GEOMORPHOLOGICAL ASPECTS OF VELD BURNING IN GOLDEN GATE HIGHLANDS NATIONAL PARK, SOUTH AFRICA

by

JESSICA MARGARET CAROLINE BIRD

Submitted in partial fulfilment of the academic requirements
for the degree of Master of Science
in the Department of Geography, University of Natal

Pietermaritzburg
1996

The grass is rich and matted, you cannot see the soil. It holds the rain and the mist, and they seep into the ground, feeding the streams in every kloof. It is well-tended, and not too many cattle feed upon it; not too many fires burn it, laying bare the soil. Stand unshod upon it for the ground is holy, being even as it came from the Creator. Keep it, guard it, care for it, for it keeps men, guards men, cares for men. Destroy it and man is destroyed.

Where you stand the grass is rich and matted, you cannot see the soil. But the rich green hills break down. They fall to the valley below, and falling, change their nature. For they grow red and bare; they cannot hold the rain and mist, and the streams are dry in the kloofs. Too many cattle feed upon the grass, and too many fires have burned it. Stand shod upon it, for it is coarse and sharp, and the stones cut under the feet. It is not kept, or guarded, or cared for, it no longer keeps men, guards men, cares for men. The titihoya does not cry here any more.

The great red hills stand desolate, and the earth has torn away like flesh. The lightning flashes over them, the clouds pour down upon them, the dead streams come to life, full of the red blood of the earth. Down in the valleys women scratch the soil that is left, and the maize hardly reaches the height of a man. They are valleys of old men and old women, of mothers and children. The men are away, the young men and the girls are away. The soil cannot keep them anymore.

Cry, The Beloved Country
-A. Paton (1964 p.7)

PREFACE

The research described in this dissertation was carried out in the Department of Geography, University of Natal, Pietermaritzburg and in Golden Gate Highlands National Park, from January 1994 to December 1995, under the supervision of Dr H.R. Beckedahl.

These studies represent original work by the author and have not otherwise been submitted in any form for any degree or diploma to any other University. Where use has been made of the work of other authors it has been duly acknowledged in the text.

ABSTRACT

Fire is widely used as a veld management tool in wilderness areas such as Golden Gate Highlands National Park. A wealth of literature exists regarding the effect of burning on vegetation but few studies address the impact of fire on soil geomorphology.

The study aimed at determining the effect of fire on soil properties and soil erosion processes. Fifteen runoff plots were installed at Golden Gate Highlands National Park on slopes of varying aspect and gradient and were subjected to different burn treatments i.e. winter, spring and no-burn. The following soil properties were investigated to determine if fire had an influence on soil erodiblity; infiltration rate, organic matter content and aggregate stability.

The intensity of grassland fires is generally not sufficient to affect soil properties especially if the burn takes place under favourable controlled conditions. Despite the poor rainfall received during the study period enough events were recorded to establish trends. Winter burning increases sediment yield and runoff compared to spring burning and the control no-burn treatment. These results were incorporated into a proposed burn policy for Golden Gate Highlands National Park.

ACKNOWLEDGEMENTS

This research would not have been possible to undertake without the generous help of the following people;

My sincerest thanks to the staff of Golden Gate Highlands National Park and in particular Corrie Pieterse, Giel de Kock, Manie Beukes and Henda Meyer for their time, patience and friendliness in dealing with the demands of the "Engelse vrou". Petrus deserves special mention for his efforts in collecting the runoff and sediment data.

The installation of the runoff plots was a major undertaking and would have been impossible without my friends and fellow Masters students; Andrew Simpson, Sarah Currie, Debbie Fenn, Megan Curry, Richard Sinclair, Christina Potgieter, Brice Gijsbertsen and Paul Sumner; who worked for little reward with much good humour.

My supervisor Heinz Beckedahl has been continually constructive, patient and supportive throughout my research for which I thank him.

Riaan de Jager at the Institute for Soil, Climate and Water (Agricultural Research Council) and Renier de Vos at the Computing Centre for Water Research came to my aid with the meteorological data used in this research. I am grateful to Dr J.E. Granger of the University of Natal, Pietermaritzburg and Dr Hugo Bezuidenhout of the National Parks Board for their advice on things botanical.

Heartfelt thanks to Helena Margeot, Toni Bodington and Olive Anderson for the computer help, maps, diagrams and endless cups of coffee.

My appreciation to Dr Fethi Ahmed for being my statistical methods saviour and to Sarah Currie for the generous loan of her printer.

Dr Maria Sala's gift of *Soil erosion as a consequence of forest fires* was a much appreciated and valuable addition to my library. Thank you to Ekerold Yamaha for the loan of a portable generator which was thoroughly tested in high-altitude, below-freezing conditions during the installation of the plots.

My enthusiasm for academic study would have waned long ago were it not for the staff and students of the Geography Department who have made my time at the University enjoyable and memorable.

My parents and family have supported me unconditionally throughout my long years at University and the debt owed to them is beyond payment.

This research was undertaken with the financial assistance of the Foundation for Research and Development and the University of Natal Graduate Assistant Scholarship.

TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER FOUR

CHAPTER FIVE

LIST OF TABLES

CHAPTER ONE

Environmental Setting

"...just as the sun was setting behind two magnificent sandstone cliffs. The sun's rays casting soft and delicate shades against the sandstone cliff-face inspired the name Golden Gate."

-S.J.L. Moodie (Van Rensburg, 1968 p. 114)

Golden Gate Highlands National Park (GGHNP) is situated in the northeastern Free State between 28°27' S - 28°37'S and 28° 33'E - 28°42' E. The Park is bordered by the former Qwaqwa homeland to the southeast and to the south by Lesotho (Figure 1.1). It was given National Park status in 1963 in recognition of the area's scenic beauty and unique geology. The Park lies in the foothills of the Maluti Mountains in the Rooiberge range and comprises an area of 10 710 hectares (Bryden and De Vos, 1994).

1.1 Geomorphology and drainage

The Park ranges in altitude from 1892m in the Little Caledon valley to Ribbokkop which at 2 836m is the highest peak in the park. The undulating landscape has been attributed to the incision by the Little Caledon River and its tributaries and the headward erosion by streams rising on the Great Escarpment. The valleys which have developed are assymetric with steeper south-facing slopes (Marker, 1989). Moon and Munro-Perry (1988) characterise the sandstone slopes which descend from the plateau area as being of two types, cliff-talus combinations and rectilinear bedrock slopes. The nature and distribution of debris on these two slope types is different. The debris found at the base of larger cliffs is comprised of sandstone boulders and blocks set into a fine sandy-clay matrix. The thickness of this matrix is believed to increase downslope where it can exceed three metres. In comparison, the rectilinear bedrock slopes are thinly veneered by a discontinuous debris layer of sandy-clay colluvium which also increases in depth downslope (Munro-Perry, 1990). The latter slopes are particularly susceptible to erosion because of the shallow sandy nature of their soils (Roberts, 1969).

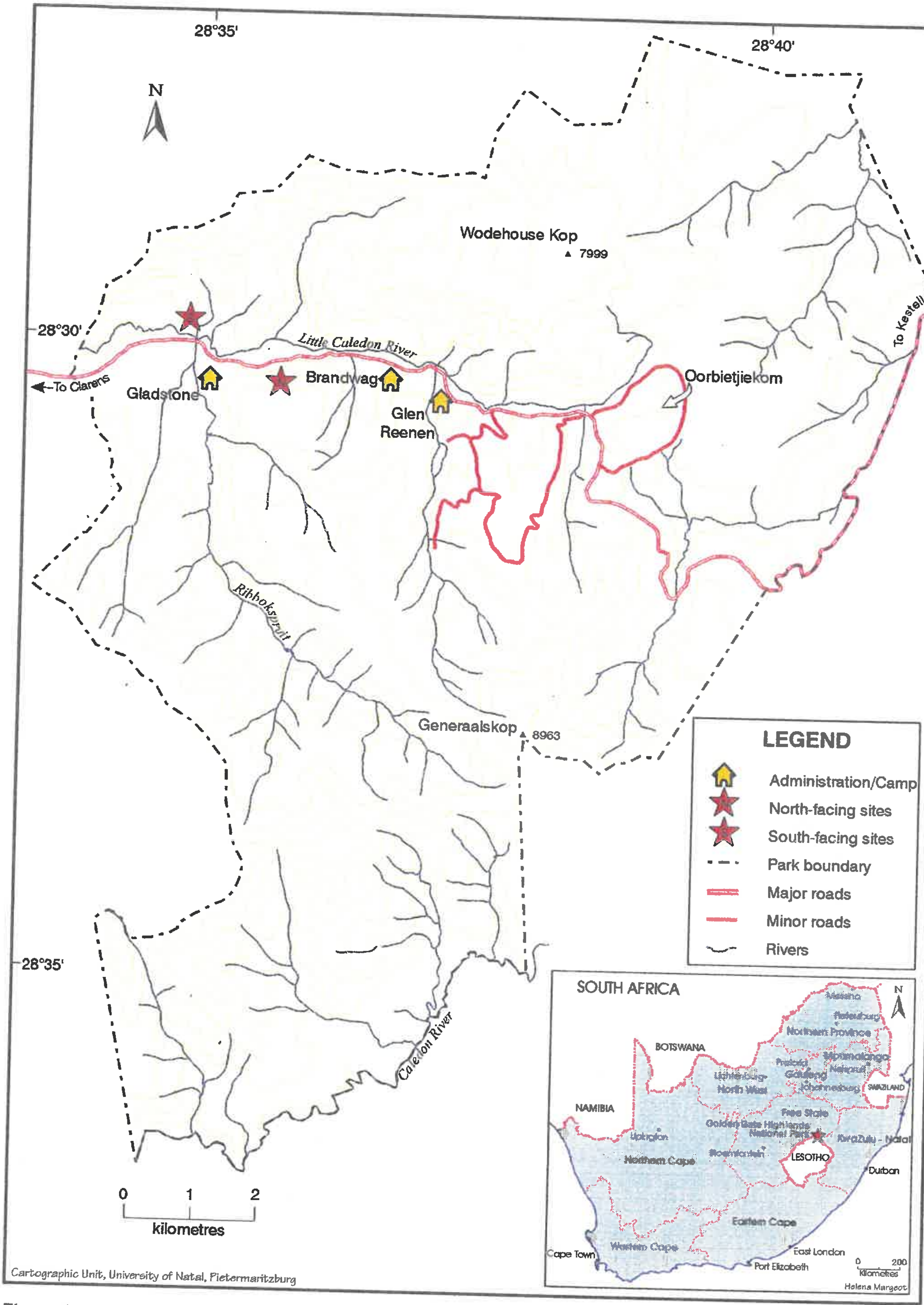

Figure 1.1: Map of Golden Gate Highlands National Park showing the location of the runoff plots.

The drainage of GGHNP to the south of Wodehouse ridge is via the Little Caledon River while the northern area is drained by the tributaries of the Wilge river. The Park is characterised by an almost dendritic drainage system of non-perennial streams and springs (Brady, 1993).

