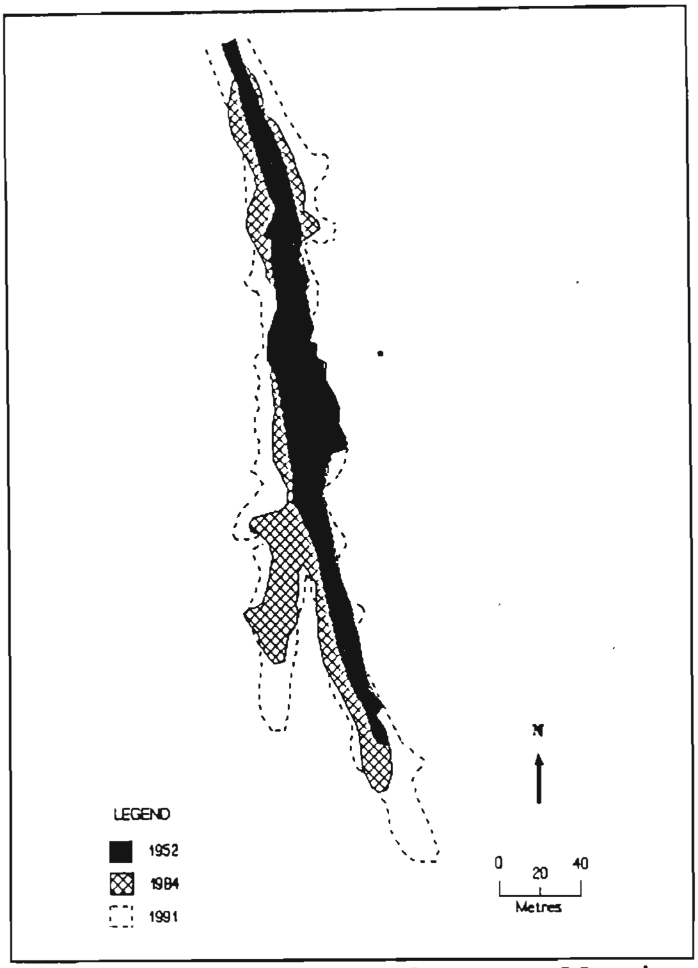

Fig. 4.28. Extent of Car gully in 1952, 1984 and 1991.

Two of the three basal endpoint control states outline by Thorne (1990) were observed in Car gully. Impeded removal or basal accumulation was found along the channel floor of headwall A, between cross-sections one to four, and between cross-sections six to eight. The type of debris that has accumulated along these reaches varies. On the one hand, the debris on the floor of headwall A and between cross-sections one to four is in the form of large vegetated blocks which have slumped onto the floor. Between cross-sections six to eight, however, the debris is in the form of bedload sediment which has been deposited by the channel flow. The sidewalls between cross-sections six to eight which have not already stablized, can according to Thorne's concept of basal endpoint control, be expected to start stabilizing so long as the flow velocity does not increase such that undercutting of the basal material is initiated.

The other basal endpoint control state observed was excess basal capacity. This state was noted along most of headwall B and between cross-sections five and six. Undercutting of the basal material of headwall B is largely responsible for the instability of the sidewalls in this reach. The excess basal energy between cross-sections five and six, on the other hand, is causing the channel to incise into the bedrock. Hannam (1983), in his study of gully morphology in the Bathurst catchment, New South Wales, classified areas which are cutting through bedrock as stable. In the present study it was found that at times of greater runoff when the flow broadens and impinges on the base of the gully wall, scouring of the sidewalls does occur. The scouring in this section of the channel does, however, not pose as great a threat to sidewall stability as is the case along headwall B. Reasons for this are that a) the bed width between cross-section five and six is such that channel flow seldom impinges on the sidewalls and b) these sidewalls are generally sloping and stable (Fig's 4.26 and 4.27). The amount of meandering exhibited by the channel flow of Car gully is not very great i.e. the sinuosity index calculated is 1.2.

The extent to which either sidewall erosion or basal incision dominate was calculated for Car gully (Table. 4.16). These results, which are shown graphically in Fig. 4.29, reveal that sidewall cutting dominates in the upper section of the gully, whereas lower down its influence tends to decrease. This finding is in keeping with the shape factor values calculated. On average gully sidewall erosion contributes 62% of the total volume of sediment removed.

Table 4.16. Ratio of sidewall cutting to downcutting, Car gully.

Cross-section	Sidewall cutting (m^3)	Downcutting (m^3)	Sidewall cutting: downcutting ratio
HWA	30	15	2.0
HWB	53	20	2.7
1	130	65	2.0
2	175	68	2.6
3	142	83	1.7
4	85	53	1.6
5	97	48	2.0
6	82	53	1.5
7	33	60	0.6
8	10	45	0.2
MEANS	83.7	51.0	1.7

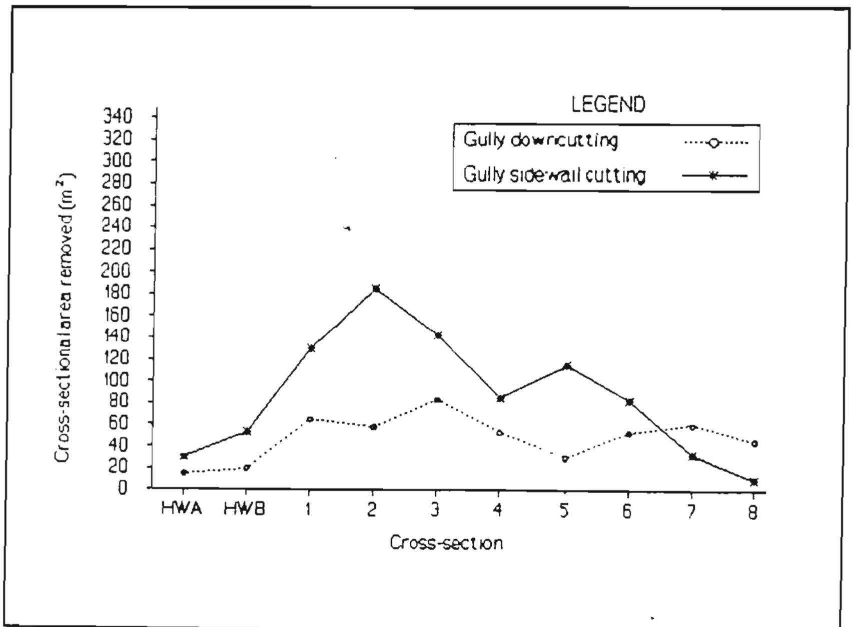

Fig. 4.29. Gully sidewall cutting compared with gully downcutting at each cross-section, Car gully.

In short it can be said that Car gully is a linear second order gully with headwall A and headwall B, constituting the two tributaries which flow into the main channel. Both gully heads are pointed. Headwall A has a vegetated vertical profile and headwall B a vertical profile. As far as cross-sectional shape is concerned, the entire gully cannot be classified as being either V- or U-shaped, but a combination of both. The upper section of the gully is predominantly V-shaped, and therefore is neither hydraulically efficient nor in equilibrium. On the other hand, the lower section which is U-shaped, is hydraulically efficient and is in equilibrium. The sidewalls are the dominant sediment producers with the left sidewall being the more active. This gully can be seen to start stabilizing fully once the upper section attains greater hydraulic efficiency and the headwalls reach their ultimate extensions.

4.4. Glen Reenen gully

Glen Reenen, which is the youngest of the six gullies is classified as follows (Table 4.17):

Table 4.17. Typological classification of Glen Reenen gully.

Form	Location	Type	Surface morphology
Bulbous	Valley-side	Type 2	Continuous

This gully which is only 20m in length has assumed a bulbous shape with a broad spatulate-shaped head (Fig. 4.30). Although Fig. 4.30 and the shape factor values calculated for each of the three cross-sections (Table 4.18) would suggest that the cross-profiles are more V-shaped than U-shaped, this gully was classified as a type 2 gully because it complies with more of the conditions set out by Imeson and Kwaad (1980) than does a type 1 gully.

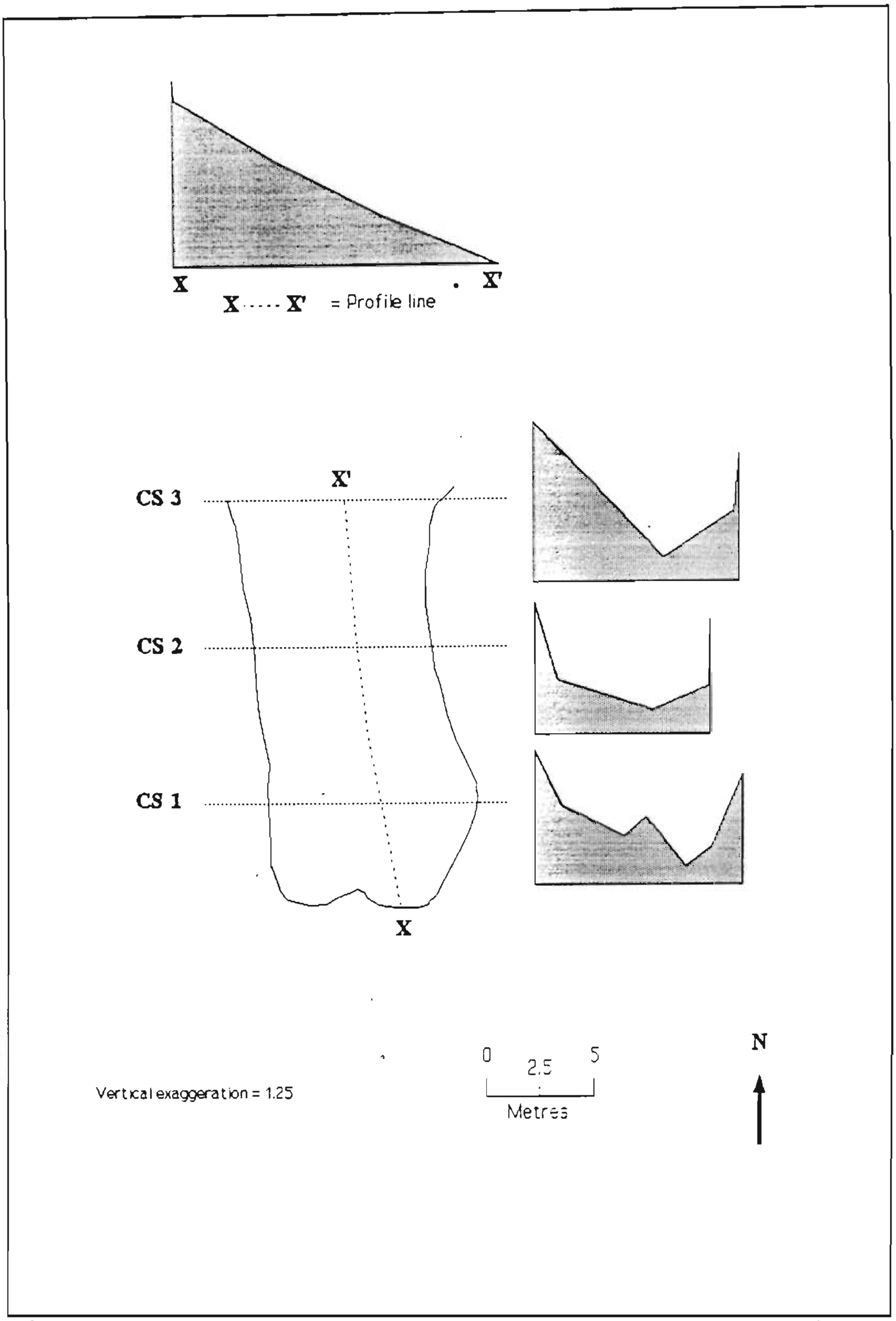

Fig. 4.30. Plan view, cross-sections and longitudinal profile of Glen Reenen gully.

The longitudinal profile of Glen Reenen gully exhibits an almost constant slope (Fig. 4.30). Not only is consistency displayed in the long profile but also in the channel flow which has a sinuosity index of 1.1, and the bank width, maximum depth, mean depth and width:depth ratio values obtained for each cross-section (Table 4.18). What Ireland *et al*. (1939) found in their investigations of gullies in the piedmont of South Carolina was that the more continuous the slope of a gully and the more homogeneous the material into which the gully has incised, the more consistent are the size and cross-profiles of the channel. Results of the textural analysis of the soil samples collected (Table 4.19) clearly indicate that the material in which Glen Reenen has developed is uniform, thereby supporting the findings of Ireland *et al*. (1939) (see Fig. 4.31).

Table 4.18. Morphometric parameters recorded at each of Glen Reenen gully's cross-sections.

Cross-section	Bed width (m)	Bank width (m)	Maximum depth (m)	Mean depth	Width:depth ratio	Bank width: bed width ratio	Shape factor
1	4.1	10.1	4.2	2.2	2.4	2.5	1.9
2	7.3	8.6	3.8	2.9	2.3	1.2	1.3
3	7.3	10.4	4.6	2.6	2.3	1.4	1.8
MEANS	6.2	9.7	4.2	2.6	2.3	1.7	1.7

Table 4.19. Gully morphometric and sediment data, Glen Reenen gully.

Cross-section	Bank width (m)	Maximum depth (m)	Width:depth ratio	% silt-clay in bank	% silt-clay in bed	"M"
1	10.1	4.2	2.4	36.1	36.0	36.0
2	8.6	3.8	2.3	36.3	36.0	36.1
3	10.4	4.6	2.3	36.0	36.0	36.0

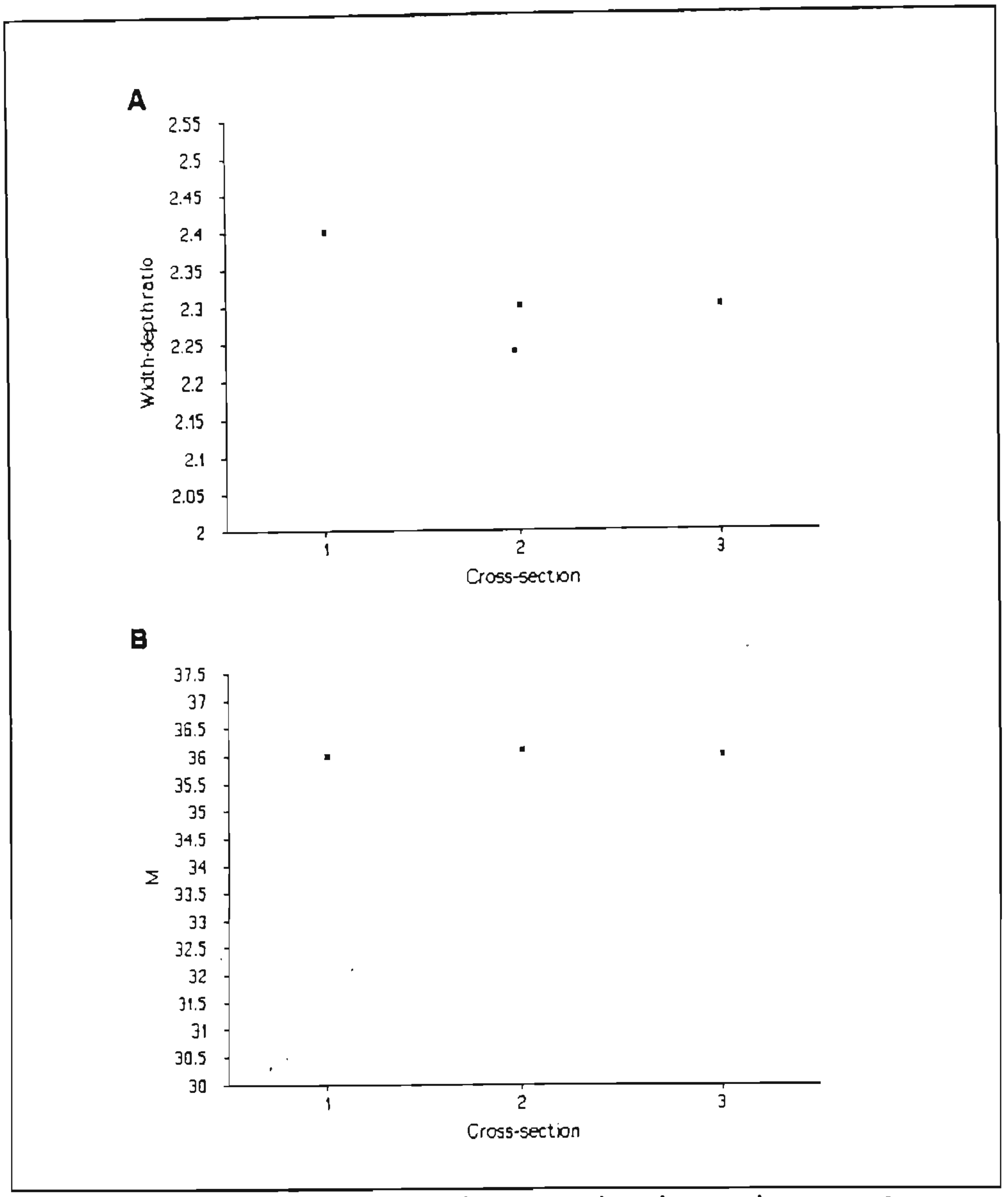

Fig. 4.31. Graphs showing variations in A: the width:depth ratio and B: M or weighted mean percent silt-clay along Glen Reenen gully.