1.2 Geology and soils

The geology of GGHNP is characteristic of the upper parts of the Karoo Supergroup. Deposits of the Beaufort Group constitute the lower lying areas of the park, overlain by the predominantly horizontal sedimentary sequences of the Molteno, Elliot and Clarens Formations. The sequence is capped by the basaltic lavas of the Drakensberg Formation (Table 1.1) which attains a total thickness of 600m at the highest peaks of the Park (Groenewald, 1985). The major pattern of structural linements within the Park is east to west and north to south, related to the dyke swarms and inherent neotectonic stress fields as suggested by Scheidegger (1995).

Table 1.1: Summary of the stratigraphic units of the Karoo Supergroup found in GGHNP (after Groenewald, 1985).

GROUP	FORMATION	LITHOLOGY	AGE	ORIGIN
Drakensberg	-	Basalt	Upper Triassic-Lower Jurassic	Volcanic
Stormberg	Clarens	Sandstone	Upper Triassic	Aeolian
	Elliot	Mudstone and siltstone	Upper Triassic	Fluvial
	Molteno	Sandstone/mudstone/shales	Middle Triassic	Fluvial
Beaufort	-	Mudstone/sandstone	Lower Triassic	Fluvial

The soils of the area are closely related to the underlying geology. The most common soil form occurring on the sandstone slopes is Glenrosa, while Hutton and Clovelly soil forms are more common on the plateaus. Mispah soils are found mainly on the high lying steep slopes. The dominant soil form found on the south-facing basalt slopes is Bonheim, while Mayo and Shortlands forms dominate the north-facing slopes (Groenewald and Groenewald, 1989). These soils which cover the steep basalt slopes are highly fertile and are thus able to support a dense vegetation cover which helps to reduce the incidence of erosion (Roberts, 1969), but little disturbance of the vegetation is needed to initiate soil movement.

1.3 Vegetation

The Park's extreme variability in topography, altitude and climatic conditions have created a complex mosaic of plant communities. Structurally the vegetation can be divided into grassland and woodland/forest.

Two veld types as recognised by Acocks (1975) are represented in the Park, the Highland Sourveld (Veld Type 44) and the *Themeda-Festuca* Alpine Veld (Veld Type 58) (Kay *et al.*, 1993). According to Kay *et al.* (1993) nine major grassland communities are recognised within the Park (Table 1.2).

Table 1.2: Description of the grassland communities found in Golden Gate Highlands National Park (after Kay *et al.*, 1993).

GRASSLAND COMMUNITY	ALTITUDE	ENVIRONMENT	ASPECT
Festuca caprina	ca. 1952-2456m	Basalt, shallow soils	South-facing slopes
Themeda triandra-Helichrysum rudolfii	1877-1967m	Sandstone, shallow soils	South-facing slopes
Rendlia altera	ca. 1907-2200m	Sandstone, shallow soils	North-facing slopes
Tristachya leucothrix-Helichrysum zeyheri	ca. 2077-2402m	Mostly basalt, relatively deep soils	North, northeast, east-facing slopes
Tristachya leucothrix-Anthospermum herbaceum	ca. 2027-2531m	Basalt, deep soils	North-facing slopes
Elionurus muticus-Tristachya leucothrix	ca. 1802-2436m	Basalt, deep soils	North-facing slopes
Cymbopogon dieterlenii-Aristida diffusa	ca. 1961-2325m	Basalt and sandstone, shallow soils	North and south-facing slopes
Chrysocoma tenuifolia-Cynodon hirsutus	ca. 1802-2496m	Rocky, overgrazed areas with shallow soils	North, northeast and east-facing slopes
Eragrostis curvula	ca. 1937-2162m	Old lands	All except northeast-facing slopes

The Afromontane forest is restricted to sheltered ravines and gorges where the necessary moisture level is maintained and the vegetation is protected from unfavourable weather conditions and fire. Isolated patches of *Protea* woodland occur in the Park, while the vegetation of the valleys and south-east facing slopes is dominated by *Leucosidea sericea* or "ouhout".

1.4 Climate

The climate of the region can be classified as a temperate climate with summer rainfall (Cw) according to Köppen's classification system (Schulze, 1947). The summers are characterised by thunderstorms with a high incidence of lightning. The rainy season extends from September to April but it can be seen from Figure 1.2 that there are, on average, no completely dry months in the Park. The average rainfall of 659.6mm occurs either as high intensity thunderstorms or low intensity frontal drizzle. The thunderstorms result either from orographically induced convergence over the Drakensberg/Maluti massif, or as convection thunderstorms brought in from the northwest by the plateau-level-airflow which dominates during the rainy period.

Subzero air temperatures may occur between May and September and severe frosts and snowfalls are often recorded during the winter months. Winter precipitation in the form of snow or drizzle is induced by the inflow of cold unstable air from the south associated with the movements of coastal depressions (Nicol, 1976).

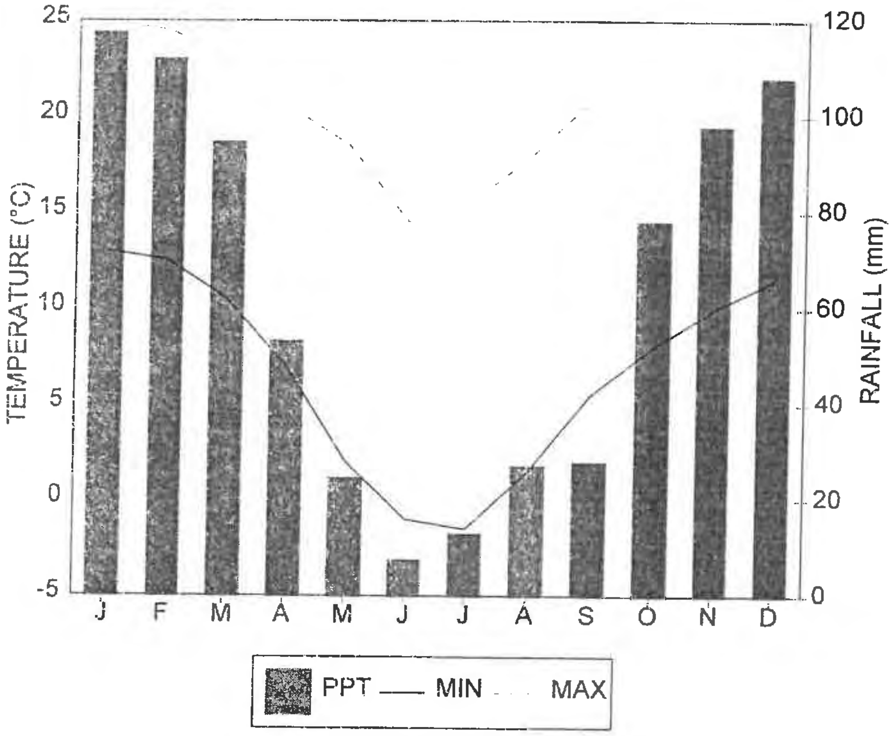

Figure 1.2: Mean monthly rainfall and temperature data recorded at Gladstone weather station, Golden Gate Highlands National Park for the years 1965-1980 and 1984-1995.

Light winds are common throughout the year, except for September when gusty conditions associated with the onset of the summer circulation pattern prevail (Nicol, 1976) as shown in Table 1.3. Summer winds are generally northwest to westerly in direction, illustrated by Figure 1.3. This summer pattern may be disrupted by high pressure cells ridging in off the east coast feeding in moist east to northeasterly air. Winter weather is strongly affected by the periodic northward outbreaks of cold polar air. This air is further cooled as it rises over the Lesotho plateau and the southwesterly may prevail for two to four days (Nicol, 1976).

Table 1.3: Seasonal windspeeds measured at Bethlehem Weather Station.

TIME	SUMMER	AUTUMN	WINTER	SPRING
00:00 - 06:00	1.46 $m.s^{-1}$	1.02 $m.s^{-1}$	0.73 $m.s^{-1}$	1.36 $m.s^{-1}$
06:00 - 12:00	2.04 $m.s^{-1}$	1.95 $m.s^{-1}$	1.65 $m.s^{-1}$	2.65 $m.s^{-1}$
12:00 - 18:00	2.74 $m.s^{-1}$	2.8 $m.s^{-1}$	3.53 $m.s^{-1}$	4.24 $m.s^{-1}$
18:00 - 00:00	2.16 $m.s^{-1}$	1.69 $m.s^{-1}$	1.02 $m.s^{-1}$	2.08 $m.s^{-1}$
AVERAGE	2.08 $m.s^{-1}$	1.87 $m.s^{-1}$	1.73 $m.s^{-1}$	2.58 $m.s^{-1}$

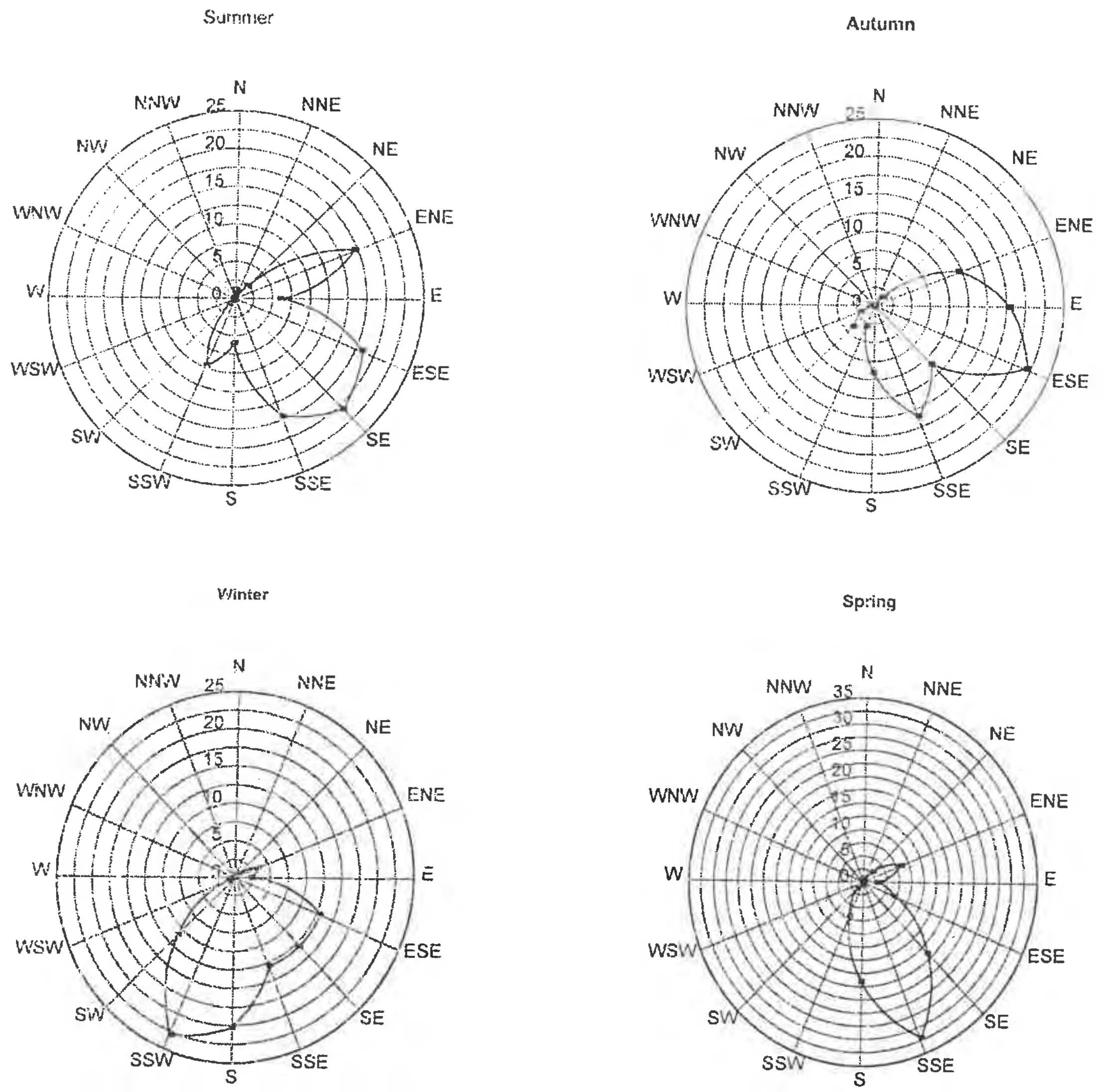

Figure 1.3: Seasonal windroses as measured at Bethlehem Weather Station.

1.5 Management of GGHNP

Golden Gate Highlands National Park is classified as a scenic park and is situated in a high energy mountain environment. This envronment requires a specific management system which recognises the problems associated with managing an area with steep slopes, shallow soils and high rainfall. The Park is managed according to an environmental management system based on ISO14000 principles in which the following are recognised by the Park management as being problem areas:

- erosion related to roads, paths and animal trails, and previous management practices prior to the area being proclaimed a National Park,
- pollution resulting from indiscriminant disposal of waste and
- pressure from outside groups wanting to obtain agricultural benefits from the Park.

GGHNP falls within the zone of 4 lightning strikes /km^2/a (Edwards, 1984) and is thus naturally prone to veld fire ignition. The high incidence of lightning strikes combined with the extreme fire hazard which exists within the Park during the dry winter months, has persuaded Park management that there is a need for a controlled burning programme.

P.J. Edwards (1984) lists the following as the objectives when burning natural vegetation:

- Fire can be used to remove surplus vegetation and facilitate access by people and animals.
- Controlled burning will reduce the fuel load and thus the intensity and frequency of accidental fires.
- Fire can be used to maintain or achieve a specific plant species diversity which is optimal for a specified management objective.
- Burning can improve the acceptability and nutritional value of existing species for grazers.
- Fire has been suggested as a means of controlling parasites although dipping and dosing are considered less drastic and more effective measures.
- Burning may be used as a soil and water conservation measure by maintaining and developing the vegetation cover.
- Fire can induce an out-of-season flush of growth.
- Game Reserves may use fire to create habitats suited to certain species and to induce game to graze in otherwise non-preferred areas.

The Park management's burning policy objectives can be summarised as follows (de Kock, 1995, *pers. comm.*);

- The reduction of the fuel load and the concomitant reduction in fire hazard, and
- the maintenance of the grassland's biodiversity

In previous years the Park was burnt on a triennial burn system for the benefit of the sour grassveld and to create a rotational grazing system to prevent overutilisation of certain areas of the Park by large grazers such as the Black Wildebeest as discussed by Van der Walt and Van Zyl (1982). This programme was abandoned in 1993. Subsequently a number of large grazers have been removed from the Park, resulting in a diminished grazing requirement and obviating the need for a rotational grazing system. Thus the Park management require a new burning policy which is based on ecological principles and takes cognisance of the aims of the Parks Board with regard to GGHNP.

Soil conservation is a primary concern of the management of the Park. The Park serves as a sponge area for both the Orange River system in the south and the Vaal River system to the north, and thus the provision of the maximum amount of high quality water is of great importance. The Park management aims at total quality management to achieve these goals i.e. the Park is not managed for the benefit of any one species but rather as an ecological whole (Pieterse, 1995, *pers. comm.*).

A wealth of knowledge has been accumulated by researchers in South Africa on the impact of seasonal burning on vegetation and the use of fire for range management but the geomorphological aspect has been largely ignored. The effect of fire on soil has received attention from researchers in other countries. Their findings are reviewed in the following chapter before the experimental design of this project is outlined in Chapter 3. This research is aimed at evaluating the effect of burning on soil properties and consideration of the effect of timing of burning on soil erosion processes. An understanding of the effect of burning on soil geomorphology will contribute to the development of a more holistic burning policy for GGHNP.

CHAPTER TWO

The Effect of Fire on the Soil

"New fire is associated with fresh hope, fresh chance for good fortune. To build new fires on old sites might nullify the fresh chance and invite misfortune."

-Traditional belief of the !Kung of the Namib (Hall, 1984 p. 42)

2.1 Backround to the study

Fire remains one of the most widely used management tools in wilderness areas such as GGHNP as it is a relatively easy and cost-effective way of managing large areas of land. Hall (1984) explains that it is difficult to establish precisely when humans began to employ controlled fires as it is virtually impossible to distinguish between anthropogenic fires and natural fires from evidence presented in soil profiles and pollen spectra. It seems likely that humans were able to control fire from the time of the Middle Pleistocene but southern Africa evidence suggests that it wasn't until 150 000 to 180 000 B.C. that fire was widely used in this area. It appears that fire has been a part of southern African ecosystems throughout the Holocene and therefore throughout the time that ecosystems have been adapting to contemporary climatic conditions. The antiquity of the relationship of fires and southern African ecosystems, implies that anthropogenic fire should be seen as a central component of some grassland and heath communities and not as an extraneous factor (Hall, 1984).

Fires may be naturally ignited by falling rocks or by lightning. Edwards (1984) states that although there is evidence from southern Africa of fire ignition by falling rocks, it is limited to mountainous areas where there is adequate fuel load under dry weather conditions. Lightning is regarded as the most significant of the natural causes of veld fires in southern Africa, but opinion differs as to the frequency and importance of lightning fires in natural ecosystems.

2.2 The effect of fire on soil properties

The extent to which fire influences soil properties depends on the nature of the vegetation, the soil type and moisture conditions, the intensity of the fire, the increase in and duration of the soil temperature occasioned by the fire and the frequency of fire occurrence. Hydrological and geomorphological changes brought about by fire vary greatly with the characteristics of the soil, vegetation, topography and climate (Cass *et al.*, 1984). Approximately 75% of the energy of combustion released during a fire is transferred as convection while the remainder is released as radiation (Luke and McArthur, 1977). Only 5% of the radiation energy is transferred from the fire to the ground (Packham, 1969). The soil temperatures during a fire are thus never as high as near-ground air temperatures. Air temperature and atmospheric relative humidity do not seem to affect soil surface temperatures in grassland fires (Britton and Wright, 1971). An increase in wind speed however, may result in a significant rise in soil surface temperature during burning. Of more importance than the maximum temperature attained during a fire is the temperature duration. The temperature duration is determined by a combination of fuel moisture, fuel load, soil moisture, amount of insulating organic material, fire intensity and duration. Soil temperature changes during burning are restricted to the top 15mm of soil as a consequence of the generally poor thermal conductivity of the soil. The extent of these changes appears to be controlled by the following factors which will be discussed in turn:

i) soil characteristics, of which soil moisture is the most significant (Scotter, 1970).
ii) fire intensity or the amount and rate of energy release, and
iii) the presence of an unincorporated insulating litter layer on the soil surface (Scott, 1994)

i) An increase in soil moisture significantly increases the soil heat capacity and conductivity. A higher proportion of air-filled pore spaces and an increase in humus content have an opposite effect, because of the low thermal conductivity of both air and organic matter and the low heat capacity of air relative to other soil components (Scott, 1994). Thus heating of a dry soil causes a greater surface temperature but less penetration of heat when compared to a moist soil (Giovannini, 1994). This has important management implications because heat from a fire burnt under moist conditions will penetrate deeper into the soil and may be detrimental to seed banks and roots (Dimitrakopoulos and Martin, 1994).

ii) The subjective definition of fire intensity by many authors means that the intensity of fires is seldom accurately given, although a distinction is generally made between wild and prescribed fires. Prescribed fires are usually characterised by a low fire intensity (Scott, 1994). Grassland fires typically have low fuel loads and consequently lower fire intensities in contrast to forest or macchia-type vegetation. The drier the fuels the more energy release and the greater the fire intensity.

iii) The low thermal conductivity of organic matter makes unincorporated litter an excellent insulator of the underlying soil (Chandler *et al.*, 1983). The effect of this litter layer is not as marked in grasslands because the frequency of fires prohibits the build-up of an extensive litter.

The main agency by which fire influences soil chemistry is the ash resulting from the combustion of organic material present on the soil surface. The residual ash affects soil chemical properties such as pH and the concentration of soluble elements (Cass *et al.*, 1984). Some ash may be lost through runoff and wind erosion before entering the soil profile.

The basic hypothesis proposed by Wischmeier and Mannering (1969), which is still generally accepted today, is that the erodibility of the soil is dependent on two components (organic matter and particle size) and two properties (structure and infiltration). Wells *et al.* (1979) cite numerous examples of increased erosion rates following fire in forest, shrub and grassland, but Scott (1994) states that few are specific as to the cause of the increased erosion rate. Generally, severe heating of the soil will increase its erodibility (DeBano, 1981; Giovannini and Lucchesi, 1983; Watson and Poulter, 1987). This increase is attributed to the combustion of organic material which aids in the micro-aggregation of soil particles. Temperatures as low as 250°C can cause the destructive distillation of organic compounds (Hosking, 1938; Dimitrakopoulos *et al.*, 1994) and cause the soil to become powdery and friable. An increase in erodibility as a result of fire will increase the soil's vulnerability to erosion by wind, raindrop impact and overland flow. According to Morgan (1986) erosion is controlled by the erosivity of the eroding agent, the erodibility of the soil, the slope of the land and the nature of the plant cover (including canopy and ground cover). Two of these namely, soil erodibility and plant cover, are affected by burning.

2.2.1 Erodibility

2.2.1.1 Organic matter

Organic matter is expected to contribute to the stability of the soil (Chaney and Swift, 1984). In some Mediterranean soils however, organic matter is not the main factor in determining soil aggregation (Molina *et al.*, 1994). The higher the temperature induced by the burn and the greater the fire frequency, the greater is the expected change in organic matter (West, 1965 cited in Cass *et al.*, 1984). Generally, fire is thought to reduce the organic matter content of soils and increases reported may be attributed to an accumulation of charcoal rather than organic matter (Daubenmire, 1968; Trabaud, 1983). Certain soils, when exposed to extreme heating, are capable of being baked to a state of improved aggregation with improved hydraulic properties (Scott and Burgy, 1955; Humphreys and Craig, 1981; Josa *et al.*, 1994). Diaz-Fierros *et al.* (1994) concludes that the effect of fire on soil stabilisation in soils which do not contain high levels of organic matter is favourable.