In terms of classifying the erosional activity and morphology of the sidewalls, Glen Reenen is the simplest of all six gullies. It is active and vertical along its entire length (Fig's. 4.32 and 4.33). The headwall is rounded in plan view and vegetated or S-shaped if viewed along its vertical profile. The form of the headcut, which is often an indicator of the processes operative (Stocking, 1980a), suggests that the resistant cap, formed by the binding

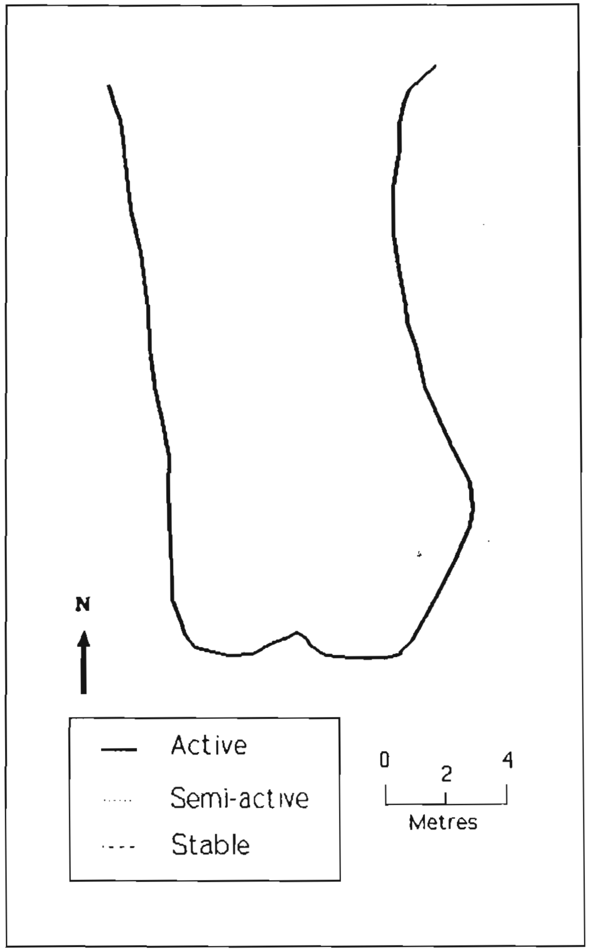

Fig. 4.32. Sidewall erosional activity in Glen Reenen gully.

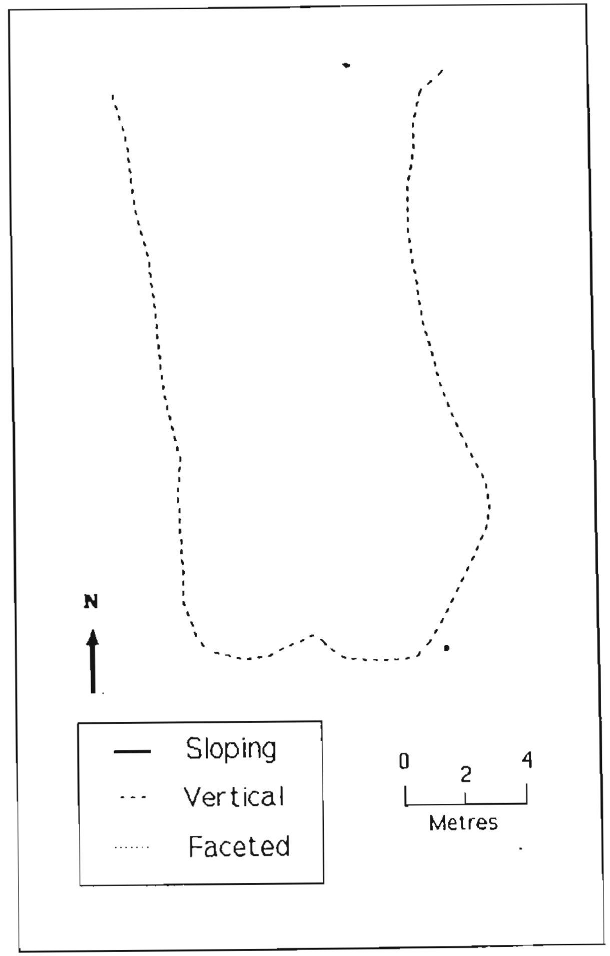

Fig. 4.33. Sidewall morphology in Glen Reenen gully.

action of the plant roots, is being undercut by spalling and sidewall wash (Fig. 4.34). The flow, which adheres to the underside of the vegetated lip by means of surface tension, flows down the lower section of the face, and in so doing undercuts it. The undermining of the overhang eventually results in the development of tension cracks, and ultimately in the collapse of the material. Consequently, the main headward erosion of Glen Reenen gully takes place below the vegetated A-horizon, where the least resistance is offered.

Fig. 4.34. Overhang of the headwall of Glen Reenen gully. Note the plant roots and the slumped material.

The side slopes of this gully are predominantly shaped by rainwash and spalling, while slumping, piping and waterfall/ plunge pool erosion were also observed. Rainwash has been described by Schumm (1956), as an eroding agent which attacks steep slopes with great energy, and in so doing removes material of almost uniform thickness. This process, together with spalling are the main processes responsible for the maintenance of the steep vertical sidewalls.

The phenomenon of piping, which is not exclusive to gully headward advance, but has also been recognized as a mechanism of sidewall erosion (Monteith, 1954; Parker, 1968; Stocking, 1976), was observed in the form of a small pipe outlet along the base of the western sidewall (Fig. 4.35). Although it currently appears to have little influence on the morphology of the sidewall, future enlargement and collapse of the pipe could considerably affect the morphology. As mentioned by Peterson (1954), the mere presence of a pipe makes a sidewall vulnerable to erosion.

Fig. 4.35. Pipe outlet at the base of the western sidewall.

Plunge pools, which have been found to decrease the stability of gully walls (Van der Poel and Schwab, 1988), are usually described in the literature in association with the headward extension of gullies, see for example the works of Leopold and Miller (1956); Hudson (1971); Ologe (1972); Bradford and Piest (1977); Bradford *et al.* (1978); Stocking (1980b) and Van der Poel and Schwab (1988). In this study, however, a plunge pool was noted along the right sidewall, towards the mouth of the gully. Here, the action of the plunge water has carved a niche out of the sidewall as well as a depression in the floor. Continual erosion by the plunge water serves to undermine the overhang above the niche, resulting in the development of tension cracks. When the driving forces of the soil equal or exceed the resisting forces the overhang collapses into the gully. The plunge pool water is then essential for the removal of the caved or slumped material on the gully floor. In instances where the slumped material is not removed from the depression in the floor, water gets dammed in the depression and in so doing, remains in contact with the sidewall material that much longer, thereby further saturating it. Consequently, slumping of this material is enhance as is undercutting.

The material removed from the headwall and sidewalls, by the above mentioned processes, has accumulated on the channel floor. What is evident from the accumulation of this debris is that the channel flow, which is the mechanism by which soil debris is removed from the gully system (Graham, 1984), is currently insufficient for gully "cleanout" (Piest *et al.*, 1975) to occur. As a consequence, a state of impeded removal exists. The sidewall cutting versus downcutting ratio's calculated (Table 4.20), however, indicate that this condition of impeded removal, as witnessed during field investigations, does not appear to constitute the norm, but that this is instead a transient phase.

Table 4.20. Ratio of sidewall cutting to downcutting, Glen Reenen gully.

Cross-section	Sidewall cutting (m^3)	Downcutting (m^3)	Sidewall cutting: downcutting ratio
1	12	12	1.0
2	2	23	0.1
3	11	16	0.7
MEANS	8.3	17.0	0.6

What is evident from the calculations and from Fig. 4.36 is that downcutting clearly dominates over sidewall cutting at cross-section two, and to a lesser extent at cross-section three. The accumulation of the basal debris observed in the field can perhaps be explained by the fact that the field investigations of this gully took place during the winter months when available runoff was insufficient to flush out the gully.

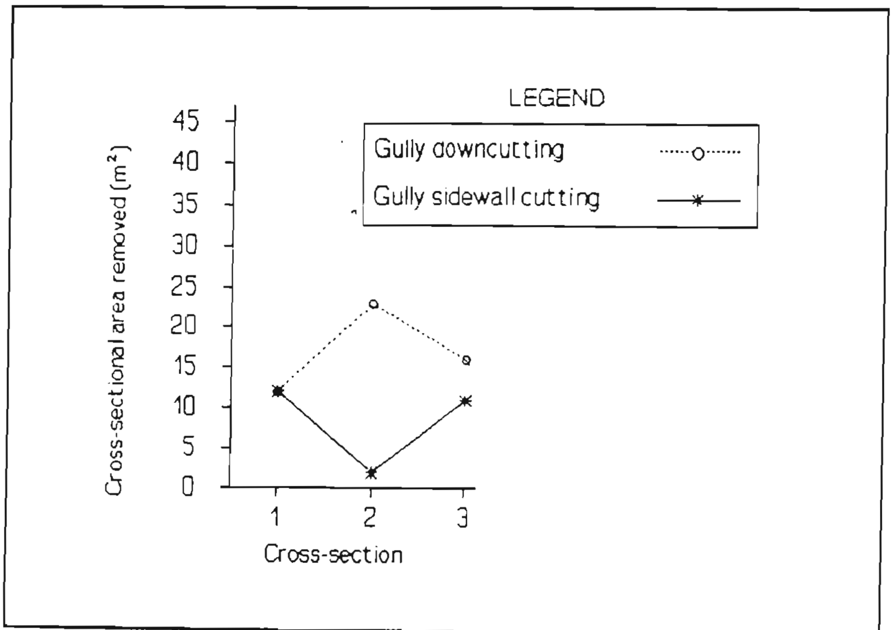

Fig. 4.36. Gully sidewall cutting compared with gully downcutting at each cross-section, Glen Reenen gully.

During the summer months when the intensity and duration of rainstorms are greater, the debris is removed by the first few runoff events. Once the debris has been flushed out of the gully the subsequent runoff events result in basal scour which dominates over sidewall erosion. This gully thus appears to follow the erosion/failure/scouring cycle as described by Hannam (1983). On average gully downcutting contributes 67% of the total volume of sediment removed.

No special features such as animal tracks, rock outcrops or trees were noted in association with the headwall, sidewalls or gully floor.

In short, Glen Reenen is characterized by a relatively consistent long profile and cross-sections as a result of the homogeneity of the material into which it has incised. Growth of the gully follows a cycle of erosion/failure/scour with downcutting as the dominant means of increase in the gully area. Based on the shape factors, the vertical and active sidewalls and headwall, and the processes operative, Glen Reenen is seen to be in a youthful stage of development. It is predicted that it will continue to be active for some time before it begins to stabilize.

4.5. Camp gully

Camp gully is typologically classified as shown in Table 4.21.

Table 4.21. Typological classification of Camp gully.

Form	Location	Type	Surface morphology
Linear	Valley-side	Type 2	Continuous

Classifying the form of this 120m long gully was problematic because, in none of the six forms described by Ireland *et al.*

(1939) is mention made of gullies which have distributaries extending off from the main channel. Mention is made only of tributaries entering the main channel. If the plan view of this gully is examined in Fig. 4.37 it can be seen that almost midway along the gully a branch extends off to the right (looking upslope) of the main channel. Both the main channel and this distributary are essentially long and narrow in form, hence the decision to classify it as a linear gully.

The longitudinal profile, which is broken by a channel scarp in the upper reaches, is concave in the downslope direction (Fig. 4.37). From a depth of about 1m at the channel mouth, the gully is cut progressively deeper in the upslope direction. This increase in depth is accompanied by an increase in width although this increase is not progressive (Table 4.22). The resulting slight fluctuation in the width:depth ratio gives some indication that Camp gully is still an unstable channel.

Table 4.22. Morphometric parameters recorded along the main channel at each of Camp gully's cross-sections.

Cross-section	Bed width (m)	Bank width (m)	Maximum depth (m)	Mean depth	Width: depth ratio	Bank width: bed width ratio	Shape factor
1	4.0	18.0	5.1	2.6	3.5	4.5	2.0
2	3.2	20.0	4.7	2.0	4.3	6.3	2.3
3	5.5	11.8	3.1	2.2	3.8	2.1	1.4
4	8.4	12.8	1.3	0.9	9.8	1.5	1.4
MEANS	5.3	15.7	3.6	1.9	5.4	3.6	1.8

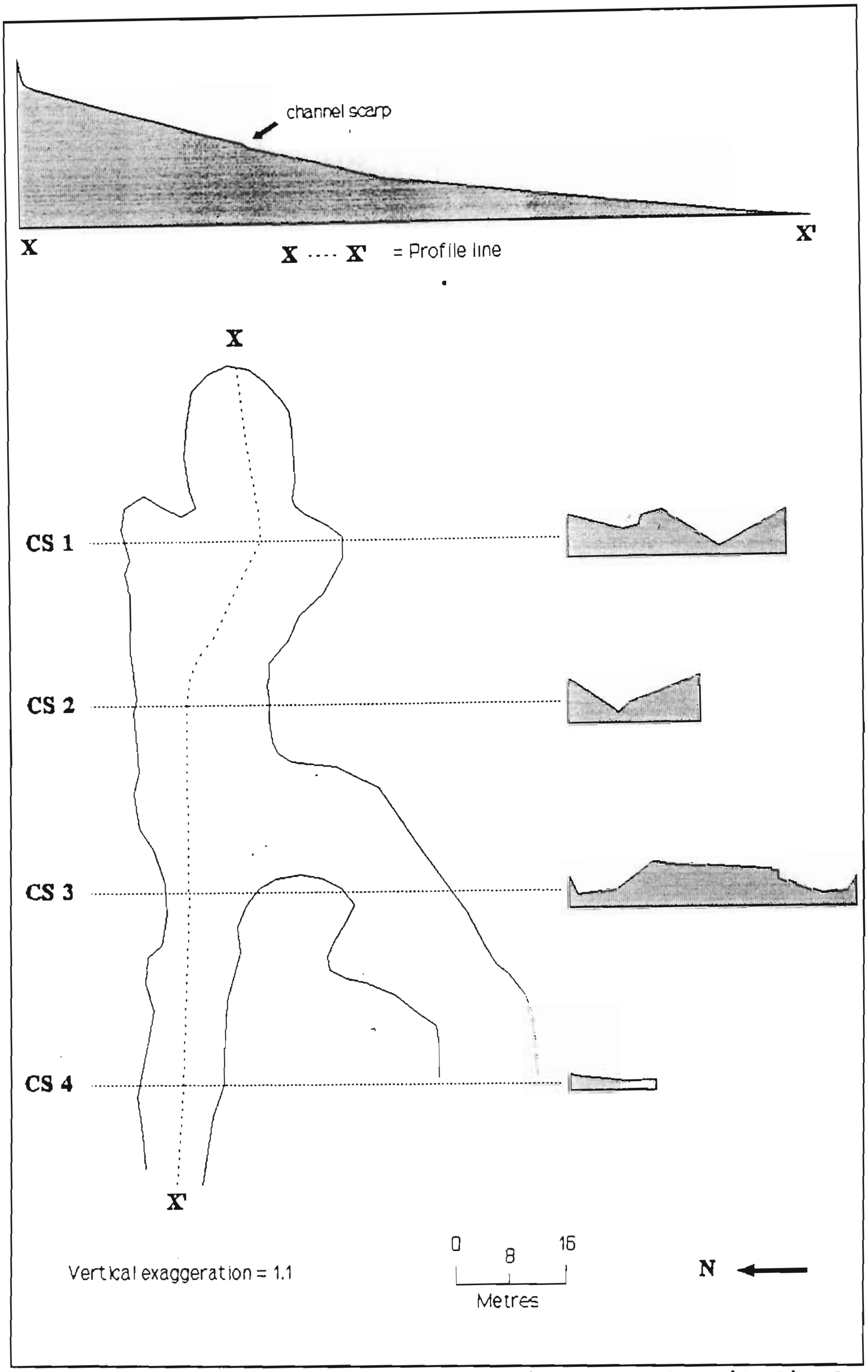

Fig. 4.37. Plan view, cross-sections and longitudinal profile of Camp gully.