In grasslands the build-up of litter is not as great as in other vegetation types because of the frequency of fires. Soil surface temperatures of grassland head fires are a linear function of the amount of uncompacted fine fuel available for burning (Wright and Bailey, 1982). Surface temperatures of 690°C have been found to destroy all the surface litter and 99% of the soil organic carbon (Raison, 1979). However soil temperatures during burning in grasslands normally vary between 102° and 388° C (Wright and Bailey, 1982) and rarely exceed 200 C which is high enough to destroy only humic acids (Cass *et al.*, 1984). Edwards (1961) and Cass (1978) found no change in organic matter content in the grasslands of Natal following burns.

2.2.1.2 Particle size

There is little evidence to show that fire is responsible for clay mineralogical transformations in the soil as the temperatures attained in grassland fires are usually not of a sufficiently high temperature (Cass, 1978; Cass *et al.*, 1984). Molina and Sanroque (1991) report an increase in percentage sand content in soils subjected to temperatures above 220°C because of the aggregation of clay particles. Other researchers (Giovannini *et al.*, 1990) have recorded this phenomenon at temperatures above 400°C. This could be the result of selective precipitation of carbonates and other soluble salts as cementing agents during dehydration (Molina *et al.*, 1994).

2.2.1.3 Structure

Studies cited in Cass *et al.* (1984) suggest that grassland fires are also generally not hot enough to effect changes in soil structure. Indirectly, however, soil porosity may be reduced through the destruction by fire of the insects and other macro-organisms that tunnel in the soil (Wells *et al.*, 1979). A decrease in bulk density was observed after a wildfire in S.E. Spain but this was not significant and could be related to the localised accumulation of ash (Martínez-Fernandez and Díaz Pereira, 1994). Evidence from South Africa and other countries supports the conclusion that burning often results in surface structural deterioration in the form of a weak crust, which may affect infiltration (Wells *et al.*, 1979; Cass *et al.*, 1984).

2.2.1.4 Infiltration

Infiltration is primarily dependent on surface structure and on those soil properties which determine hydraulic conductivity. Surface structure is sensitive to changes in the litter layer, vegetation cover and faunal activity. Burning has been shown to have a negative effect on these three factors and to reduce infiltration rate and hydraulic conductivity (Edwards, 1961; Wells *et al.*, 1979). This decrease is attributed to the formation of a thin crust of soil at the surface where bulk density is higher and porosity lower than in unburnt soils.

Infiltration may also be reduced by the development of water repellency in sandy soils as a result of fire (Wells *et al.*, 1979). Scott (1991; 1994) cites examples of fire-induced water repellency recorded in New Zealand, Australia, Chile, South Africa and the American states of southern California, Montana, Arizona, Oregon and Michigan.

Water repellency is an abnormal soil condition which occurs when soil water decreases below limiting values, or when soil particles are coated with hydrophobic organic substances which act to reduce the normal attraction between soil particles and water (DeBano *et al.*, 1967). Decomposed and undecomposed plant matter has been suggested by Savage *et al.* (1972) as the source of these hydrophobic substances. Repellency may occur at depth or on the surface. The degree of repellency is related to the contact time between plant litter and the soil surface (Teramura, 1980). The most obvious effect of induced repellency is that infiltration into the soil is impeded which may result in the generation of overland flow and/or the restriction of percolation to preferred pathways with the soil (DeBano, 1971; Van Dam *et al.*, 1990; Scott, 1991). An increase in soil temperature has also been found to increase water repellency (DeBano and Krammes, 1966). A model of the processes involved in the development of water repellency has been provided by work undertaken in California (DeBano *et al.*, 1976). Heating of sufficient duration and temperature may denature or vaporise existing hydrophobic coatings of soil particles leaving the soil surface wettable. However, less heating may cause repellency to be intensified (DeBano, 1966). Josa *et al.* (1994) state that in a laboratory simulation using Mediterranean forest soils, hydrophobicity was at a maximum at 200°C and disappeared at 300°C. Vaporised repellent substances from overlying soil and litter layers may move down through the soil profile, in response to a temperature gradient. They may then distil onto soil particles thereby increasing the band of repellency (Figure 2.1). Heating by a fire may not be sufficient to produce any changes in soil wettability deeper in the soil profile.

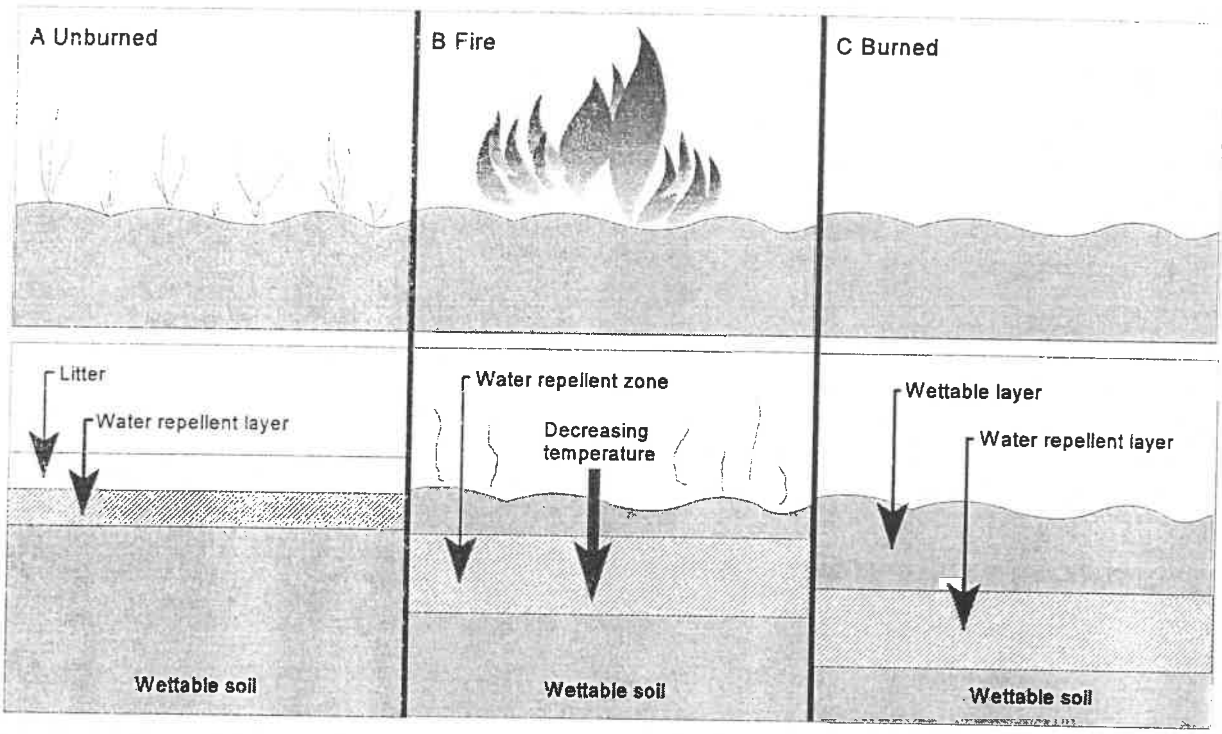

Figure 2.1: Water repellency in soil as altered by fire:
A. Before fire hydrophobic substances accumulate in the litter layer and in the mineral soil immediately beneath it;
B. During fire the surface is heated, destroying some repellent substances while others are volatised and move into the soil profile along a temperature gradient; and
C. After the fire the water repellent layer is below and parallel to the soil surface (modified after DeBano, 1969).

The majority of examples of fire-induced water repellency are recorded in areas of macchia-type vegetation, forests or plantations. In grasslands, the present frequency of fires ensures that there is insufficient build-up of organic matter as litter and therefore soil water repellency as described above is unlikely to develop. Scott (1995, *pers. comm.*) has observed one such case of induced soil water repellency in the midlands of KwaZulu/Natal, in an area which had been unburnt for a number of years but this is regarded as an exceptional example rather than the rule.

A more likely scenario in grasssiands is repellency resulting from desiccation of the upper soil layer. In unsaturated soils the macropores act as impermeable zones with water moving preferentially through the smaller pores (Gilman and Newson, 1980) thus inhibiting rapid infiltration. Desiccation could be caused by increased evaporation of soil moisture from the heat of the fire or indirectly from the change in albedo occasioned by the passage of the fire.

2.2.2 Plant cover

Vegetation cover acts to reduce rainfall intensity at the soil surface (Hudson *et al.*, 1983; Coelho *et al.*, 1990) and drastic reduction may lead to increased surface runoff. Reductions in plant cover can increase runoff as the result of decreased evapotransiration which increases soil moisture and reduces infiltration capacity (Link *et al.*, 1990). An increase in surface runoff leads to increased rates of detachment and removal of soil, especially where the passage of fire has left the soil more vulnerable to erosion through its effects on soil properties. The removal of plant cover may increase soil evaporation because of the increased heat load at the surface. Increased soil evaporation rates may be compounded by the reduction in the reflectivity coefficient as a result of the darkening of the soil surface by fire (Bosch *et al.*, 1984). Such increased evaporation rates may aid the development of repellency caused by desiccation as described above in Section 2.2.1.

Díaz-Fierros *et al.* (1994) state that to determine the effects of fire on the soil the vegetation strata which have been affected by the fire must first be identified. The strata can be divided as follows:

- Tree
- Shrub
- Herbaceous (grasses, phorbs, *etc.*)
- Litter
- Mosses, lichens and algae
- Roots

The tree, shrub and herbaceous strata act to attenuate the energy of the rainfall, either through evaporation from the vegetation cover or by absorbing the intensity of surface impact by reducing the velocity of the raindrops. Hudson (1971), however, observes that the concentration of raindrops beneath the canopy may act to increase erosion rates by increasing drop size and therefore the force of drop impact on the soil surface. Surface litter serves a multiple protective function by reducing evaporation, by absorbing rainfall intensity, by increasing surface roughness and hence reducing the velocity of surface runoff. Cryptogams that may colonise the soil surface can have a protective effect and simultaneously create a more irregular micro-relief for improved infiltration. Greene *et al.* (1990) found that this layer may have a contradictory effect similar to surface sealing. Finally, the roots aid soil retention by increasing resistance to detachment by increasing the shear strength of the soil (Díaz-Fierros *et al.*, 1994).

The effect of fire on vegetation will initially depend on the type of fire produced i.e. canopy, ground vegetation or soil organic matter fires (Díaz-Fierros *et al.*, 1994). This classification system as described by Díaz-Fierros *et al.* (1994) is based on forest fires and thus the first category (canopy fire) can be excluded from grassland fires. The effect of fire on erosion is usually higher the closer the fire occurs to the ground (Díaz-Fierros *et al.*, 1994). Indirectly, the changes in microclimate, brought about by the change in vegetation, may affect soil properties, vegetation growth and microbial populations (Cass *et al.*, 1984).