On the basis of cross-sectional shape, the gully can be divided into an upper and lower section. The upper section (cross-sections one and two) is characterized by V-shaped cross-profiles (shape factor values of 2.0 and 2.3 respectively, see Table 4.22), while the lower section (cross-sections three and four) is characterized by U-shaped cross-profiles (both having shape factors of 1.4).

From the results of the linear regression analysis (r^2 = 0.55) it can be seen that the material in which Camp gully has incised exerts an influence on the shape of the cross-sections. Table 4.23 and Fig. 4.38 clearly indicate that the increase in the width:depth ratio conforms with the decrease of the average percent silt-clay (M) in the measured load.

Table 4.23. Gully morphometric and sediment data, Camp gully.

Cross-section	Bank width (m)	Maximum depth (m)	Width:depth ratio	% silt-clay in bank	% silt-clay in bed	"M"
1	18.0	5.1	3.5	41.2	32.0	35.0
2	20.0	4.7	4.3	41.7	bedrock	-
3	11.8	3.1	3.8	40.8	30.0	33.7
4	12.8	1.3	9.8	39.5	32.0	33.2

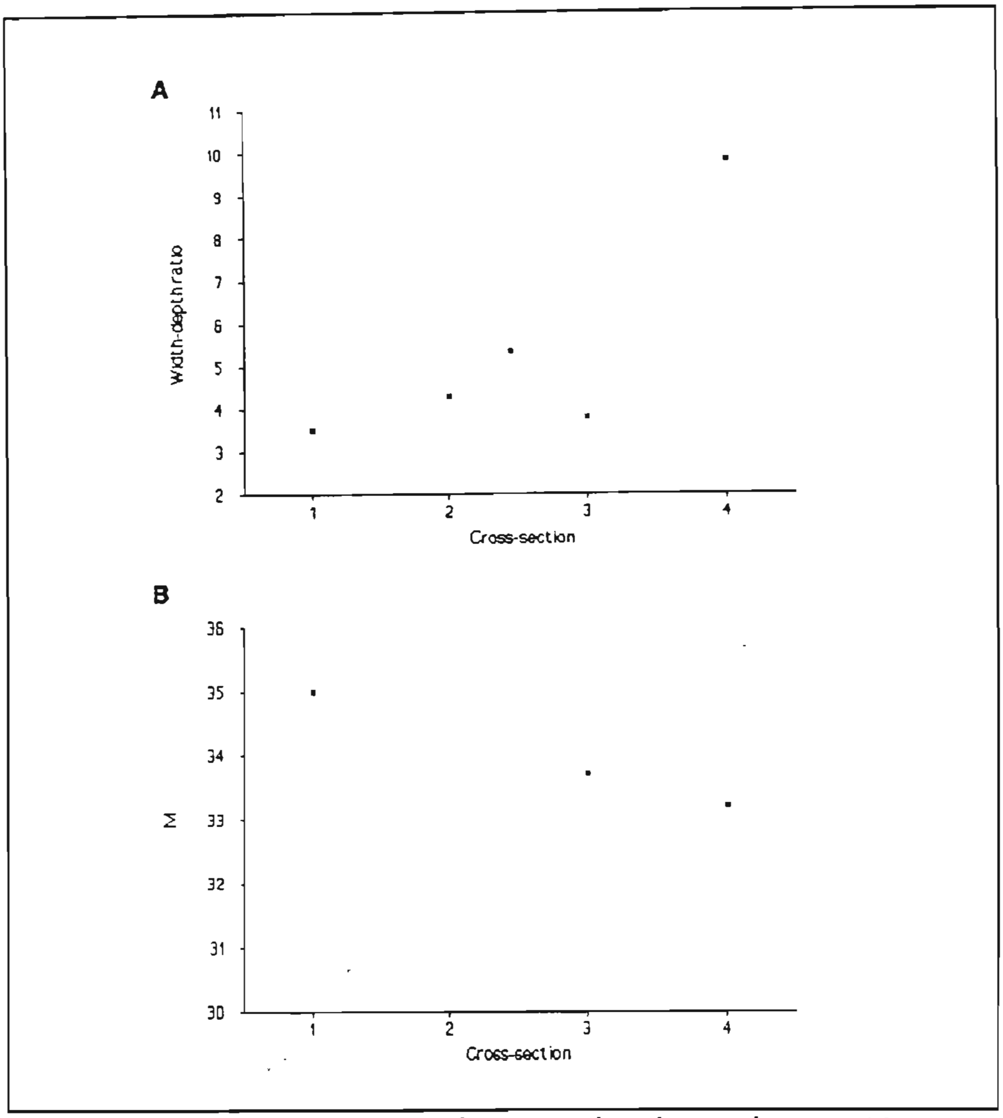

Fig. 4.38. Graphs showing variations in A: the width:depth ratio and B: M or weighted mean silt-clay percent along Camp gully.

Results of the linear regression analysis correlating certain cross-sectional parameters with distance along the thalweg (Table 4.24), reveal that the cross-sectional and longitudinal variables are not orthogonal but that a great amount of interdependence exists between them. Maximum depth, which shows the strongest correlation with thalweg distance, decreases progressively with distance downslope, while the other parameters tend to fluctuate slightly in the downslope direction (Table 4.22) thereby accounting for the lower correlations. The relatively strong correlation between distance along the thalweg and width:depth ratio is in support of the "M" versus width:depth ratio findings.

Table 4.24. Results of the linear regression analysis, Camp gully.

Parameters	r^2
Maximum depth	0.93
Mean depth	0.75
Bank width	0.59
Width:depth ratio	0.63
Shape factor	0.60

The distinction between the upper and lower gully cross-sections is not only apparent in terms of cross-sectional shape but also in terms of the erosional characteristics of the channel flow. The flow, which has a relatively straight course i.e. sinuosity index of 1.3, is actively eroding in the upper section and in some places has cut down onto bedrock. On the other hand, the flow in the lower section is depositing material along its reach. The role played by the exposed bedrock on the channel floor is apparent just above cross-section two, where an outcrop has resulted in the formation of a channel scarp (Fig. 4.37 and Fig. 4.39). The increase in basal scouring at cross-section two, as evidenced by the decrease in the bed width (Table 4.22), and the cutting of the gully down to bedrock, can be attributed to the scarp because, the action of a plunge pool at the base of a channel scarp is known to have the effect of deepening a channel (Leopold and Miller, 1956). Besides this, however, the overall effect of the scarp on the gully appears to be negligible.

Fig. 4.39. Channel scarp caused by an outcrop of bedrock occurring just above cross-section two of Camp gully.

A noticeable feature of Camp gully is the number of trees growing along the channel floor (see Fig. 4.41). These trees appear to have little stabilizing effect on the gully for the area supporting the greatest density viz, between cross-section one and two, is actively eroding. As has been mentioned before the black wattle, which is the dominant species occurring in this gully, is an exotic and invasive species. If these trees are not removed (contrary to the current management strategy employed within the Park), then perhaps, with an increase in size, their stabilizing effect may be felt.

Since this gully is topographically located on a spur little water flows over the sidewalls. Consequently, the side-slopes, which are largely active (Fig. 4.40), are shaped mainly by processes of rain wash down the sidewalls, rilling and slumping. Together these processes are responsible for maintaining the vertical sidewalls, and where the channel flow fails to remove the slumped debris, the faceted sidewalls (Fig. 4.41). Subsurface flow in the form of piping was also noted as a process occurring along the sidewalls. An inlet pipe (Fig. 4.42), was observed on the central island between the main channel and the distributary. The reason for classifying it as an inlet pipe, and not as roof collapse or a shaft (cf. Ward, 1966), is because no other inlet could be found. The outlet was found along the left wall of the distributary which itself is seen to be the result of piping erosion. This was inferred from the way in which it has developed over the 39 year period i.e. it began its development as a discontinuous gully (1952). By 1984 the headwall had migrated upslope and merged with the main gully (Fig. 4.43). Based on the interpretation of the aerial photographs its development and subsequent upslope, as well as downslope migration appears to be the result of piping.

On the basis of the gully's topographic location (i.e. on a spur), its form, particularly the development of the distributary, and the manner in which it has extended over the past 39 years (Fig. 4.43), it is felt that the observation of this single pipe inlet and outlet underestimates the extent to which this process is active. Field evidence is currently the missing supporting factor but may be provided in future in the form of tunnel collapse, because piping, which by its very nature is insidious (Stocking, 1976) often only becomes apparent once tunnel collapse has occurred.

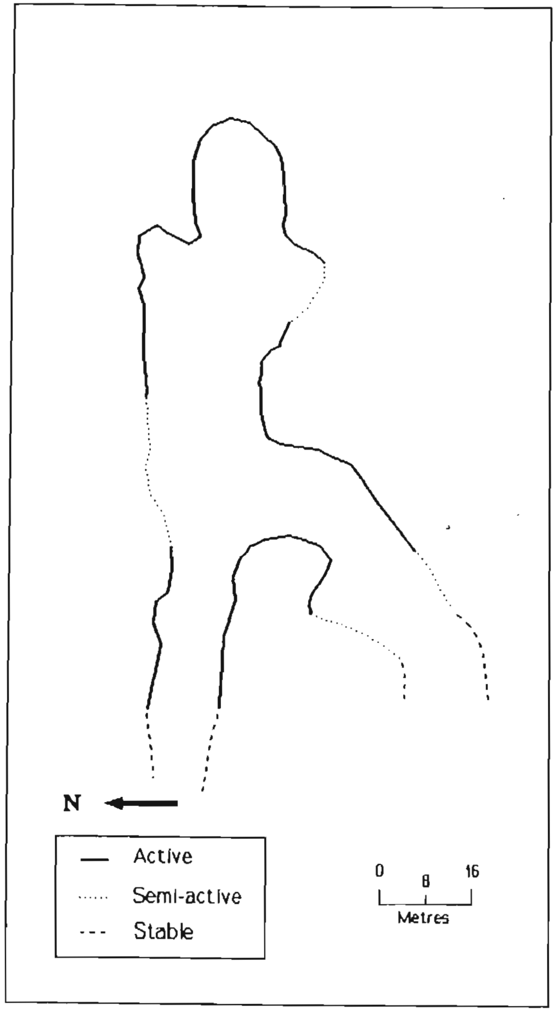

Fig. 4.40. Sidewall erosional activity in Camp gully.

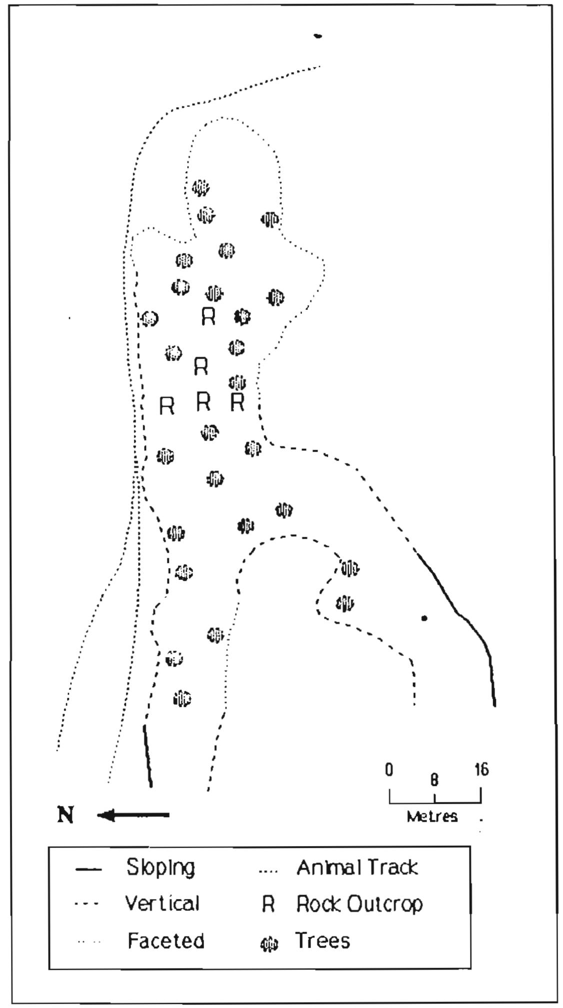

Fig. 4.41. Sidewall morphology and special features in Camp gully.

Fig. 4.42. Close up view of the pipe inlet which is 1m by 2m across and roughly 4m deep.

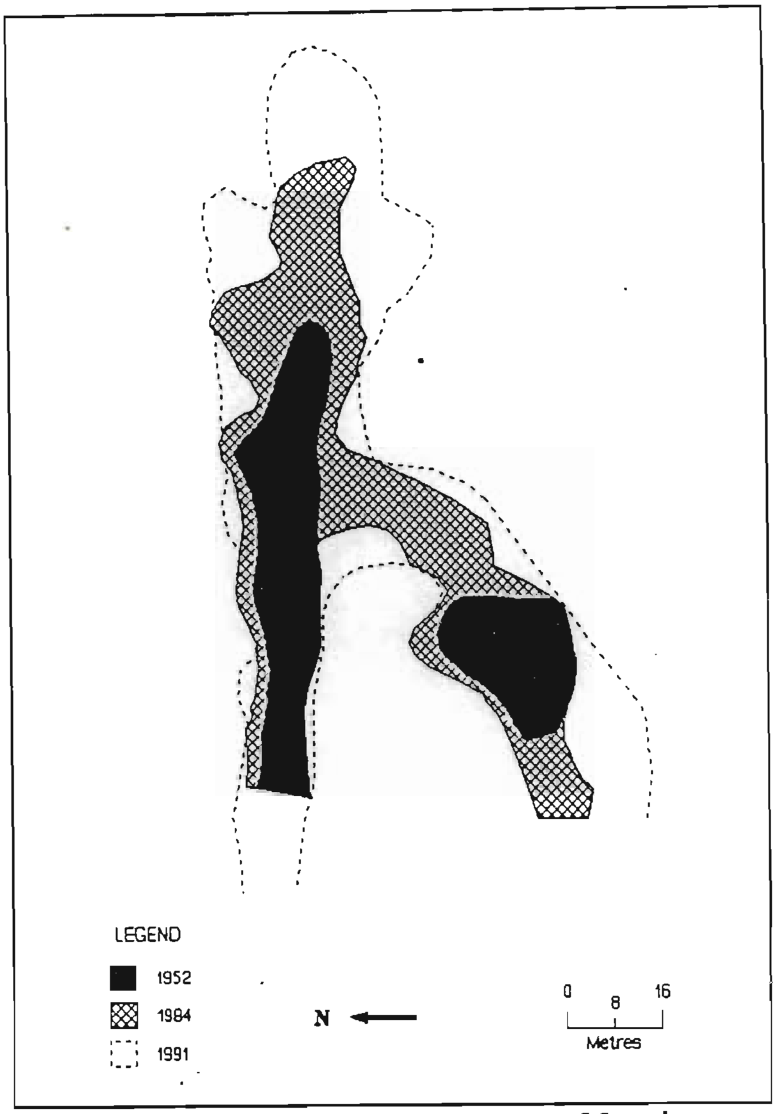

Fig. 4.43. Extent of Camp gully in 1952, 1984 and 1991.

The two animal tracks, which join to form a single track along the left sidewall of the main gully (Fig. 4.41), appear not to influence the erosional activity of the gully at present. If, however, the sidewall and headwall extend, these tracks could play a more active role by promoting slumping for example.

The contribution made by the sidewalls to total sediment production in Camp gully is 59%. Much of this comes from the sidewalls located near the gully headwall for downslope the from the headwall the importance of sidewall erosion decreases (Table 4.25 and Fig. 4.44).

Table 4.25. Ratio of sidewall cutting to downcutting, Camp gully.

Cross-section	Sidewall cutting (m^3)	Downcutting (m^3)	Sidewall cutting: downcutting ratio
1	31	15	2.1
2	27	13	2.1
3	12	14	0.9
4	2	9	0.2
MEANS	18.0	12.8	1.3

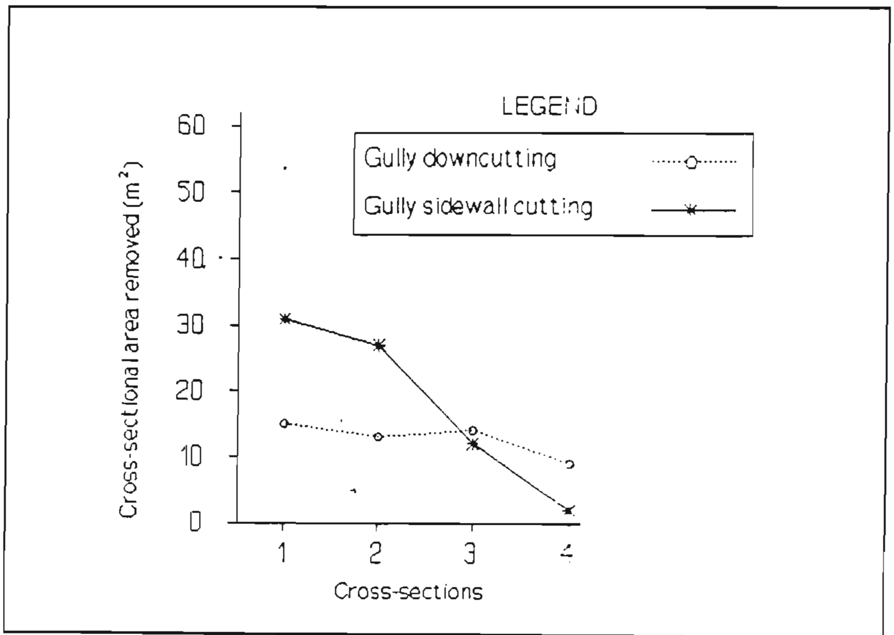

Fig. 4.44. Gully sidewall cutting compared with gully downcutting at each cross-section, Camp gully.

The headwall, which is rounded in shape, is active and faceted (Fig. 4.40 and Fig. 4.41) and is migrating upslope as a result of surface runoff and slumping. Waterfall erosion and piping were not observed along this headwall.

From the above discussion of Camp gully it is evident that it can be divided into an upper and lower section on the basis of channel shape and channel floor erosion. The results of the linear regression analyses show that the material in which Camp gully has incised exerts quite a strong influence on the shape of the channel and that there exists a strong interdependence between the cross-sectional and longitudinal variables. The distributary extending off the main channel has added another dimension to classifying gullies - one which as yet has not been taken into account when classifying gullies on the basis of form.

4.6. Noord Brabant gully

Noord Brabant which is 160 metres long, is a continuous first order gully. Topographically it is located on a valley-side where it receives its principal source of runoff in the form of overland flow. It is bulbous in form (Fig. 4.45 and Fig. 4.46), with U-shaped cross-sections (Fig. 4.45), and thus is classified as shown in Table 4.26.

Table 4.26. Typological classification of Noord Brabant gully.

Form	Location	Type	Surface morphology
Bulbous	Valley-side	Type 2	Continuous

Although it is bulbous in form, being broad and spatulate in the upper reaches with a semicircular-shaped head, it does not tend to narrow downslope as Ireland *et al.* (1939) suggest may occur, but instead extends laterally across the slope. This lateral expansion, which is seen as a product of the contour banks built by the farmer who owned the land prior to its incorporation into the Park in 1981, has given rise to the formation of a series of parallel rills. As a result of this Noord Brabant can be classified as a gully system comprised of a main channel with a series of adjacent

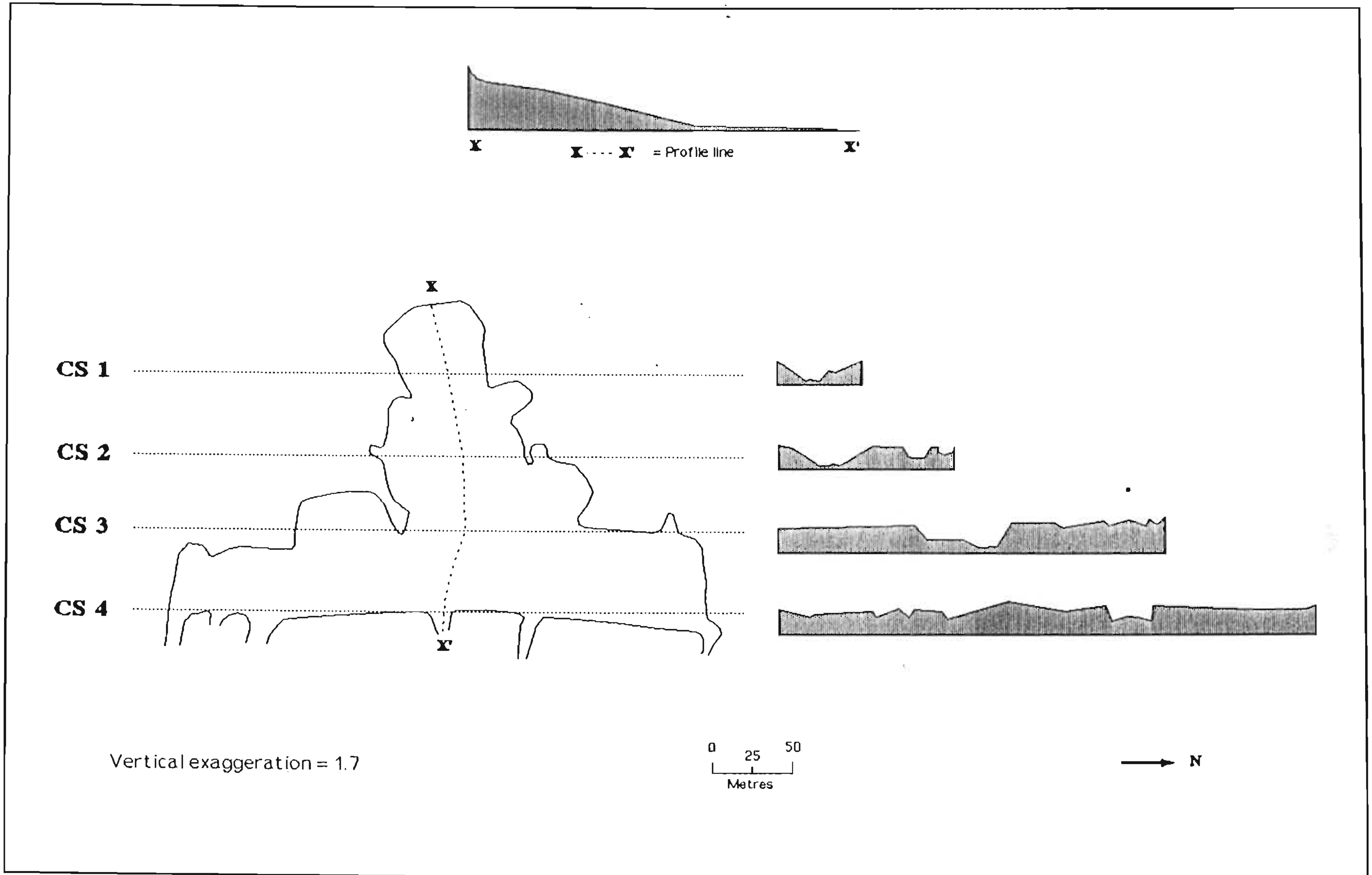

Fig. 4.45. Plan view, cross-sections and longitudinal profile of Noord Brabant gully.

Fig. 4.46. Oblique view of Noord Brabant gully taken in 1988 showing its bulbous form and lateral expansion across the slope. Note the retaining walls (Source: G. Groenewald).

parallel rills.

This gully begins its main course with a sloping active headcut and is terminated where the gully mouth intersects the valley slope in the form of an alluvial fan. The flow of the main channel maintains a straight course downslope having a sinuosity index of 1.1. The long profile of this channel is concave at the headwall but exhibits a weak convexity in the downslope direction where it flattens out towards the gully mouth (Fig. 4.45).

The cross-sectional parameters measured along the main channel, tend to fluctuate downslope, with the exception of bed width, which displays a progressive increase (Table 4.27). Shape factor values calculated vary between 1.8 and 1.3 with a mean value of 1.6. The cross-sections are thus essentially U- or parabolic in shape and are hydraulically efficient.

Table 4.27. Morphometric parameters recorded along the main channel at each of Noord Brabant gully's cross-sections.

Cross-section	Bed width (m)	Bank width (m)	Maximum depth (m)	Mean depth	Width:depth ratio	Bank width: bed width ratio	Shape factor
1	7.5	37.3	5.9	3.5	6.3	5.0	1.7
2	8.8	39.8	5.7	3.1	7.0	4.5	1.8
3	9.3	39.5	7.1	4.7	5.6	4.2	1.5
4	15.5	20.0	4.1	3.1	4.9	1.3	1.3
MEANS	10.3	34.2	5.7	3.6	6.0	3.8	1.6

Results of the linear regression analysis which correlate five of the main channels cross-sectional parameters with distance along the thalweg, reveal that maximum and mean depth are extremely poorly correlated with the longitudinal variable while the remaining three variables exhibit moderate correlations (Table 4.28). Consequently, some inter-dependency exists between distance along the thalweg and the width variables but not the depth variables.

Table 4.28. Results of the linear regression analysis, Noord Brabant gully.

Parameters	r^2
Maximum depth	0.17
Mean depth	0.001
Bank width	0.50
Width:depth ratio	0.64
Shape factor	0.55

The influence that the material, into which Noord Brabant has incised, exerts on the shape of the cross-sections of the main channel, was illustrated by linear regression analysis. The result indicates a moderate correlation i.e. $r^2 = 0.57$. What is interesting to note, however, is that the results of the textural analysis of the soil samples collected (Table 4.29 and Fig. 4.47), reveal that as the percent silt-clay (M) decreases downgully so too does the width:depth ratio. This is contrary to the findings of Schumm (1960a, 1960b; 1961) and suggests other factors play a more dominant role in determining cross-sectional shape.

Table 4.29. Gully morphometric and sediment data, Noord Brabant gully.

Cross-section	Bank width (m)	Maximum depth (m)	Width: depth ratio	% silt-clay in bank	% silt-clay in bed	"M"
1	37.3	5.9	6.3	25.8	bedrock	-
2	39.8	5.7	7.0	25.7	26.0	25.9
3	39.5	7.1	5.6	25.7	26.0	25.9
4	20.0	4.1	4.9	22.8	20.0	20.8

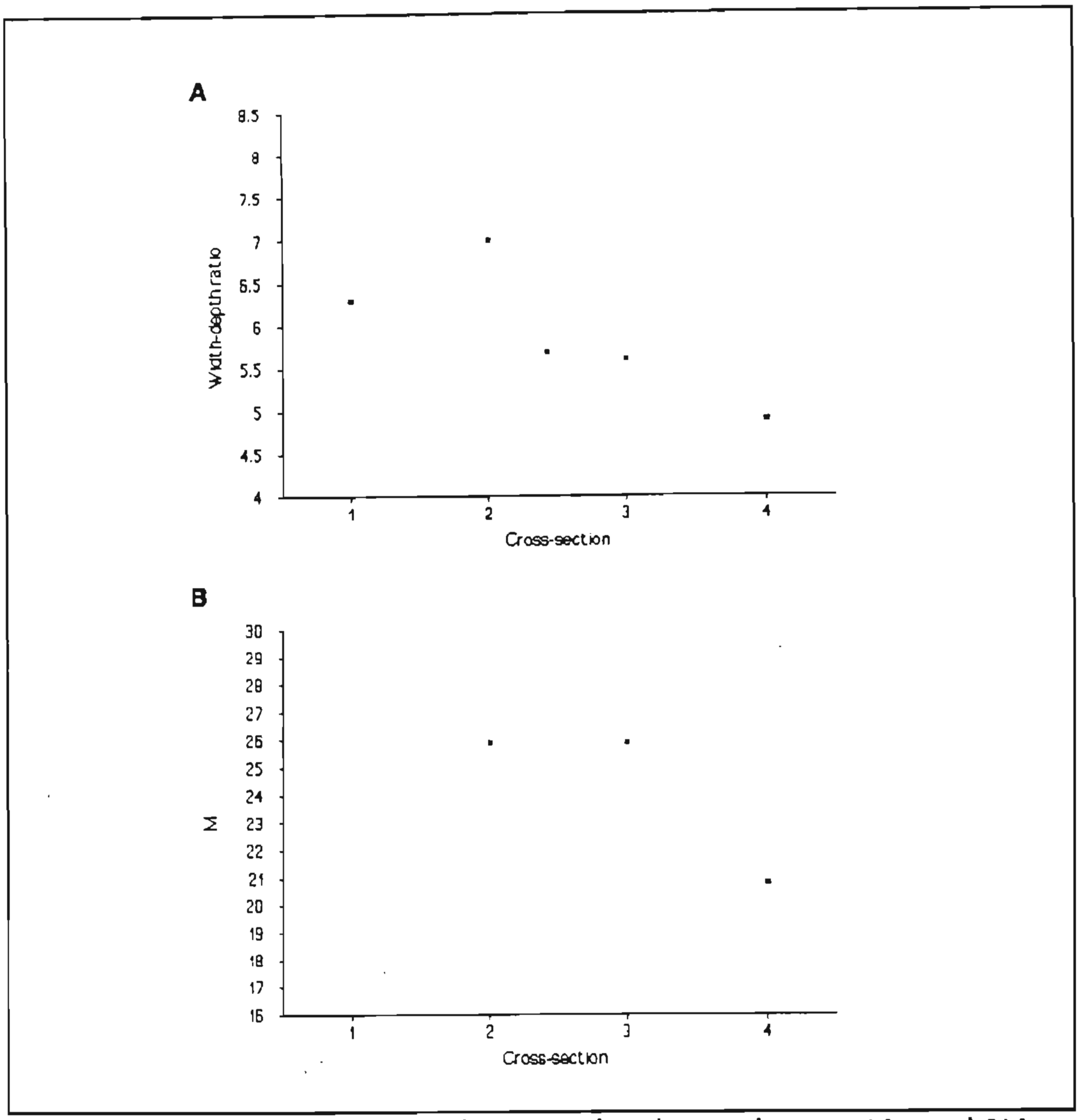

Fig. 4.47. Graphs showing variations in A: the width: depth ratio and B: M or weighted mean percent silt-clay along the main channel of Noord Brabant gully.

Classification of the erosional activity and morphology of the gully systems sideslopes (Fig. 4.48 and Fig. 4.49), show them to be both active and vertical. The dominant processes responsible for maintaining their active and vertical state are rainwash and failure by bank undercutting, cracking and slumping (Fig. 4.50 and Fig. 4.51). Waterfall erosion was also noted to be occurring at two points along the sidewalls but is not regarded as a dominant process.

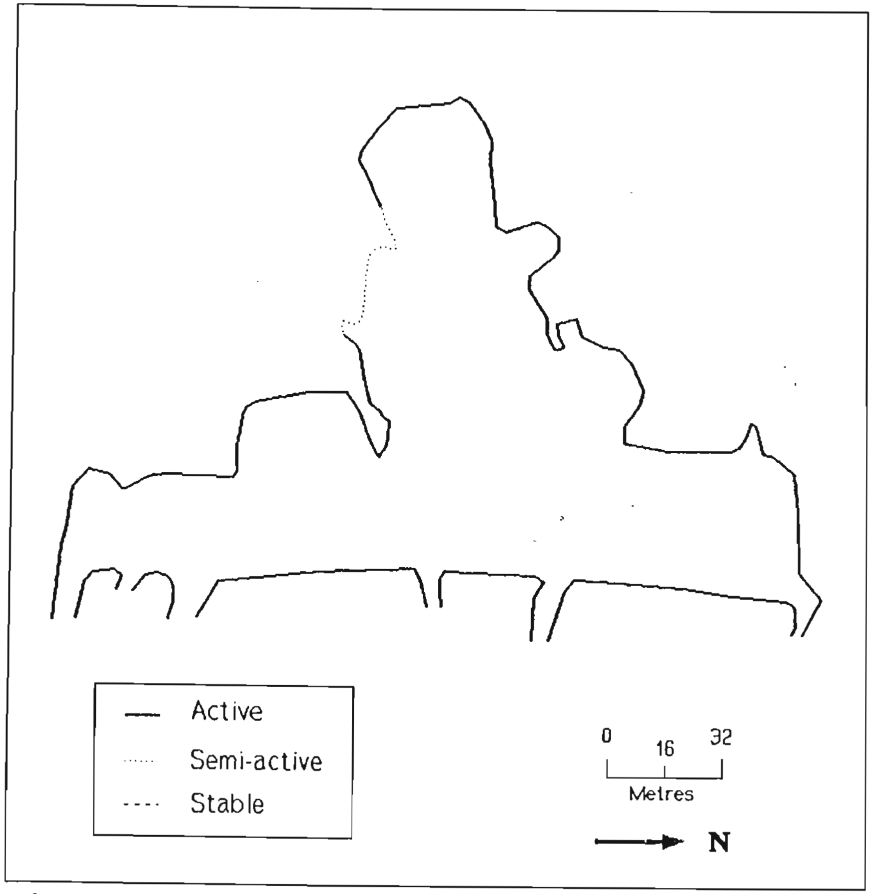

Fig. 4.48. Sidewall erosional activity in Noord Brabant gully.