2.3 Effect of fire on sediment yield and soil hydrology

In recent years the Mediterranean ecosystem has been the focus of much research on the role of fire in erosion (e.g. Díaz-Fierros *et al.*, 1990; Soler and Sala, 1992, Soto *et al.*, 1994; Soler *et al.*, 1994; Lavee *et al.*, 1995; Kutiel *et al.*, 1995). The relationship between fire and sediment yield is complex as evident from the contradictory results reported in the literature. Accelerated erosion and marked changes in the hydrological behaviour of catchments as a result of widfire have also been recorded in the chaparral of California, coniferous forest of Washington, Oregon and Arizon (Helvey *et al.*, 1976; Anderson, 1976; Campbell *et al.*, 1977), from eucalypt forest in Australia, Portugal and South Africa (Leitch *et al.*, 1983; Terry, 1994; Scott, 1991) and the fynbos and pine plantation areas of South Africa (Lindley *et al.*, 1988; Scott, 1994). Other authors working in the Mediterranean region have asserted that runoff and erosion increase immediately after fire but fall to pre-fire levels within a few weeks (Díaz-Fierros *et al.*, 1990) or that there are no significant changes in geomorphic processes as a result of burning (Kutiel and Inbar, 1993). A summary of research results from catchment and plot studies is presented in Tables 2.1 and 2.2.

Table 2.1 Summary of catchment responses to fire.

CATCHMENT LOCATION	VEGETATION DESCRIPTION	TREATMENT	STREAMFLOW RESPONSE	SEDIMENT YIELD RESPONSE	REFERENCE
SOUTH AFRICA					
Bosboukloof, Jonkershoek, SW Cape	*Pinus* plantation/ mountain fynbos	Wildfire	TF increased by 12 11% in 1st and 2nd yrs PF increased by 290% and 108%	Suspended sediment yield incresed from 1.6 t/ha to 6 t/ha	Scott and Van Wyk, 1990
Swartboskloof, Jonkershoek, SW Cape	Mountain fynbos	Prescribed fire	TF increased by 16% over the 2 yrs after the fire	No significant increase	Scott and Van Wyk, 1992
Ntabamhlope, KwaZulu-Natal	*Eucalyptus*/grassland	Wildfire	Decrease in TF but significant shortening in time-to-rise of the hydrograph	1.35 t/ha	Scott, 1994
Kasteelskloof and Zachariashoek, SW Cape	Mountain fynbos	6 and 12 year prescribed burn	TF increased by 15% in 1st year reducing to 0 by 4th year	Sediment yields normal within 10 months	Lindley *et al.*, 1988
Langrivier, Jonkershoek, SW Cape	Mountain fynbos	Wildfire	No significnt changes in measured storm flow variables	Sediment yield normal by the first wet season	Van Wyk and Lesch, 1989, cited in Scott, 1994; Scott, 1994
Cathedral Peak, KwaZulu-Natal	Dense short grasslands	Wildfire and prescribed burn	Low flows unaffected by burning		Nänni, 1960
Cathedral Peak, KwaZulu-Natal	Dense short grasslands	Biennially burned grassland	No change in TF Small increase in SF	1.8 t/ha/a	Bosch *et al.*, 1984
		Annually burned firebreak	No increase in TF	0.02 t/ha/a	Watson, 1981
		Wildfire in pine plantation		At least 37 t/ha/a in 1st year	Van Wyk, 1985

CATCHMENT LOCATION	VEGETATION DESCRIPTION	TREATMENT	STREAMFLOW RESPONSE	SEDIMENT YIELD RESPONSE	REFERENCE
Cathedral Peak cont.		Unburned grassland	No change in TF	0.4 t/ha/a	
AUSTRALIA					
Snowy River Mountains, NSW	*Eucalyptus* forest	Wildfire	Large increases in PF and TF	25 000 to 100 000% increases in suspended sediment load	Brown, 1972
Warburton, Victorian Central Highlands	*Eucalyptus* forest	Wildfire	Estimated maximum of 51-103mm/h from single storm	Estimated net loss of 22t/ha from single storm	Leitch *et al.*, 1983
USA					
Tillamook Burns, Oregon	Coastal rainforest	Wildfire	TF increase of 11% PF 45% higher immediately after fire declining over 8 yrs	400-700% increase in sediment yield	Anderson, 1976
Burns watershed, Washington		Wildfire	TF increase of 120% over first 3 yrs	Observed debris, rock and soil flows	Helvey *et al.*, 1976
Coconino National Forest, Arizona	*Pinus* forest	Wildfire	TF increase of 700 and 280% in 1st and 2nd yrs	1.7 t/ha in first 2 yrs (40 000% increase)	Campbell *et al.*, 1977
SPAIN					
Sierra de Almijara, S Spain	*Pinus* woodland	Wildfire	TF reverted within 2 yrs PF increased after fire but reverted within 5-8 yrs		May, 1990

TF - Total annual runoff; PF - Peak discharge

Table 2.2: Summary of measurements of sediment yield and runoff from plots.

LOCATION	PLOT SIZE	VEGETATION TYPE	TREATMENT	RUNOFF (as % of rainfall)	SEDIMENT YIELD	REFERENCE
SOUTH AFRICA						
Ntabamhlope, KwaZulu-Natal	1 x 23m	Short, dense grassland	Unburnt	12.6%	0.088 t/ha/a	Scott, 1951
			Annual winter burn	9.2%	0.514 t/ha/a	Scott, 1994
Ntabamhlope, KwaZulu-Natal	3 x 22m	*Eucalyptus* plantation	Wildfire		Estimated at 52 t/ha (control: 0.1 t/ha)	Scott, 1994
Kamberg, KwaZulu-Natal	2 x 22m	Short, dense grassland	Prescribed biennial burn		10-80g/m^2 (control: 0)	Garland, 1987
Bosboukloof, Jonkershoek, SW Cape	3 x 18m	*Pinus* plantation	Wildfire		9.9 to 25.9 t/ha/a	Scott and Van Wyk, 1990
Swartboskloof, Jonkershoek, SW Cape	3 x 22m	Mountain fynbos	Prescribed burn	2.2 - 4.5% (control: 0.8)	16.4 - 57.4 t/ha (control: 0.4 t/ha)	Scott, 1994
Langrivier, Jonkershoek, SW Cape	3 x 22m	Mountain fynbos	Wildfire	2.17 to 2.06% for 1st and 2nd yrs (control: 0.81 to 0.66%)	1.1 to 1.99 t/ha/a (control: 0.0132 to 0.0016 t/ha/a)	Scott, 1994
AUSTRALIA						
Narrabeen Lagoon, NSW	2 x 4m	Bushland	Wildfire	Mean: 3-5%	2.5 to 8.2 t/ha/a	Blong *et al.*, 1982
USA						
San Gabriel and Santa Ana mtns	3 x 12m	Chaparral	Hot prescribed burn		Gentle slopes: 2.8 Steep:7.3 t/ha/a	Krammes and Osborn, 1969

LOCATION	PLOT SIZE	VEGETATION TYPE	TREATMENT	RUNOFF (as % of rainfall)	SEDIMENT YIELD	REFERENCE
CENTRAL AMERICA						
Siguatepeque, Honduras	1 x 10m	*Pinus*/savanna	Low intensity prescribed burns	5% (3 x higher than control)	0.8 t/ha/a (20 x higher than control)	Hudson *et al.*, 1983
SPAIN						
Galicia	4 x 20m	*Ulex europaeus* scrub	Prescribed burn		0.27 t/ha (control: 0.19)	Díaz-Fierros *et al.*, 1990
Prades mtns, Catalan Coastal Ranges	20 x 40m²	Mixed woodland	Prescribed burn	c.14 x greater than control	0.162 t/ha/a (control: 0.017 t/ha/a)	Soler and Sala, 1992
Albatera	20 x 4m		Low intensity prescribed burn	Pre-burn yr: 9.5% Post-burn yr: 0.8%	Before: 8.87g/m² After: 0.02g/m²	Sanchez *et al.*, 1994
Porta-Coeli, Valencia	40 x 8m	*Rosmarinus/Ericion*	Wildfire (14 yrs ago)		8.32 t/ha	Andreu *et al.*, 1994
NW Spain	4 x 20m	*Ulex europaeus* scrub	Control	3%	50 to 153.8g/m² for 1st and 2nd yrs	Soto *et al.*, 1994
			Light fire	6.7%	225.7 to 247.7g/m²	
			Moderate fire	5.4%	219.8 to 418.8g/m²	
Sierra de los Bosques, Pedralba	0.19 - 0.23m²	*Pinus*/matorral	Wildfire (simulated rainfall)	Mean: 0.33%	Mean: 106.47g/m²	Calvo-Cases and Cerda-Bolinches, 1994
Prades mtns, Catalan Coastal Ranges	200m²	Mixed woodland	Prescribed burn (simulated rainfall)	14.6 x greater than control	16.4 x greater than control	Soler *et al.*, 1994
ISRAEL						
Yoqneam Forest	162 - 149m²	*Pinus* forest	Moderate wildfire	0.6 x greater than control	0.046g/m² (control: 0.08g/m²)	Kutiel and Inbar, 1993

LOCATION	PLOT SIZE	VEGETATION TYPE	TREATMENT	RUNOFF (as % of rainfall)	SEDIMENT YIELD	REFERENCE
Mount Carmel	1 x 1m	Open-closed *Pinus/Quercus*	Wildfire and prescribed	22.9% (control: 6.1%)	37.3g/m^2 (control: 13.5g/m^2)	Kutiel *et al.*, 1995
PORTUGAL						
Agueda Basin	8 x 2m	*Pinus* forest	Wildfire		22.59g/m^2 (control:0.66g/m2)	Shakesby *et al.*, 1994
Agueda Basin	8 x 2m	*Pinus* forest	Wildfire	9.2% (control:0.1%)	85.5g/m^2 (control: 0.5g/m^2)	Terry, 1994

2.3.1 Sediment yield

Terry (1994) found that the erosion rate in forests in Portugal one year after burning is 170 times that of unburnt mature pine. Soil loss from experimental plots in the wooded Catalan Coastal Ranges in Spain were 12.1 to 8.4 times higher for the burnt plot than for the woodland control plot (Soler and Sala, 1992; Soler *et al.*, 1994). These authors emphasise that in forest areas the erosion rates following burning are determined as much by the changes resulting from burning as by the post-burn land use practices of the landowner.

Although Soto *et al.* (1994) reported a higher soil loss from burnt plots than from control plots, no significant difference between plots burnt by a moderate fire and those which received a light burn was recorded. This was attributed to the similar loss in vegetation cover experienced by the two plots and that the temperatures induced by the fire were insufficient to alter the soil structure.

Fourteen years after a fire, the long term effects of fire on soil erosion was tested in Valencia using adjacent experimental plots. Andreu *et al.* (1994) found that soil loss from a bare plot was greater than from the vegetated plot. Only three rain events were analysed and soil loss was not excessively high. This is attributed by the authors to the high percentage of organic material and the good stability of the soil together with the armouring of the soil by stones. Armouring was also noted by Calvo-Cases and Cerda-Bolinches (1994) as a significant factor in the reduction of sediment yield from burnt plots in the same area.