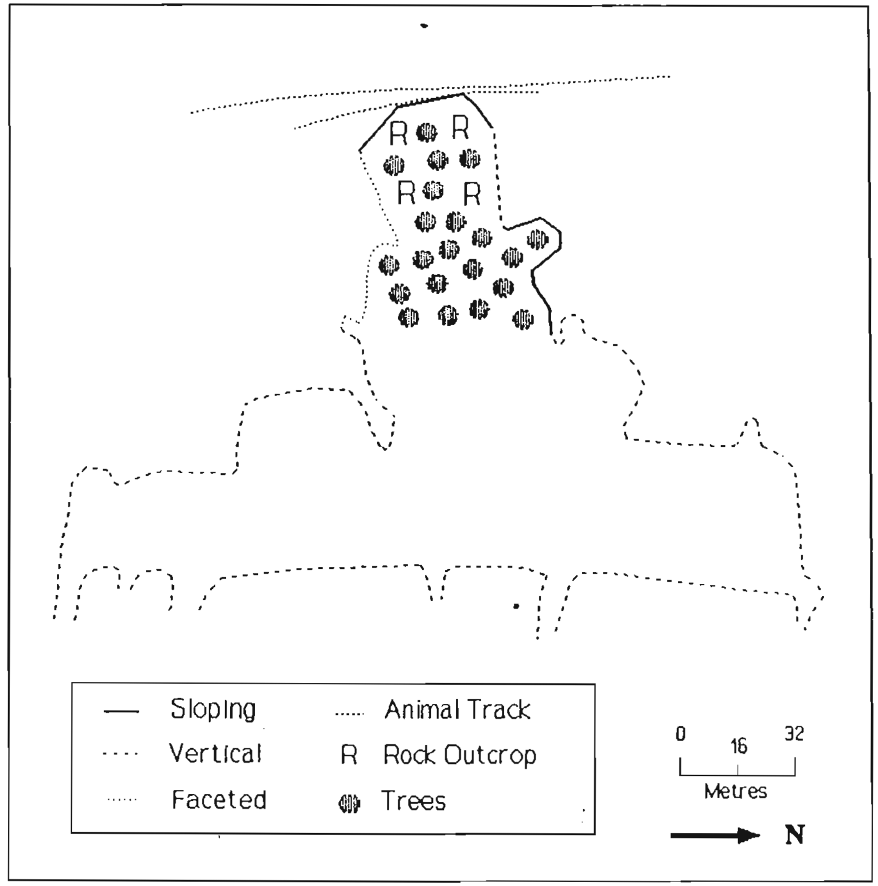

Fig. 4.49. Sidewall morphology and special features in Noord Brabant gully.

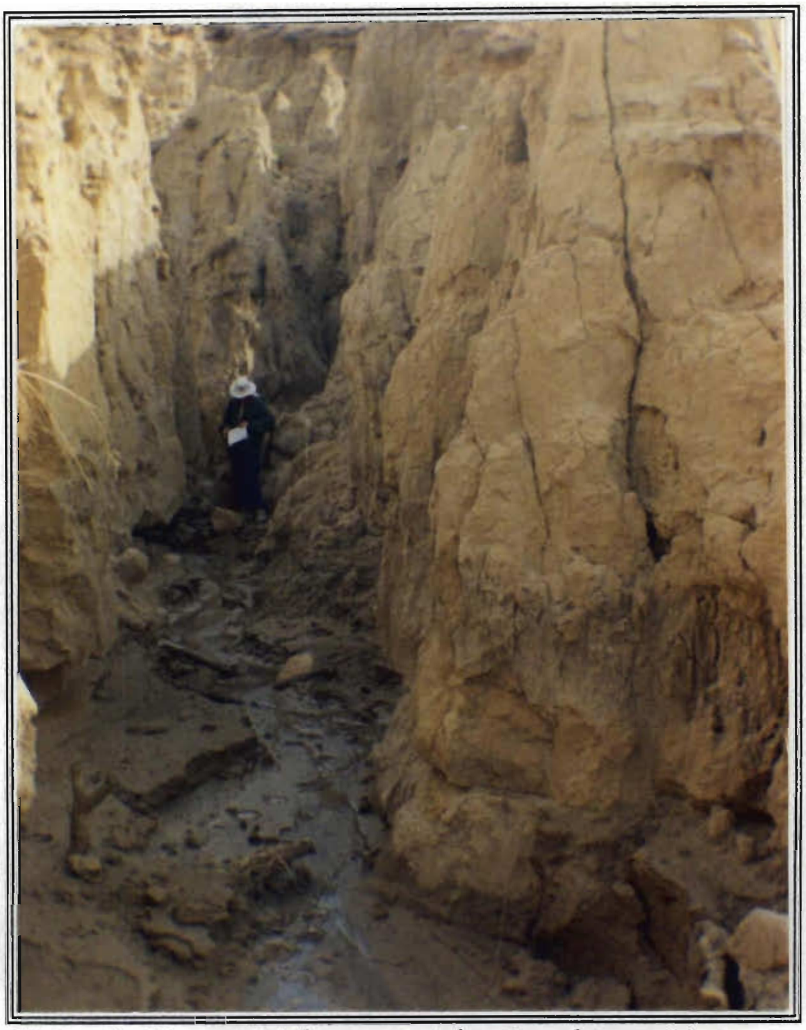

Fig. 4.50. Active vertical sidewalls exhibiting processes of rainwash, cracking and undercutting. Note the evenness of the undercutting.

Fig. 4.51. Massive sidewall slumping.

The contour banks which were built in an attempt to halt the erosion process (Burls, 1992, pers. comm.) have in actual fact enhanced, and in some instances been the cause of increased, sidewall erosion. This being caused mainly by the banks having altered the flow regime of the gully. The way in which these banks have altered the flow regime, and thereby influenced the sidewall as well as gully floor processes, is by allowing the build up of concentrations of water on the surface and by forcing the natural downslope flow of discharge from the main channel to flow instead across the slope. The lateral flow of water causes undercutting of the banks which together with saturation of the soil at the base of the banks (caused by the build up of water) has resulted in slumping and weakening of the banks at numerous points (Fig. 4.52). It is at these points of weakness that the flow eventually breaks through and continues its downslope course (Fig. 4.53). The breaking through of flow at various points along the banks has given rise to the numerous parallel rills and the development of localized badland topography (Fig. 4.54). It is as a consequence of this induced change in the flow regime that Noord Brabant has evolved into what is termed a gully system.

Fig. 4.52. Slumping at the base of a contour bank caused by soil saturation and undercutting.

Fig. 4.53. Point of weakening along the contour bank through which the flow has broken.

Fig. 4.54. Numerous channels which have broken through the contour bank have resulted in parallel rilling and localized badland topography.

Although the building of the contour banks in this gully have exerted a different influence on the processes operative to that described by Stocking (1976) in Zimbabwe and Baillie *et al.* (1986) in Tunisia (in these instances they promoted tunnelling), proof has none the less been provided that their implementation can actually be far more detrimental than beneficial. Furthermore, they provide a classic example of a situation where processes have changed human activities and human activities have altered processes (Stocking, 1992, pers. comm.).

The extent to which the contour banks have influenced the erosion processes in Noord Brabant gully is evident in Fig. 4.55. This figure shows the vast increase in degraded area, particularly lateral expansion, between the 1952 and 1984 period. Inspection of the aerial photographs taken during the 1952-1984 period viz. 1962, 1969 and 1978, reveal however, that it was not until 1978 that this dramatic increase evident. Consequently, the increase in degraded area of almost 7000m², did not occur gradually over the 32 year period, but rather occurred over only the last ten or so years of this period and occurred as a direct consequence of the contour banks.

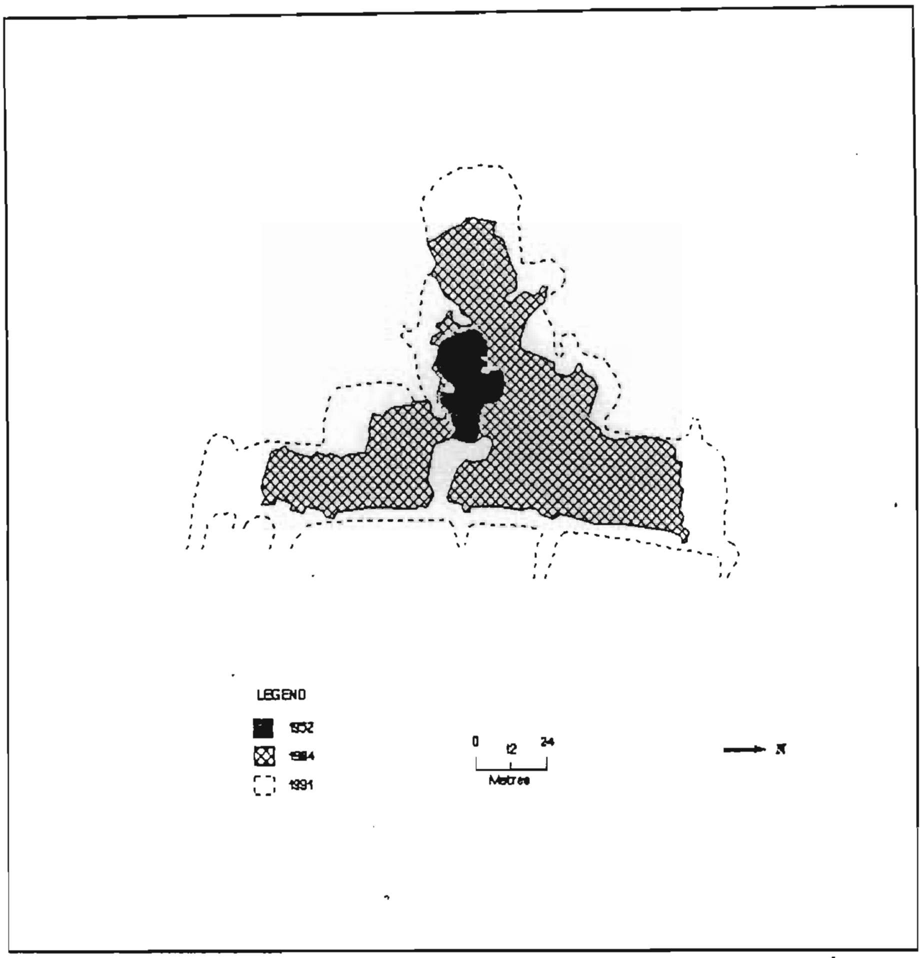

Fig. 4.55. Extent of Noord Brabant gully in 1952, 1984, 1991.

Two basal endpoint control states were observed in this gully. At the base of the headwall the amount of debris which is delivered to the gully is in excess of that which the channel flow can remove. Consequently a state of impeded removal exists here. Excess basal capacity was, however, observed to be the dominant basal endpoint control state in the rest of Noord Brabant gully. Despite this being the case at the time the gully was investigated, field observations suggest that the state of excess basal capacity appears to alternate with periods during which impeded removal dominates. This implies that basal endpoint control does not represent a steady state, but rather one which fluctuates, depending on the availability of material and the velocity of channel flow. These, in turn, are seen to be controlled (as was found for Glen Reenen gully) by seasonal fluctuations.

The large number of trees growing on the channel floor between the headwall and cross-section two (Fig. 4.49) appear, as they do in Camp gully, to have little influence on the erosional activity of the gully as they do not appear to be supporting the soil.

The ratio of sidewall erosion to downcutting was calculated for the main gully channel to get some idea of which of the two dominate (Table 4.30). Table 4.30 and Fig. 4.56 show that sidewall cutting dominates in the upper reaches of the gully but decreases in importance downslope. On average sidewall erosion accounts for 51% of the volume of sediment removed from Noord Brabant gully.

Table 4.30. Ratio of sidewall cutting to downcutting, Noord Brabant gully.

Cross-section	Sidewall cutting (m^3)	Downcutting (m^3)	Sidewall cutting: downcutting ratio
1	78	51	1.53
2	66	59	1.12
3	95	92	1.03
4	18	44	0.41
MEANS	64.3	61.5	1.02

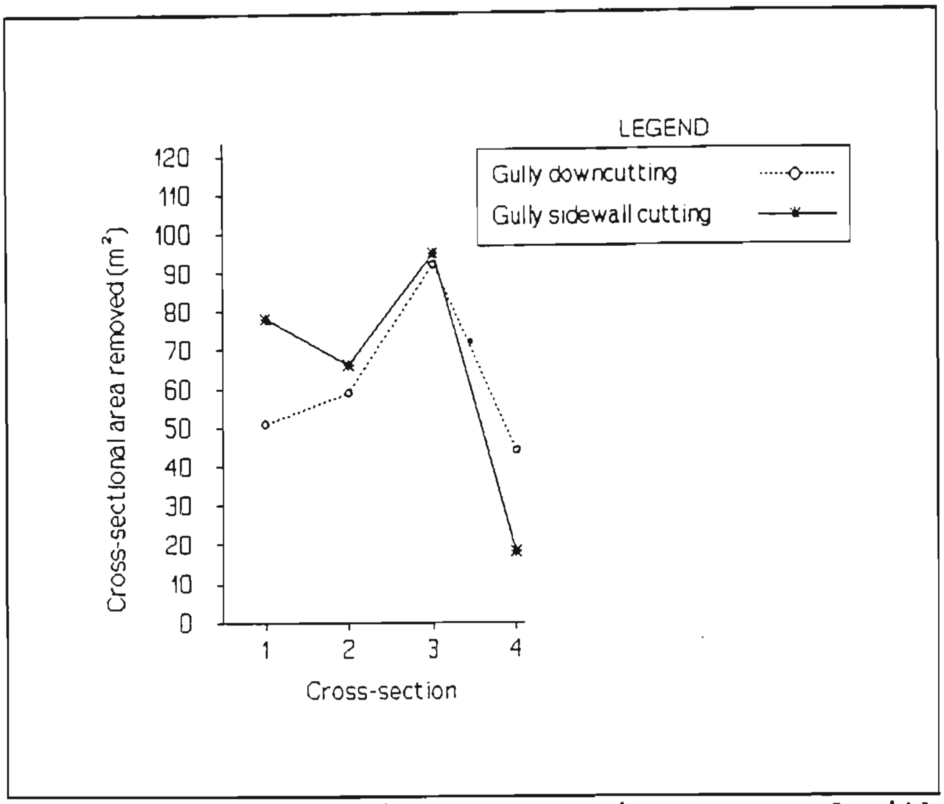

Fig. 4.56. Gully sidewall cutting compared with gully downcutting at each cross-section along the main channel, Noord Brabant gully.

The headwall, which has eroded onto bedrock, is rounded in plan view and inclined in profile. The dominant processes observed to be occurring at the headwall were sheetwash and slumping. Slumping was observed to be the result of two factors. On the one hand, it is caused by overland flow which on entering the gully undercuts the B-horizon material until such time as there are little more than vegetated tufts left on the bedrock surface. These tufts are eventually transported down onto the channel floor by surface runoff. On the other hand slumping was noted to be caused by animal tracks. These tracks are situated so close to the edge of the headwall (Fig. 4.49) that the compaction of the soil and the vibrations caused by the passing animals cause the soil to slump away.

In summarizing the observations concerning Noord Brabant it can be said that it is still actively eroding with predominantly active and vertical sidewalls. The active but sloping headwall has reached its ultimate extension having eroded back onto bedrock. A remarkable feature of this gully is its lateral extension across the slope and the consequent development of an irreversible degraded condition of localized badland topography. This condition is seen to be the product of the contour banks which altered the flow regime and hence have led to the classification of Noord Brabant as a gully system.

An overview of each of the six gullies has been provided, highlighting their individual typological and morphological characteristics. The relationships between their morphometric properties and the temporal differences of these gullies are examined in the following chapter.

CHAPTER FIVE

ANALYSIS AND EVALUATION OF THE MORPHOMETRIC PROPERTIES AND TEMPORAL DIFFERENCES OF THE GULLIES

The discussion so far has focused primarily on describing the morphometric parameters of the individual gullies. To aid in interpreting the quantitative data principal component analysis and canonical variate analysis were undertaken: principal component analysis being undertaken to highlight the relationships that exist between the morphometric variables, whereas canonical variate analysis highlights the similarities or differences that exist between the gullies.

5.1. Principal component analysis

The result of the principal component analysis presented in Table 5.1 indicates that most of the gully morphometric parameters are strongly interrelated. Of the 36 correlation coefficients, only 6 (17%) are not significant at the 1% level. This finding suggests the existence of a steady state of adjustment between the form elements of the gullies. Similar observations were made by Thompson (1964) and Ebisemiju (1989), but unlike Ebisemiju's results, the longitudinal variable and cross-sectional variables of the gullies in this study are not orthogonal, but are strongly interdependent. This finding thus supports those of the linear regression analysis which correlated distance along the thalweg with the maximum depth, mean depth, bank width, width:depth ratio and shape factor values of each gully. The only variable to have low correlations with most of the morphometric properties is shape factor. Consequently, the correlation matrix reveals a strong but complex relationship between the morphometric properties of the gullies. In order to get a clearer indication of the relationships, the data set was reduced. In this analysis the cumulative percentage eigenvalues indicate that the first two components explain 88.92 percent of the total variation in the data (Table 5.2). Thus, instead of the data being examined in terms of all nine variables, it need only be examined in terms of two principal components.

Table 5.1. Principal component correlation coefficients[1] of gully morphometric properties[2].

	L	Wb	Ws	Dmax	Dm	W/Dm	Ws/Wb	Sf	A
L									
Wb	0.57								
Ws	0.91	0.84							
Dmax	0.82	0.52	0.82						
Dm	0.63	0.66	0.77	0.90					
W/Dm	0.83	0.78	0.90	0.52	0.45				
Ws/Wb	0.91	0.35	0.79	0.76	0.56	0.74			
Sf	0.65	-0.21	0.30	0.52	0.12	0.22	0.66		
A	0.90	0.81	0.98	0.89	0.83	0.82	0.77	0.37	

[1] Correlations which exceed 0.42 are significant at the 1% level.
[2] For notations, see Table 5.2.

Table 5.2. The two principal components.

Variables	Principal components	
	1	2
Length (L)	-0.37	-0.20
Mean bed width (Wb)	-0.29	0.52
Mean bank width (Ws)	-0.39	0.13
Mean maximum depth (Dmax)	-0.35	-0.12
Mean depth (Dm)	-0.31	0.18
Mean width:depth ratio (W/Dm)	-0.33	0.14
Mean bank width:mean bed width (Ws/Wb)	-0.34	-0.31
Mean shape factor (Sf)	-0.17	-0.70
Mean cross-sectional area (A)	-0.39	0.09
Eigenvalue	6.47	1.53
Percentage of eigenvalue	71.88	17.04
Cumulative percentage of eigenvalue	71.88	88.92

When the six gullies are projected onto a co-ordinate system consisting of these first two components, it becomes apparent that the gullies can be separated into three broad groups on the basis of their morphometric properties (Fig. 5.1). These are Ribbok and Noord Brabant which comprise group one, Oorbietjie and Car group two, and Glen Reenen and Camp constituting the third group. It may, however, be argued that Ribbok gully and Car gully should be grouped together (Fig. 5.1). In the light of the results presented in Chapter 4 i.e. the typological classifications and morphometric and sediment characteristics of the gullies, Ribbok and Noord Brabant and Oorbietjie and Car gullies were instead grouped together. It must also be noted that although the scaling on the horizontal and vertical axes is the same the distance between the points on the x-axis is greater than that on the y-axis.

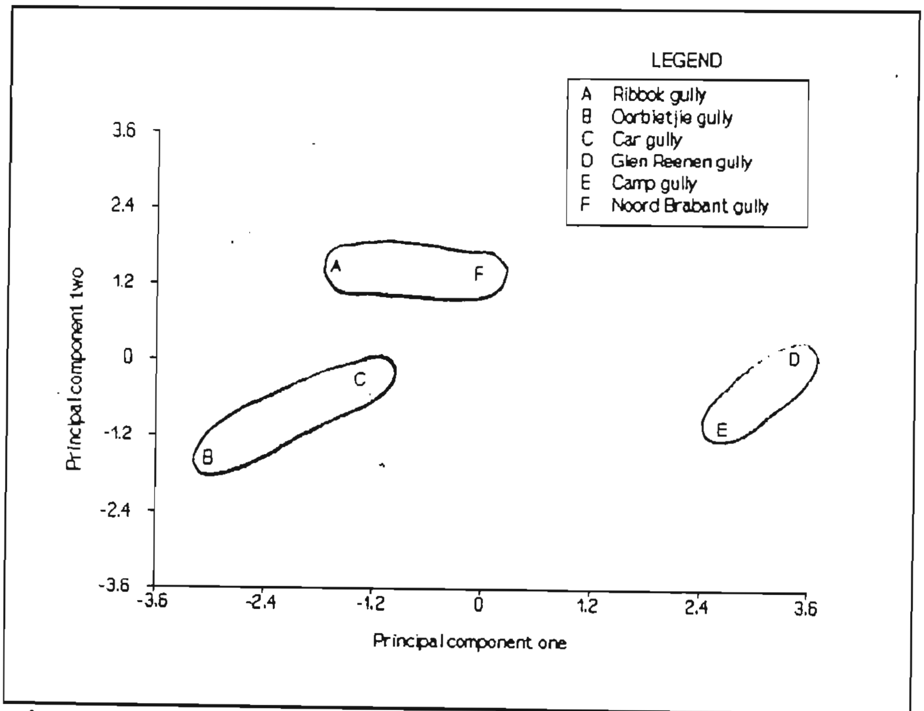

Fig. 5.1. Co-ordinate system showing the first two principal components.

Principal component analysis thus highlights one important factor about the morphology of the gullies in this study i.e.

that the morphometric properties investigated are strongly interrelated. This is shown in both Table 5.1 and Table 5.2 where in neither of the two principal components are any of the variables particularly dominant. This suggests the existence of a steady state of adjustment between the form elements of the gullies, and is in conformance with the geometric similarity of fluvially developed landforms as recognized by Strahler (1958).

5.2. Canonical variate analysis

From the above discussion it is clear that there exists a strong interrelationship between the morphometric variables. To get an indication of the similarities and differences that exist between the individual gullies, data were collected from the 37 cross-sectional sites in the six gullies. Canonical variate analysis was then undertaken to predict the group membership of the gullies on the basis of this assembled data. The aim of this analysis is to find the best combination of variables that maximizes the differences between the gullies.

The result of the canonical variate analysis presented in Table 5.3, indicates that the first two variates account for 90.56 percent of the total variation in the data collected. Hence, the data are examined in terms of these two canonical variates rather than in terms of all 12 variables.

When the first two variates are projected onto a co-ordinate system (Fig. 5.2), it can be seen that, as with principal component analysis, the gullies are divided into three broad groups, namely Ribbok and Noord Brabant; Oorbietjie and Car; and Glen Reenen and Camp. It may be argued that Camp and Noord Brabant gullies should be grouped together but, again, it must be borne in mind that the groupings were not made solely on the basis of the statistical findings but rather in conjunction with the findings presented in Chapter Four.

Differences and similarities clearly exist between the gully groups. These are discussed in Chapter Six, and where possible, explanations for these are given.

Table 5.3. The two canonical variates.

Variables	Canonical variates	
	1	2
Bed slope	-0.13	-0.15
Bed width	0.11	0.01
Bank width	-0.06	0.04
Maximum depth	0.08	-0.27
Mean depth	1.29	1.01
Width:depth ratio	0.25	0.27
Bank width:bed width ratio	0.50	0.26
Shape factor	-0.08	2.78
Bed silt-clay percent (Sc)	0.22	-0.16
Bank silt-clay percent (Sb)	0.42	-0.62
Weighted mean percent silt + clay (M)	-0.43	0.61
Cross-sectional area	-0.01	-0.01
Eigenvalue	8.56	7.97
Percentage of eigenvalue	46.90	43.66
Cumulative percentage of eigenvalue	46.90	90.56

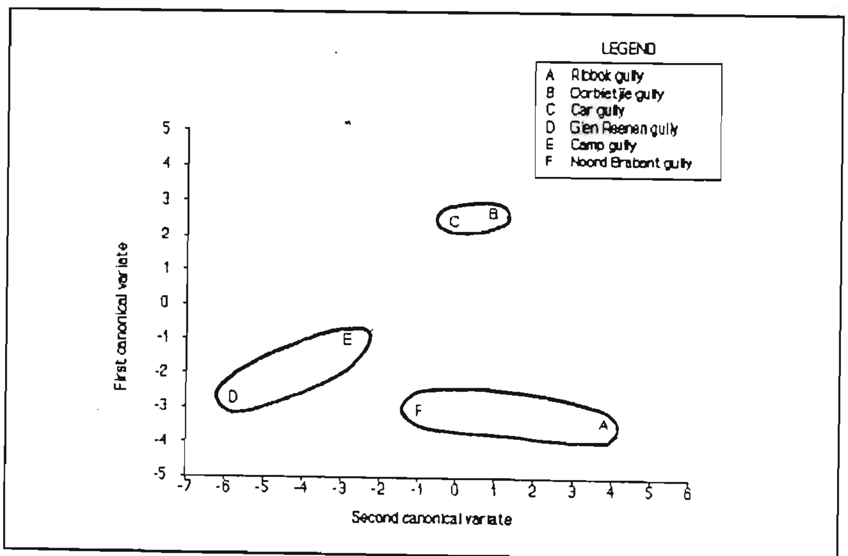

Fig. 5.2. A co-ordinate system representing gully differences.

5.3. AIR PHOTO INTERPRETATION, GULLY LENGTH AND AREA MEASUREMENTS

The study thus far, has centred mainly around the spatial i.e. typological and morphological characteristics of the six gullies as they occur today. Temporal variations of these gullies (with the exception of Glen Reenen gully) were, however, also investigated using aerial photographs. The reason for excluding Glen Reenen gully is that it only developed subsequent to the last set of aerial photographs taken. The results of the air photo interpretation are presented below in three sections. First the gully length and extension measurements and calculations are presented. This is followed by the results of the gully area, expansion and volume estimates and the extension:expansion ratio calculations.

5.3.1. Gully length and extension

Results of the length measurements of the gullies as they occurred in 1952, 1984 and 1991, together with the calculations of their rates of extension during the periods 1952-1984 and 1984-1991, are presented in Table 5.4 and Fig. 5.3. Figure 5.3A, shows Oorbietjie to be the longest of the five gullies measured during all three time periods, followed by Car and then Ribbok gullies. The highest rate of extension during the first period (1952-1984), was experienced by Noord Brabant, while the lowest was recorded for Ribbok gully (Fig. 5.3B). During the second period (1984-1991), however, Ribbok experienced an enormous increase in its rate of extension. Similarly, increases in extension rates were recorded for all five gullies during this second period.

Table 5.4. Results of gully length and area measurements and calculations.

	Ribbok	Oorbietjie	Car	Camp	Noord Brabant	Glen Reenen
LENGTH (m):						
1952	288	400	363	67	43	
1984	300	470	385	90	120	
1991	355	500	400	120	160	20
GULLY AREA (m^2):						
1952	6272	7575	5344	874	740	
1984	10 000	17 750	9392	1868	7400	
1991	19 440	29 825	14 592	3073	13 080	179
EXTENSION RATE (m^2/year):						
1952-1984	0.3	2.2	0.7	0.7	2.4	
1984-1991	7.7	4.3	2.1	4.3	5.7	
EXPANSION RATE (m^2/year):						
1952-1984	116.5	318.0	126.5	31.1	208.1	
1984-1991	1348.6	1725.0	742.9	172.1	811.4	
EXTENSION:EXPANSION RATIO (m^{-1}):						
1952-1984	0.003	0.007	0.006	0.02	0.01	
1984-1991	0.006	0.002	0.003	0.02	0.007	
VOLUME (m^3):						
1991	103 032	226 670	81 715	10 756	73 248	752

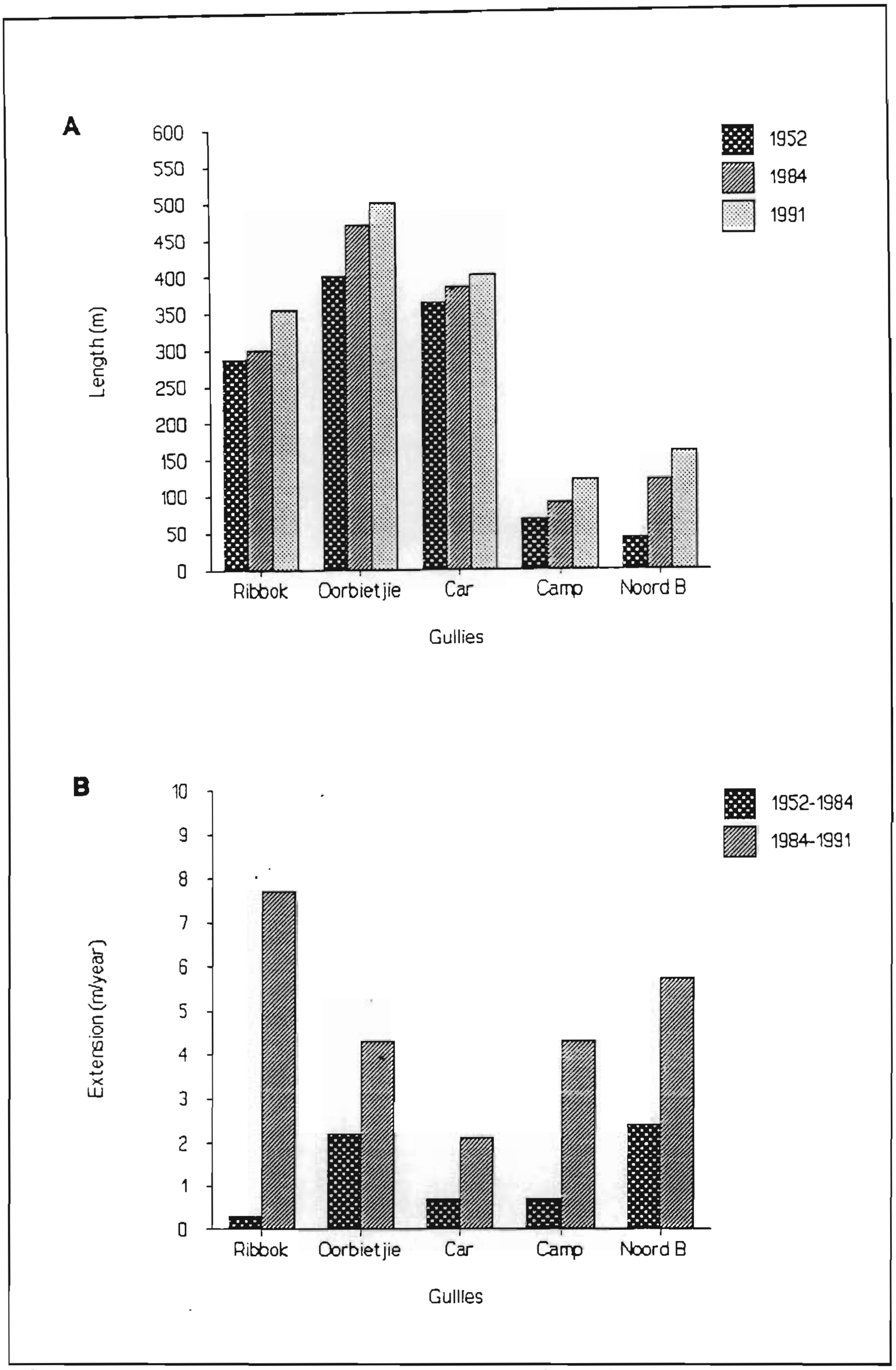

Fig. 5.3. A: Lengths of the gullies in 1952, 1984 and 1991, and B: Extension rates of the gullies during the periods 1952-1984 and 1984-1991.