In Israel a light wildfire in the Yoqneam Forest did not result in an increase in sediment yield because the temperature was not intense enough to cause changes in soil structure (Kutiel and Inbar, 1993). At Mount Carmel spatial variability was noted as a dominant factor in the response of the area to both wild and prescribed fires (Lavee *et al.*, 1995; Kutiel *et al.*, 1995). Aspect also played a role in a severe wildfire in the Snowy River Mountains of Australia (Brown, 1972), where observations of sheet erosion, particularly on north-facing slopes, were made. Garland (1987) recorded an increased soil loss from soil plots in the KwaZulu-Natal Drakensberg after a prescibed burn treatment. A wildfire in a grassland catchment at Cathedral Peak resulted in a significant increase in sediment yield in comparison to a protected grassland (Van Wyk, 1985). Longer term studies are needed to improve the reliability of studies undertaken in the KwaZulu-Natal

Drakensberg so that a data base of catchment response to fire can be built up allowing for a more inclusive burning policy to be formulated. The protected grassland yielded 0.4 tons/ha/a whereas the burnt catchment released 1.8 tons/ha/a. Stocking (1984) indicates that normal rates of erosion in Africa should not exceed 5 tons/ha/a suggesting that the short term losses experienced by the burnt catchment are not excessive. It appears therefore that fire does play a role in increasing erosion rates from both catchments and from runoff plots but that the severity of the losses are dependent on the vegetation type and how quickly it regenerates. Much of the controversy surrounding the effect of burning seems to arise out of the varying impacts which fire has on different vegetation types. Grassland areas recover from fire faster than, for example, a forest does and the fire temperatures generated by the biomass of a forest will also be much higher than for a grassland.

2.3.2 Soil hydrology

In Valencia, Spain, low soil moisture following a severe forest fire aided rapid infiltration and only with rainfall intensities in excess of 180 $mm.hr^{-1}$ was runoff generated (Calvo-Cases and Cerda-Bolinches, 1994). Other researchers report that the mean annual runoff coefficient for burnt plots in the same area were consistently higher than for the control plots (Soler and Sala, 1992; Soto *et al.* 1994), although meaningful runoff was only produced when rainfall intensity exceeded $20mm.day^{-1}$. Research on afforestation by Terry (1994) has shown that in burned pine the runoff coefficient (9.2%) immediately after burning was higher than for mature forest (0.1%) but is comparitively low when compared to rip-ploughed land (16.7%). A ground fire in Israel failed to result in a significant increase in runoff because of the high rate of interception by the undamaged forest canopy (Kutiel and Inbar, 1993). They observed that total runoff was actually higher in the unburnt than in the burnt plot which was attributed to increased surface roughness. Lavee *et al.* (1991) observed a similar phenomenon and emphasise the importance of micro-environmental conditions, i.e. the amount of burnt woody material which acts as a mulch, small depressions created during the fire and the existence of a fine ash on the soil surface, on overland flow generation and erosion. In stable structured soils these factors are believed to play an important role in preventing overland flow. Further research by Lavee *et al.* (1995) has shown that the main effect of low to moderate intensity fires is the production of a mosaic-like surface of rough patches in which there is little probability of runoff generation and smooth patches with higher runoff and erosion rates. This mosaic of runoff generating and runoff accepting areas means that the probability of overland flow reaching the valley is small (Imeson *et al.*, 1992;

Kutiel and Inbar, 1993; Kutiel *et al.*, 1995; Lavee *et al.*, 1995) and at the macro-scale runoff and sediment yield after a fire are insignificant. However, a high intensity fire will consume the vegetation completely, leaving a layer of white ash and producing a smooth homogeneous soil surface. In this case more overland flow and sediment yield even at the macro-scale would be expected. An ash layer may also act as a protective layer for the soil against the direct impact of rainfall and runoff.

The duration of the effects of burning will depend upon the time taken for the vegetation to recover to pre-fire conditions (Díaz-Fierros *et al.*, 1990). In forest areas pre-burn conditions may take 10 years to return and vegetation recovery in Mediterranean ecosystems may take several decades. In fynbos catchments of the south-western Cape the effects of fire on water yield are largely mitigated by the rapid recovery of the vegetation (Lindley *et al.*, 1988; Davies *et al.*, 1993). Similarly, fire in the montane grassland of the KwaZulu/Natal Drakensberg resulted in no significant changes in stream flow or sediment yield (Nänni, 1960; Bosch, 1980; Watson, 1981) which can also be attributed to the recovery of the grassland to full canopy biomass within two months of the growing season (Everson *et al.*, 1989).

It is clear from the above review that fire does influence erosion rates. However, the significance of this influence varies because of site-specific conditions such as vegetation type and soil moisture. In order to clarify some of the more contradictory results presented in the literature, 15 runoff plots were installed at GGHNP, to monitor the effect of burning on runoff, sediment yield and soil properties in a grassland area. The experimental design for the research at GGHNP is outlined in the following chapter.

CHAPTER THREE

Experimental Design and Plot Description

"When Prometheus in Greek mythology brought fire to man, he gave him life and made him into a demigod..."

-J. Bronowski, 1973 (p. 124)

The study was based on two geomorphological considerations; the effect of fire on soil properties and how fire influences runoff and sediment yield. For these purposes 15 runoff plots were installed in GGHNP on slopes of varying gradients and aspects.

3.1 Plot design

Runoff plots are used to establish erosion rates for predetermined areas under specific soil, rainfall and vegetation cover conditions (Mutchler *et al.*, 1994, Sumner, 1994). Plot design was based on that used by Williams and Buckhouse (1991) and adapted from that used by Day *et al.* (1994) and Sumner (1994) for the monitoring of path erosion in the KwaZulu-Natal Drakensberg. Plot size was optimised at 2m x 10m. The plot length was largely determined by the constraints of the slope length to insure that the gradients were mostly constant within the plots. Plot size was constrained by the need to have the plots in close proximity to one another to minimise the spatial variation in rainfall. This sized plot is large enough to represent the combined processes of rill and interrill ersoion and is classified as a USLE type plot (Mutchler *et al.*, 1994).

The plots were drained at their lower end by means of a customised nose cone constructed of metal sheeting. This was linked to a length of galvanised metal gutter which fed into a tipping bucket system. The design of this is shown in Figure 3.1. Each tip of the one litre capacity bucket was registered by an electronic counter. The soil was collected in two buckets which were adapted to trap sediment coarser than 0.063mm (4ϕ). The loss of material finer than 0.063mm was seen as insignificant because sandy soils predominate in GGHNP as a result of the underlying Sandstone geology, with fines making up only a small percentage. The mesh enabled the water to flow out of the buckets preventing overflow and loss of sediment. The use of a smaller mesh was also rejected because it became blocked more easily thus preventing water outflow.

Figure 3.1: The customised nose cone and tipping bucket system used to monitor runoff and sediment yield.

The plots were installed over a period of four months from April to July 1994.

3.2 Plot location

The location of the plots was determined by gradient, aspect and ease of access for purposes of installation and data collection. The nature and variation of both vegetation and soils were also considered when selecting sites for the plots. The plot sites on both slopes were demarcated by signposts which informed the public of the aims of the project and requested them not to interfere with the equipment.

A summary of each plot's physical characteristics and the treatment applied are presented in Table 3.1 while a plan view of the plots is provided in Figure 3.2.

Table 3.1: Summary of the aspect, gradient and treatment of the 15 runoff plots installed at GGHNP

PLOT	ASPECT	GRADIENT	TREATMENT
A	North-facing	14°	Winter burn
B	North-facing	13°	Spring burn
C	North- facing	13°	No burn
D	North-facing	20°	Winter burn
E	North-facing	19°	Spring burn
F	North-facing	21°	No burn
G	North-facing	27°	Winter burn
H	North-facing	29°	Spring burn
I	North-facing	28°	No burn
J	South-facing	10°	Spring burn
K	South-facing	15°	Spring burn
L	South-facing	18°	No burn
M	South-facing	28°	Spring burn
N	South-facing	21°	Annual firebreak
O	South-facing	8°	Annual firebreak

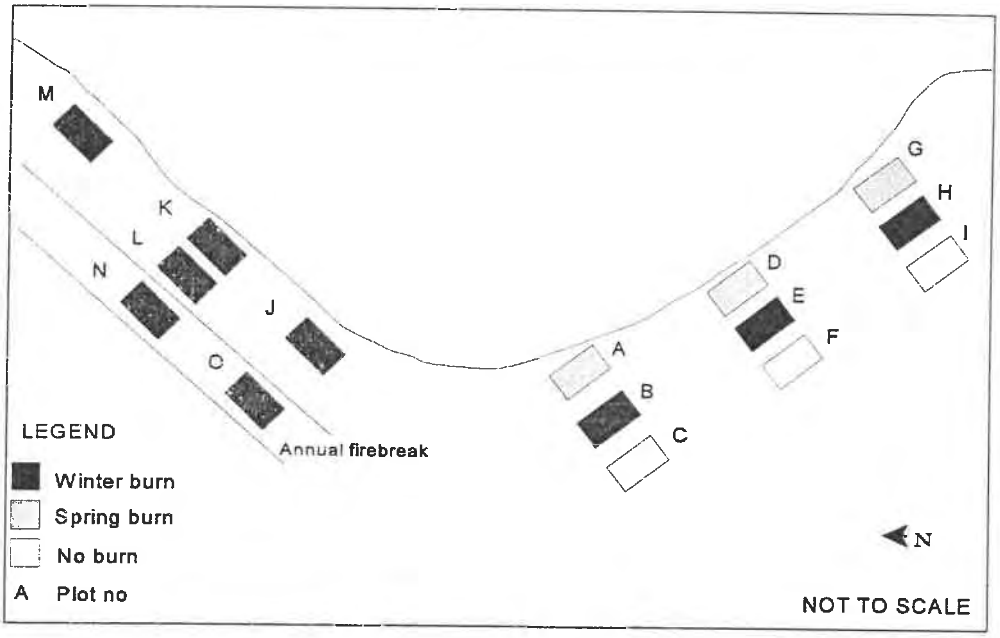

Figure 3.2: Plan view of the relative position of the runoff plots.

A longitudinal profile of each plot was taken and these showed that despite attempting to situate the plots on slope lengths of constant gradient, small variations of gradient do occur within the plots (Figures 3.3a-o).