5.3.2. Gully area, expansion and volume estimates

Table 5.4 and Fig. 5.4 present the results of the area measurements and expansion calculations. The gully that covered the largest area during all three time frames i.e. (1952, 1984, 1991), was Oorbietjie, followed by Ribbok and then Car (Fig. 5.4A). The smallest area covered by a gully during the three periods was that of Noord Brabant in 1952. Oorbietjie gully also experienced the highest rate of expansion during both periods (1952-1984, 1984-1991), whilst the lowest rate calculated for both periods was that of Camp gully (Fig. 5.4B).

Although, the results of the extension and expansion calculations are presented as averages per year, it must be borne in mind, that by nature, gully growth is not consistent, but is rather sporadic (Bocco, 1991). The results are, however, presented in this manner so that comparisons between the gullies may be drawn.

Visual representation of the increase in expansion and extension experienced by the gullies have already been provided in Chapter 4 which discusses the individual gullies, but in order to get an overall and comparative view, they are presented again in Fig. 5.5.

Rough estimates of volume of sediment removed from each gully, reveal that the largest volume has been removed from Oorbietjie gully, followed by Ribbok and Car (Table 5.4). The smallest amount of sediment has been removed from Glen Reenen gully. This finding is not surprising when one considers the area covered by the above mentioned gullies i.e. Oorbietjie covers the largest area while Glen Reenen covers the smallest.

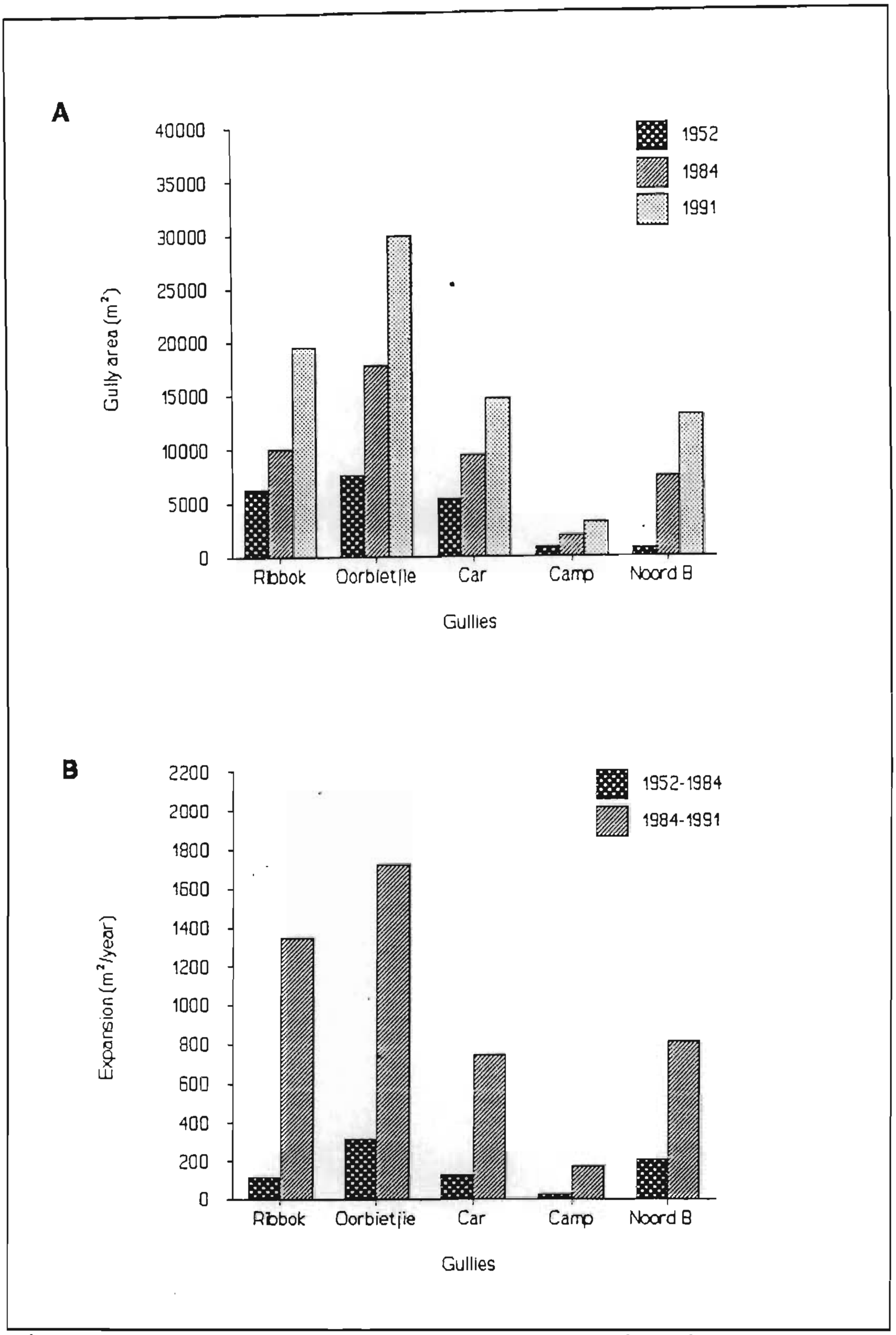

Fig. 5.4. A: Area covered by the gullies in 1952, 1984 and 1991, and B: Expansion rates experienced by the gullies during the periods 1952-1984 and 1984-1991.

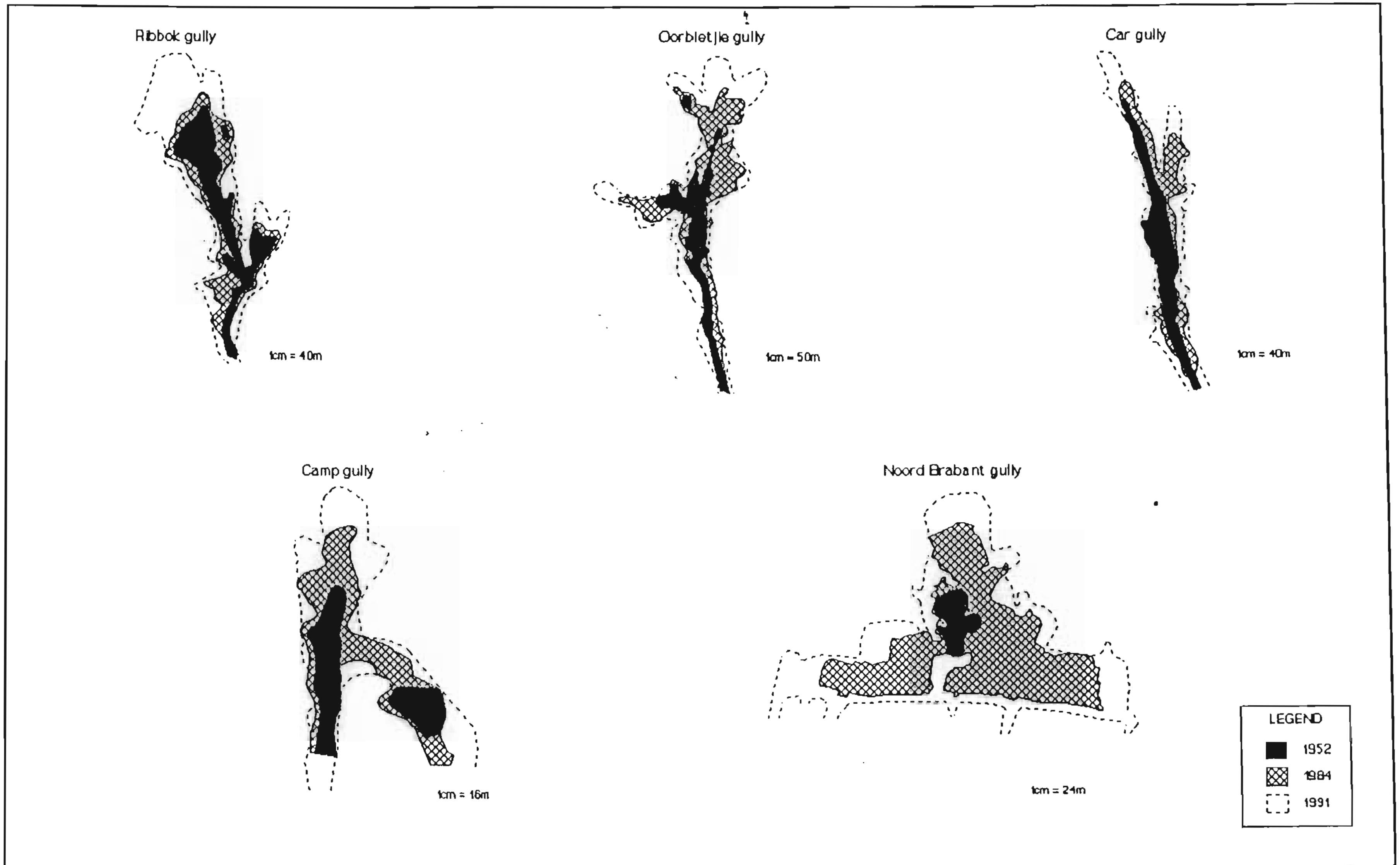

Fig. 5.5. Extent of Ribbok, Oorbietjie, Car, Camp and Noord Brabant gullies in 1952, 1984 and 1991.

5.3.3. Extension:expansion ratio

Due to the fact that the extension (increase in length) of a gully also contributes to its expansion (increase in area), it is not possible to set a ratio of 1.0 as the limit between dominance of either parameter. Gully extension may dominate even if the ratio is less than 1.0 (Nördstrom, 1988). This ratio is, however, useful in detecting possible trends in the impact of either parameter between the two periods (1952-1984, 1984-1991). What should be noted, is that the results calculated represent the cumulative influence of the two parameters over relatively long periods of time viz 32 years and 7 years, respectively. Hence, the dominance of either parameter may have varied during the two periods.

From the results (Table 5.4), it is evident that gully extension was not very active during either of the two periods. The impact of gully expansion appears to have been greater in Noord Brabant, Oorbietjie and Car gullies during the later period, as evidenced by the decrease in ratio. On the other hand, an increase in the ratio for Ribbok gully, during the same period, indicates the dominance of extension.

The typological and morphological characteristics of the six gullies, together with the results of the relationships of their dimensional parameters, and their increase in extent over time, have been presented in Chapters 4 and 5. It is now appropriate to discuss these findings in the context of the spatial and temporal similarities and differences that exist between the gullies, and where possible relate these findings to initiating and controlling factors.

CHAPTER SIX

DISCUSSION

The results presented in Chapter Four highlight the typological, morphological, hydraulic, and sediment characteristics of the six gullies; the processes operative in each gully; the relationship between their morphometric properties, as well as the increase in extent of the gullies over the 1952-1991 period. Furthermore, they reveal that the six gullies can be separated into three broad groups on the basis of their morphometric and sediment properties. These groups are: Ribbok and Noord Brabant, Oorbietjie and Car, and Glen Reenen and Camp.

A summary of the average hydraulic, sediment and slope characteristics, together with the typological classifications of each gully is presented in Table 6.1. This table not only provides a summary of the above mentioned features, it also serves to highlight the similarities and differences that exist between the gullies.

Besides the obvious differences in length, and to a lesser extent cross-sectional area, the gullies comprising group one i.e. Ribbok and Noord Brabant, are remarkably similar. The same can be said for group two. On the other hand, the gullies in group three i.e. Glen Reenen and Camp, share similar sediment and hydraulic properties - again with the exception of length - but occur on different facing slopes of varying gradients. Furthermore, their forms differ in plan view and the sidewall contribution to total sediment production of Glen Reenen is well below that of Camp gully.

A feature common to all the gullies is that they are all continuous (Table 6.1). In terms of sediment characteristics, another feature shared by all is that the material

Table 6.1. A summary of the average hydraulic, sediment, slope and typological characteristics of the three groups of gullies.

CHARACTERISTICS	GROUP 1		GROUP 2		GROUP 3	
	Ribbok	Noord Brabant	Oorbietjie	Car	Glen Reenen	Camp
Length (m)	355	160	500	400	20	120
Maximum depth (m)	5.4	5.7	7.6	5.6	4.2	3.6
Mean depth	3.1	3.6	3.7	3.2	2.6	1.9
Bed width (m)	13.5	10.3	9.1	9.4	6.2	5.3
Bank width (m)	47.7	34.2	47.1	40.5	9.7	15.7
Shape factor	1.7	1.6	2.0	1.8	1.7	1.8
Cross-sectional area (m^2)	178.7	125.8	196.3	134.7	25.3	30.8
Sinuosity index	1.3	1.1	1.2	1.2	1.1	1.3
"M"	17.7	24.2	39.0	42.9	36.0	34.0
Width:depth versus "M"	0.04	0.57	0.34	0.35	-	0.55
Sidewall contribution to total sediment production (%)	57%	57%	64%	62%	33%	59%
Slope gradient (°)	11°18′	16°13′	4°00′	4°34′	30°58′	14°55′
Slope aspect	east facing	east facing	north facing	north facing	north facing	west facing
Typology	bulbous valley-side type 2 continuous	bulbous valley-side type 2 continuous	linear valley-bottom type 4 continuous	linear valley-bottom type 4 continuous	bulbous valley-side type 2 continuous	linear valley-side type 2 continuous

in which these gullies have incised appears to have had only a minor effect on the shape of the channels. Perhaps the lack of correlation can be explained by the following: a) some soil samples were not collected at stable cross-sections, b) the homogeneity of the material i.e. although extensive sampling was carried out in each gully no meaningful differences in texture were found and c) the role played by bedrock and other factors such as sidewall vegetation are likely to have further influenced the results.

The differences between the three groups of gullies include: sediment type, slope gradient, slope aspect, gully type and topographic location. While the gullies in groups one and three are both type 2 gullies and are located on valley-sides, the gullies in group two are type 4 gullies and are located on the valley-bottom. In attempting to explain the above findings and the observed gully forms, factors responsible for their initiation and development were examined.

6.1. FACTORS RESPONSIBLE FOR THE INITIATION AND DEVELOPMENT OF THE SIX GULLIES

The earliest aerial photographs taken of the region covering the Park i.e. 1952 show all the gullies, with the exception of Glen Reenen, to be well established. Consequently, inferences about the genesis of these gullies have had to be drawn, because once a gully has become large it is very difficult to ascertain the exact way in which it was initiated (Brice, 1966). Insight into the possible sequence of events leading to their initiation was gained from studies conducted by other researchers.

According to Butzer's (1971) research findings, a particular geomorphic trend of gully-cutting was established in the Orange-Vaal drainage basin during the period 1880 to 1930. It was about this time that the first European farmers began settling in this area. The arrival of these trek-farmers was marked by sudden and intensive disturbances in the grassveld (Butzer, 1971). These disturbances, caused by overstocking of sheep and cattle, and the repeated burning of the veld, resulted in the encroachment of undesirable veld types (Acocks, 1953; Mostert and Donaldson, 1956; Talbot, 1961; Butzer, 1971), and in the initiation of gully erosion (van Eeden, 1937; Roberts, 1969; Nicol, 1976).

Although the advent of the Europeans is seen as the major cause responsible for initiating this geomorphic trend, two other factors may have operated in conjunction with European interference to upset the existing steady state and result in rapid downcutting. The first of these is veld burning by the local inhabitants prior to European settlement. When the first white farmers arrived in the southern and central Orange Free State, evidence of veld burning by the indigenous tribes was found (Mostert and Donaldson, 1956). This burning may thus have been the mechanism triggering the accelerated process of range deterioration. The second factor is that of climatic fluctuations. It cannot be categorically stated that the Orange Free State experienced climatic fluctuations during this period, as no climatic records predating the turn of the century exist for this province. However, Vorster (1957) and Hofmeyer and Schulze (1963) observed a noticeable decline in precipitation along the Mediterranean rainfall belt of the Cape between 1892 and 1930, after which time it increased again. It is presumed, on the basis of the above, that the Orange Free State experienced similar climatic fluctuations (Butzer, 1971).