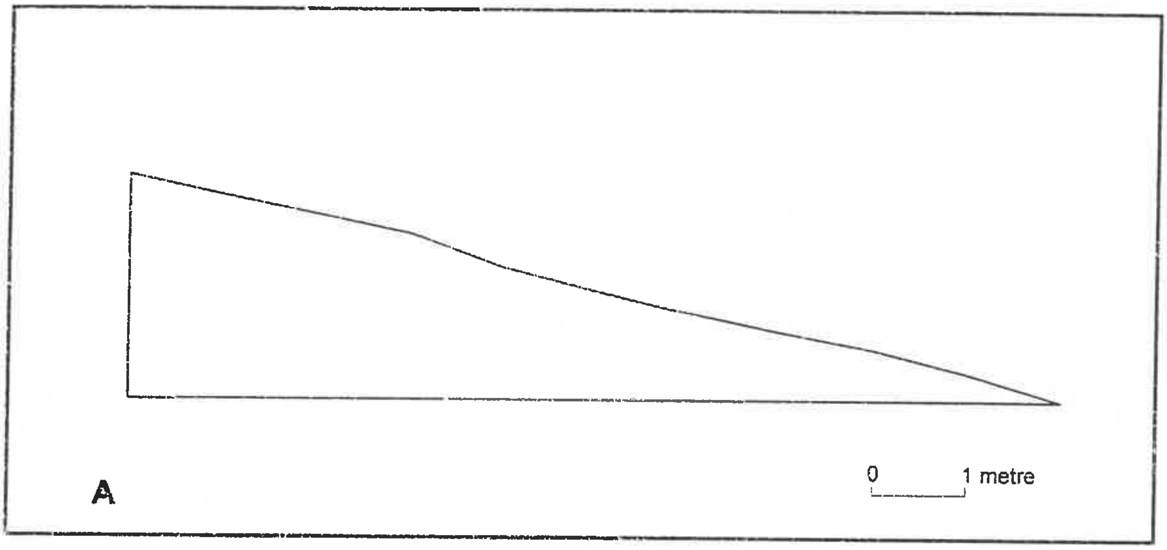

Figure 3.3a: Longitudinal profile of plot A.

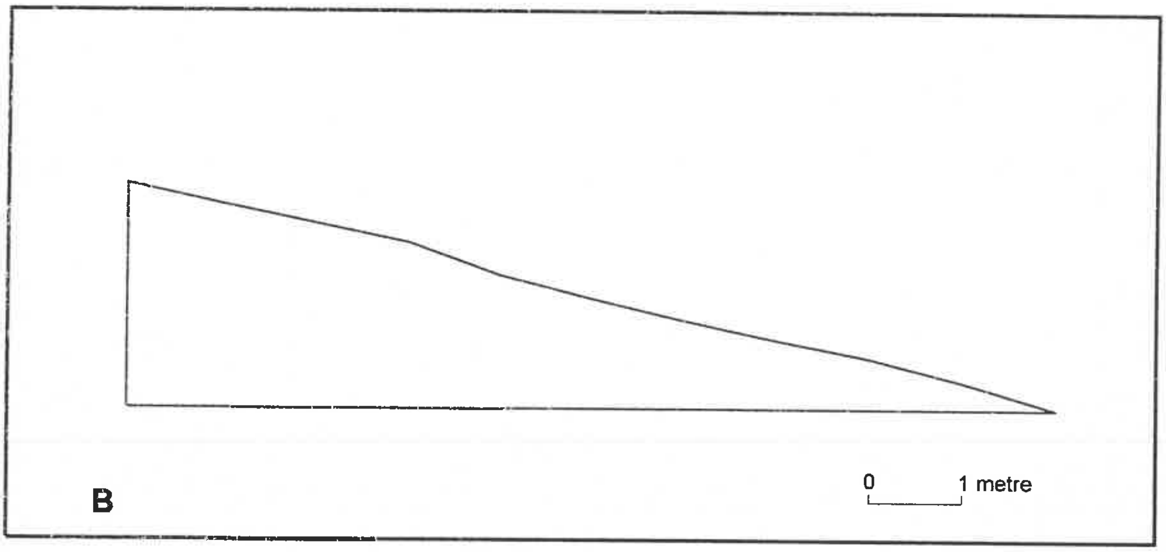

Figure 3.3b: Longitudinal profile of plot B.

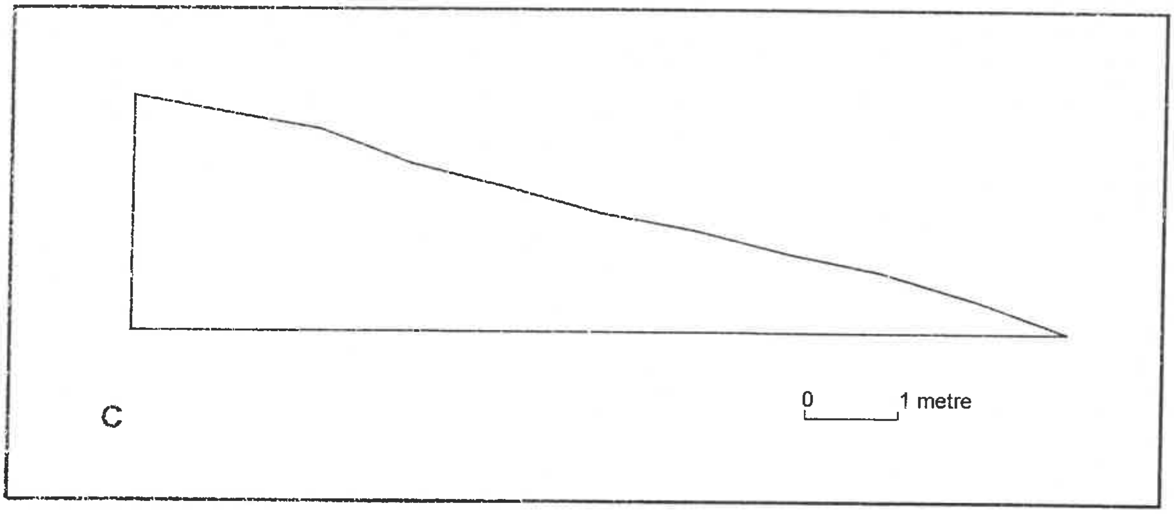

Figure 3.3c: Longitudinal profile of plot C.

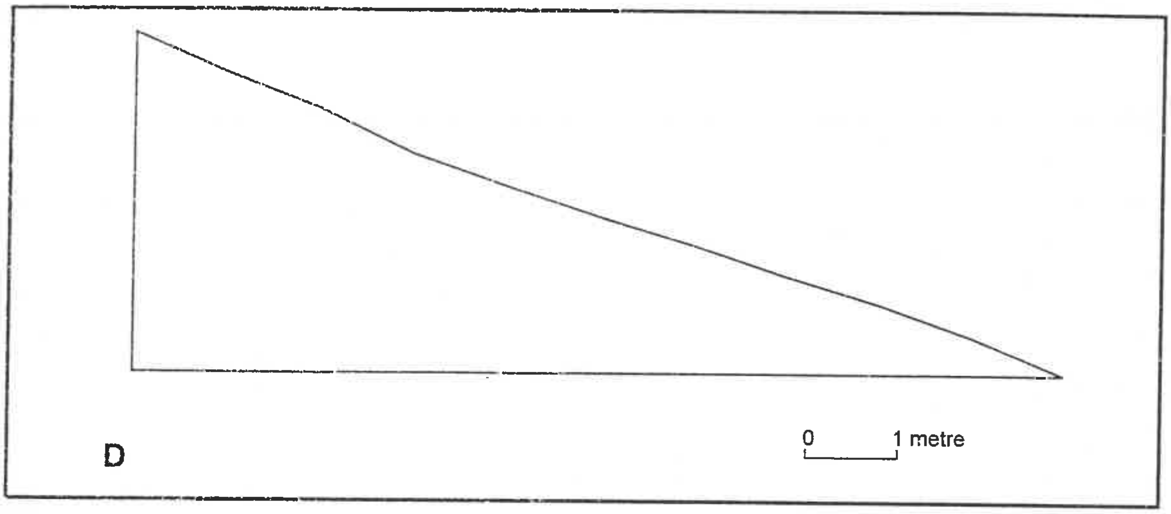

Figure 3.3d: Longitudinal profile of plot D.

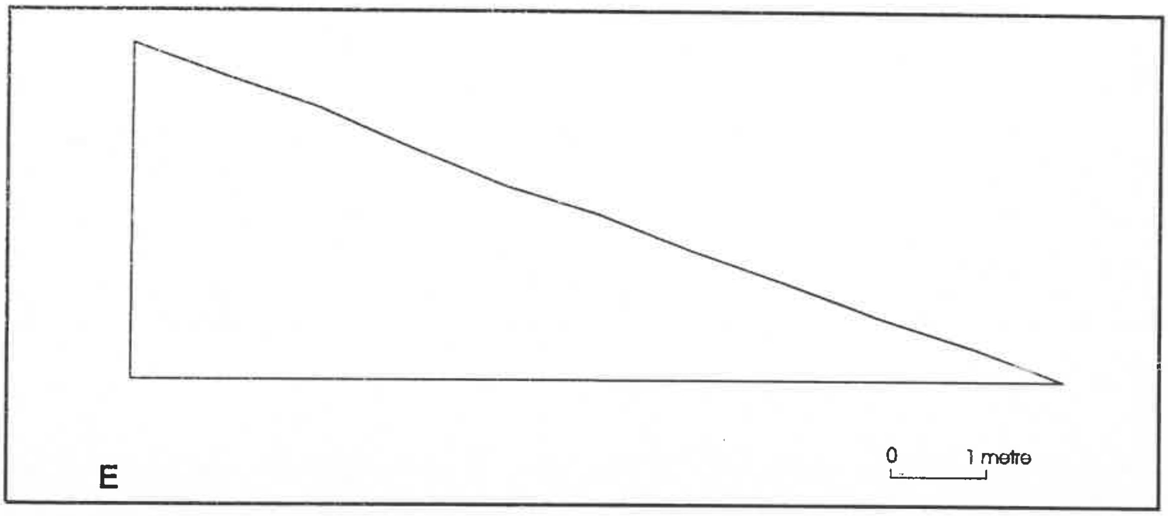

Figure 3.3e: Longitudinal profile of plot E.

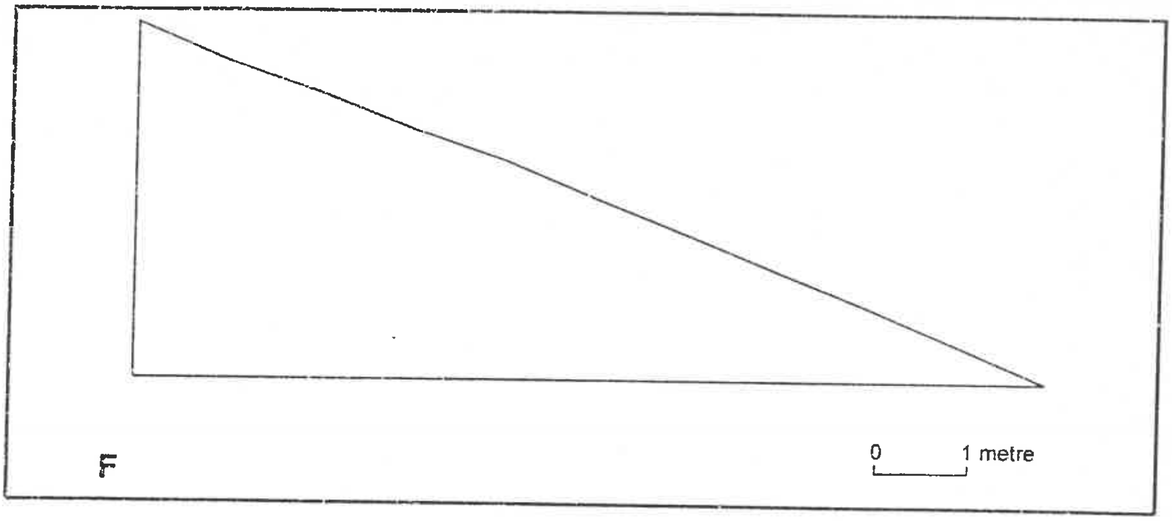

Figure 3.3f: Longitudinal profile of plot F.