Thus, the sequence of events leading to the establishment of the geomorphic trend of gully erosion in the Orange-Vaal drainage basin appears to be as follows: veld deterioration initiated by burning by indigenous tribes, followed by enhanced degradation with the advent of European farmers, perhaps in conjunction with climatic fluctuations. Together these factors served to alter the natural vegetation from that of grassveld which afforded the soil good protection to open shrub-like vegetation (Karoo veld) which exposed the soils susceptible to erosion.

There is consequently little doubt that general veld deterioration caused by overgrazing and other farming malpractises such as injudicious ploughing of areas best left under their natural grass cover have been largely responsible for the initiating the erosion problem in the region of the Park. A particular problem pertaining to the Park, however, is that in the lower reaches the underlying geology has produced soils that are susceptible to erosion (Roberts, 1969). These include the shallow sandy soils produced by the Clarens Formation Sandstone and the structureless powdery soils produced by the reddish brown mudstone. The close spatial correlation of these susceptible soils with the arable lands and homesteads of the original farms that now constitute the Park, exacerbated the erosion problem when they were overgrazed and depleted of much of their natural vegetation (Roberts, 1969). It is in these lower lying regions of the Park that the six gullies investigated in this study occur.

Varying combinations of the above mentioned natural and anthropogenic factors are seen to be responsible for the spatial and temporal similarities and differences that exist between the gullies. Each group of gullies and the combination of factors seen to be responsible for their initiation and development are discussed below.

6.1.1. Ribbok and Noord Brabant

Despite the fact that these two gullies occur some distance from one another and developed on what were two separate farms, they appear to be have been initiated by similar processes namely, overgrazing and veld burning combined with direct runoff from exposed sandstone rocks. Overgrazing and burning of the two east facing slopes on which these gullies have formed served to diminish their natural vegetation cover, which under normal circumstances, would have reduced the velocity of waterflow coming down off the exposed rock surfaces. The result was that during high rainfall events the reduced vegetation cover was unable to withstand the erosivity of runoff and gully-cutting was initiated. As the headcuts of both gullies retreated upslope they eroded back onto the underlying sandstone rocks. The resulting increase in water concentration and velocity at the headwalls has given rise to the broad spatulate shaped heads of these gullies and their overall bulbous morphology. Although both gullies are classified as bulbous there is an obvious difference in their morphologies i.e. Ribbok extends linearly downslope while, Noord Brabant extends laterally across the slope. This difference is attributed to two additional factors that have influenced the development of Noord Brabant gully viz, the annual burning of a fire break in the area above the gully's current headwall and below the exposed sandstone rocks, and the implementation of misguided and inappropriate conservation measures i.e. building of the contour banks.

Annual fire break burning, instituted prior to the declaration of the Park and continued by Park officials, has destroyed the organic matter on the soil surface. This has resulted in the exposure of bare patches of soil and the encroachment of short low-growing plants. Consequently, the runoff of water from this area above the headwall is enhanced. This in conjunction with the effects of overgrazing, the location of the exposed sandstone rocks, and the building of the contour banks are all factors that have attributed to the unusual morphology of Noord Brabant.

6.1.2. Oorbietjie and Car

The area of the Park in which these two gullies occur was, prior to 1963, under extensive agricultural cultivation. The replacement of the natural grassveld vegetation with agricultural crops, in particular maize, is seen as the factor responsible for the genesis of Oorbietjie and Car gullies. This land-use change, served to increase the amount of runoff, which due to slope form, tended to converge in the natural drainageways. Here, the gentle sloping topography afforded the surplus water sufficient time to infiltrate the soil thereby, exposing it to erosion by piping. Once gullying had been initiated, the pipes drained the adjacent fields and reduce the storage capacity of their sediments. The action of the pipes resulted in the increase of flow received by the two gullies and the reduction in crop cover in the adjacent fields. A vicious cycle of erosion was initiated as the reduced crop cover produced even less ground cover and hence more runoff. The declaring of a National Park in 1963 saw this area revert back to grassveld but the damage had already been done, so much so, that the scars of the agricultural fields are still evident on the 1984 aerial photographs.

The long linear morphology of these two gullies is seen as a function of their development in natural drainageways and the control exerted by piping.

6.1.3. Glen Reenen and Camp

Spatially Glen Reenen and Camp gullies are located close to one another, but temporally, many years separate their genesis i.e. Camp gully was initiated prior to 1952 whereas, Glen Reenen was only formed in 1988.

The youth of Glen Reenen gully is particularly evident in the dominance of downcutting over sidewall erosion. Table 6.1

indicates that in all the other gullies the contribution of sidewall erosion to total sediment production is greater than that of downcutting. Although it is acknowledged that a gully can be formed and reach, what Heede (1974) terms, a mature stage, in a single runoff event, it is conjectured that Glen Reenen gully is still in the process of initial development, where initial incision and headward recession i.e. downcutting dominates over sidewall erosion.

Not only do these two gullies differ according to when they were formed but also in the manner in which they were initiated.

On the one hand, Camp gully, which occurs on an unstable west facing slope, has developed in response to overgrazing of the slope. What appears to have happened is that overgrazing left the slope bare of vegetation which either resulted in increased runoff and gully-cutting, or it encouraged increased infiltration of surface water and the development of piping erosion. On the basis of the way in which it has developed over the 39 year period i.e. 1952 to 1991, and the presence of piping in the gully today, it is presumed that the latter sequence of events best describes its initiation.

Glen Reenen gully, on the other hand, was formed by a process largely overlooked in gully initiation studies viz, mass movement (cf. Bocco, 1991) (Fig. 6.1). During March 1988 the Park experienced unusually high rainfalls with 107mm being recorded on the particular day that Glen Reenen was formed. The high antecedent moisture content of the soil together with the high rainfall amount and the lack of a retaining force due to the road-cutting, resulted in what has been described by Dvorak (in, Piest *et al.*, 1975) as "disproportionate gullying".

The genesis of this gully provides a clear example of the dramatic way in which the land surface may respond during a short time due to the exceeding of a geomorphic threshold. Although Glen Reenen was formed during an extreme event its continued development has been largely due to the fact that the short steep slope above its headwall has increased the effects of concentrated overland flow.

Fig. 6.1. The mudflow which lead to the formation of Glen Reenen gully in March 1988 (Source: G. Groenewald).

The differences in the plan view forms of Camp and Glen Reenen, are largely attributed to the different ways in which they were initiated.

Ribbok, Oorbietjie, Car, Camp and Noord Brabant gullies have continued to increase in size during the 39 year period, with the greatest amount of growth being recorded during the 1984 to 1991 period. Their continued development is seen not only as the function of the processes described as being operative in each gully (Chapter 4), but also the result of the burning policy adopted by the Park.

The burning policy which is '... relatively indiscriminate and does not allow for any external factors in deciding whether an area should be burned or not' (Groenewald, 1990:2), is particularly troublesome in that burning is often carried out in winter, and is used as a means of luring black wildebeest and blesbok away from overgrazed areas (Groenewald, 1988). The problem with winter burning is that it has a significant effect on both the total percentage basal cover and the deterioration of *Themeda triandra* grasses (Mostert and Donaldson, 1956). Furthermore, the Park receives a fair amount of precipitation during the winter months, and this combined with the reduced ground cover leads to significant soil losses as witnessed during a storm in July 1992. The scouring of the banks of Oorbietjie and Car gullies by the increased sediment concentration and in-channel flow during this storm was far more than had been witnessed during any of the storms that occurred during the summer months. The use of veld burning as a means of luring the black wildebeest and blesbok away from overgrazed areas itself poses a serious erosion threat, particularly since immediate grazing of the burnt areas is allowed (Groenewald, 1988). The reduced vegetation cover, together with the grazing of the new shoots as they appear, the trampling effect of the animals, the good rainfalls received, and the susceptible geology covering much of the Park, are all factors that have contributed to the development of the gullies. It is clearly evident that there is an urgent need for the establishment of a constructive burning programme that does take into account external factors if regular burning is to continue and the Parks management committee are to uphold their policy of protecting the geological and biological aspects of the environment.

The gullies described have shown that any one factor cannot be highlighted as being solely responsible for the accelerated gully erosion in the Park. Instead many different factors are interrelated, and the typology and morphology of each gully depends on the combination of factors that are interrelated.

6.2. GULLY GROWTH RATES BETWEEN THE PERIODS 1952-1984 AND 1984-1991

Results of the gully length and area measurements and calculations (see Table 5.4:147) show the rates of extension and expansion of the gullies during the shorter of the two time periods i.e. 1984-1991 to be far in excess of those during the 1952-1984 period. It is difficult to ascertain precisely why such tremendous growth was experienced by the gullies (except Glen Reenen) during the 1984-1991 period as opposed to between 1952 and 1984. However, it is well documented that by nature gully evolution is spasmodic (see for example, Bocco, 1991). Research has shown that long periods of stagnation are often followed by periods of rapid expansion and extension (e.g. Ireland *et al.*, 1939). Often the rapid growth is associated with the gully eroding through a weak layer and the alteration of the resistance forces in the system (Bradford and Piest, 1980). Perhaps the accelerated erosion of the gullies in this study is associated with them reaching and rapidly eroding through the structureless soils produced by the mudstone. The recording of the greatest amount of growth during the 1984 to 1991 period concurs with the findings of Blong (1985), i.e. that the rate of gully erosion and sediment yield from gullies in New South Wales, Australia, was highest 20 to 40 years after their initiation.

CHAPTER SEVEN

CONCLUSION

The general aim of this study was to gain an insight into the nature and rate of gully erosion at Golden Gate Highlands National Park. In order to achieve this, the spatial and temporal characteristics of six gullies were analyzed by examining their typological and morphological characteristics, the relationship between their morphometric properties and their increase in extent over a 39 year period. Where possible the above findings and observed gully forms were related to causal factors. The results of these findings can be summarized as follows:

On the basis of their typological and morphological characteristics the gullies are divided into three groups viz. Ribbok and Noord Brabant; Oorbietjie and Car; and Glen Reenen and Camp. The spatial location of the gullies in relation to one another appears to have exerted little influence on these two characteristics. However, their spatial position in the landscape, for example, on a spur or in natural drainageways, and the characteristics of the slopes on which they have developed i.e. slope gradient and aspect, have clearly influenced both their typological and morphological characteristics by determining runoff types, which in turn largely control the processes operative in each gully.

Temporally, the typological and morphological characteristics of Ribbok, Oorbietjie, Car, Camp and Noord Brabant have altered only slightly over the 1952 to 1991 period. Changes that have occurred in Ribbok (change in form from linear to bulbous); Oorbietjie (branching of the headcut); and Car (developed from a first order into a second order gully) are attributed to the upslope migration of their respective headcuts, while the development of Camp gully from a discontinuous to a continuous gully is seen as the function of processes operative, in particular piping erosion. The above mentioned changes in the gullies are seen as the result of endogenous factors while the change that has occurred in Noord Brabant gully (lateral extension across the slope) is attributed to exogenous factors i.e. the building of the contour banks. Based on the bifurcation of Glen Reenen's headwall, it is expected that with time this gully will also experience changes in its typological and morphological characteristics. Further changes may also be initiated when, as has happened in the other five gullies, vertical channel processes give way to lateral channel processes. The current dominance of vertical channel processes in Glen Reenen being indicated by the results of the sidewall versus downcutting calculations, while the transition from vertical processes to lateral processes in the other gullies is indicated by both the sidewall versus downcutting calculations and the extension versus expansion ratio's. In all the gullies vertical incision is seen to be controlled by fluvial processes on the gully floor, while the lateral channel processes are controlled largely by mass movements.

Statistical analysis of the morphometric variables examined in this study show them to be strongly interrelated, thus suggesting the existence of a consistent state of adjustment between the form elements of the gullies in both space and time. Furthermore, it highlights the geometric similarity of fluvially developed landforms as well as the extent to which exogenous interference can influence the morphometric properties of gullies.

Analysis of the expansion and extension trends since 1952 showed Oorbietjie to have experienced the greatest rate of expansion (i.e. 116.5m^2/yr during the 1952-1984 period, and 1348.6m^2/yr during the 1984-1991 period), while the greatest extension rate was recorded for Noord Brabant during the

1952-1984 period (2.4m²/yr) and Ribbok gully during the 1984-1991 period (7.7m²/yr). The extension versus expansion calculations revealed a slight dominance of gully expansion over extension since 1952. These calculations suggest, as mentioned above, that vertical channel processes in Ribbok, Oorbietjie, Car, Camp and Noord Brabant are giving way to lateral channel processes.

The nature of the increase in extent of the gullies over the 39 year period together with their typological and morphological characteristics and the relationships that exist between their morphometric properties are ultimately all the product of the factors that have governed their initiation and development. The genesis and development of the six gullies are attributed to factors extrinsic to the systems, for example, overgrazing, cultivation and veld burning, although intrinsic variables, for example, soil types and antecedent moisture content have rendered these systems susceptible to erosion. What was found in this study is that gullies sharing similar typological, morphological, hydraulic, and sediment characteristics appear to have been initiated by similar processes, and that slight variations between them were due to differing combinations of intrinsic and extrinsic variables. These various combinations have given rise to the particular spatial and temporal characteristics of each gully.

In summarizing the general nature of gully erosion at Golden Gate Highlands National Park it can be said that the gullies are essentially simple in plan and morphology having few tributaries and relatively direct courses. Factors such as vegetation growth in the gullies and the silt-clay percent in the soils appear to exert only a minor influence on gully morphology in this area. Spatial and temporal differences between the gullies are seen as the result of varying combinations of exogenous and endogenous factors. It must be borne in mind that the present distribution of gullies in the Park is not only the result of recent events and conditions, since gullying was evident in this area since about the turn of the century. As a result, the Park inherited much of the erosion problem. Despite this and the fact that a certain amount of gullying occurring in the Park is undoubtedly natural, anthropogenic activities have been and are out of concord with that of the environment such that the impact of extrinsic variables in accelerating gullying has been considerable. It is important that conservation methods and other factors extrinsic to the system e.g. veld burning, are adapted to the intrinsic conditions if future attempts to halt or prevent erosion are to succeed.

In the final analysis it can be said that the methods of data collection and analysis adopted in this study were found to be very useful in fulfilling the set aims. It is, however, suggested that future studies of a similar nature investigate the effects of slope aspect and gradient on gully morphology in greater detail; these factors having emerged from this study as variables warranting further investigation.

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APPENDIX 1

FIELD AND LABORATORY INSTRUMENTATION

The practical fieldwork, laboratory analysis and preparation of maps were carried out using the following items of equipment:

Notebook
Pencil and soft rubber
Field map
Compass
Measure tape
Abney level
Camera
Soil auger
Sample bags
Tags and pen
String
Theodolite
Staff
Vibration shaker and sieves
Hydrometer
Sartorius balance
Wild Heerbrugg A8-522 stereoplotter

APPENDIX 2

DATA SOURCES AND APPLICATIONS

1. TOPOGRAPHICAL MAPS:

   1:50 000 Sheet no. 2828 BC Kestell
   2828 DA Golden Gate

   Contour interval: 20m

   Source: Department of Survey and Mapping, Mowbray

   Application: field orientation

2. AERIAL PHOTOGRAPHS:

   1:30 000
   - Job 247, Strip 3, Nos. 60915 to 60918
     Strip 4, Nos. 60927 to 60932
     Date: 1952
   - Job 477, Strip 1, Nos. 1732 to 1735
     Strip 2, Nos. 1744 to 1747
     Strip C7, Nos. 040 to 044
     Date: 1962
   - Job 654, Strip 17, Nos. 8490 to 8492
     Strip 18, Nos. 9085 to 9091
     Strip 19, Nos. 8831 to 8834
     Strip 20, Nos. 8797 to 8799
     Date: 1969
   - Job 801, Strip 14, Nos. 2056, 2057
     Strip 15, Nos. 2071, 2072
     Date: 1978
   - Job 878, Strip 12, Nos. 6053, 6054
     Strip 13, Nos. 3309, 3310
     Date: 1984

   Film type: panchromatic, black and white

   Source: Department of Survey and Mapping, Mowbray

   Application: aerial photographic interpretation
   selection of study sites

3. DIAPOSITIVES:

1:30 000 - Job 247, Strip 4, Nos. 60929 to 60931
Date: 1952
- Job 878, Strip 12, Nos. 6054, 6055
Date: 1984

Source: Department of Survey and Mapping, Mowbray

Application: Map temporal changes in gullies.