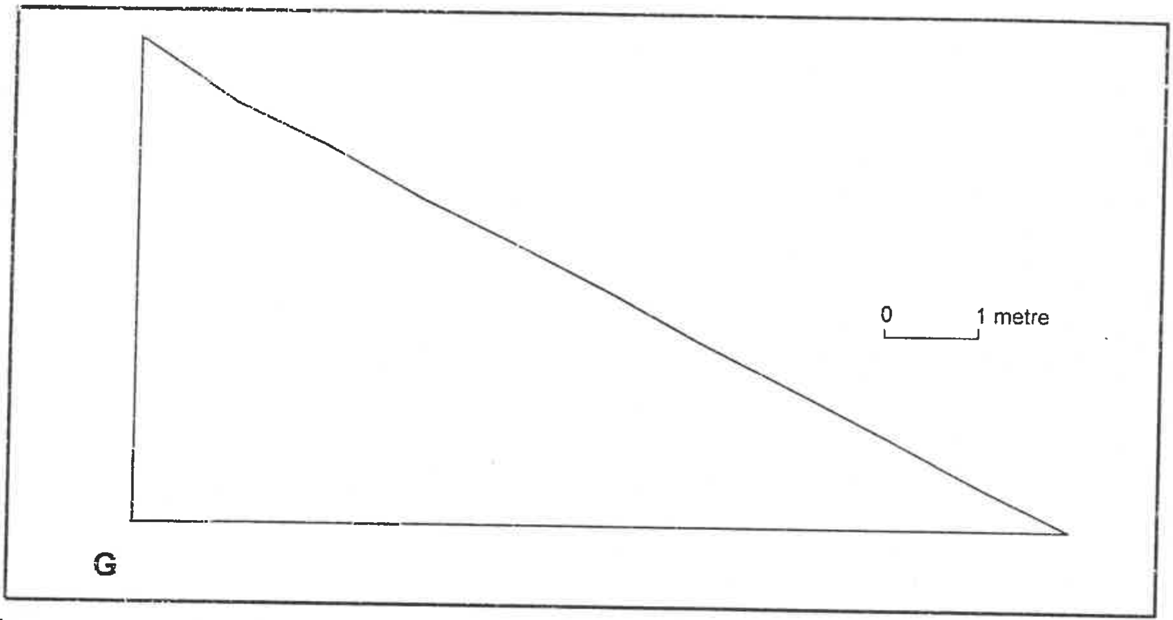

Figure 3.3g: Longitudinal profile of plot G.

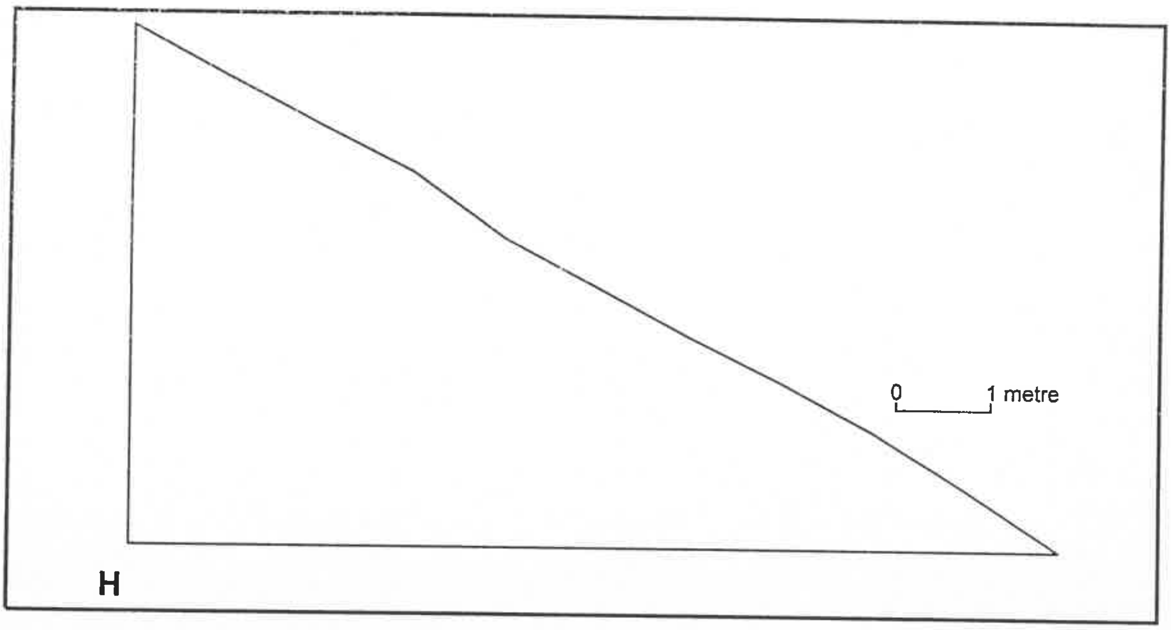

Figure 3.3h: Longitudinal profile of plot H.

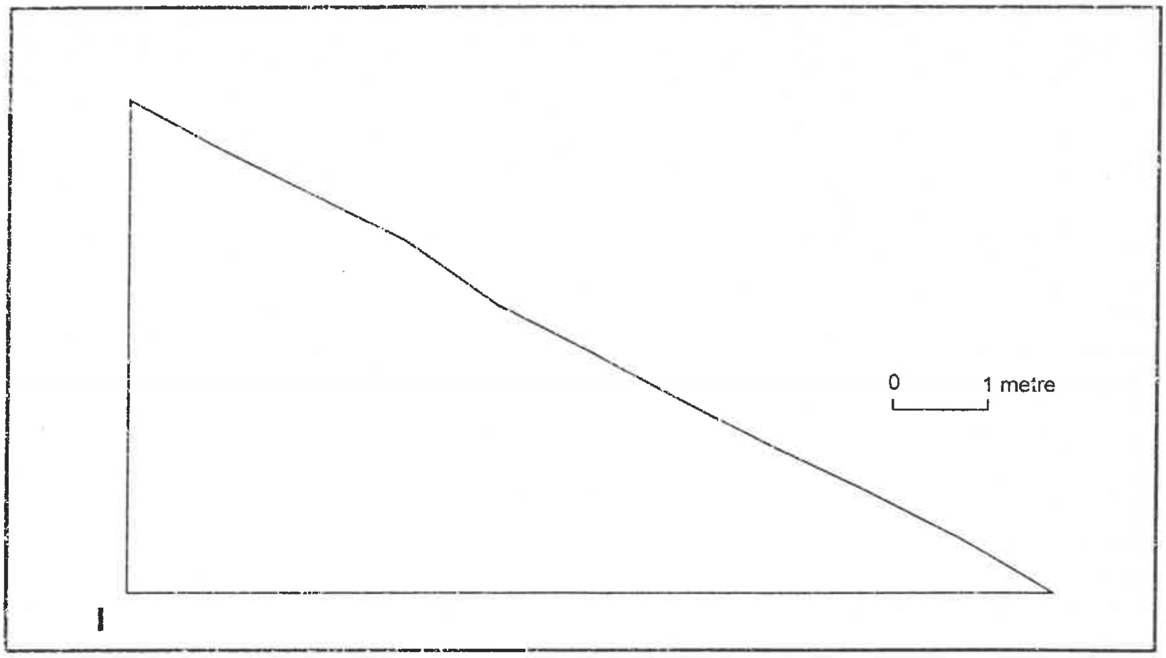

Figure 3.3i: Longitudinal profile of plot I.

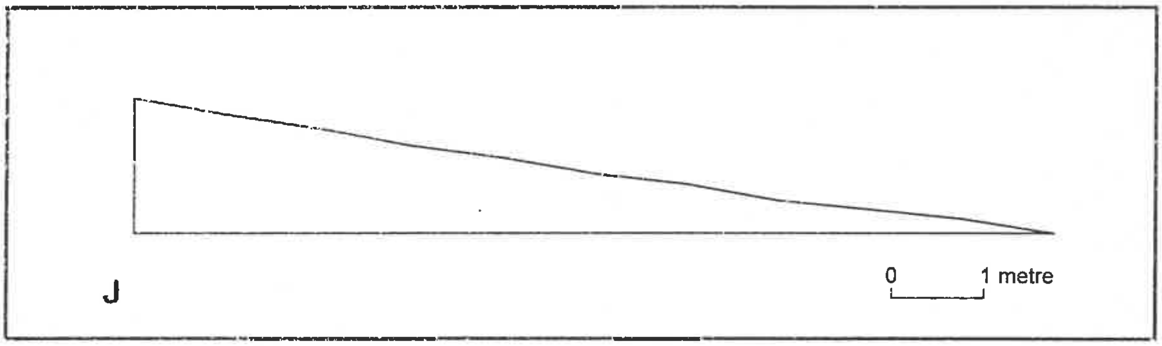

Figure 3.3j: Longitudinal profile of plot J.

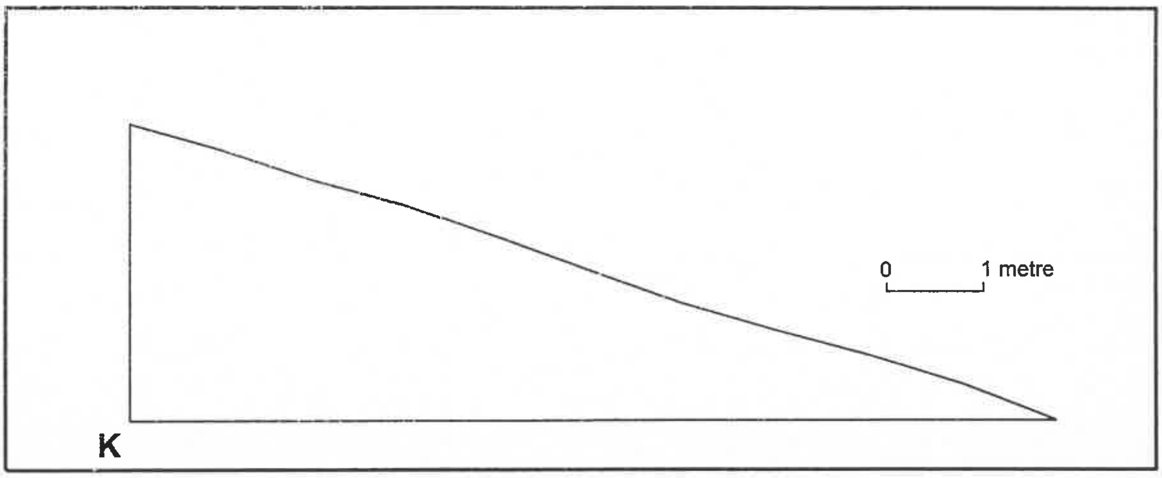

Figure 3.3k: Longitudinal profile of plot K.

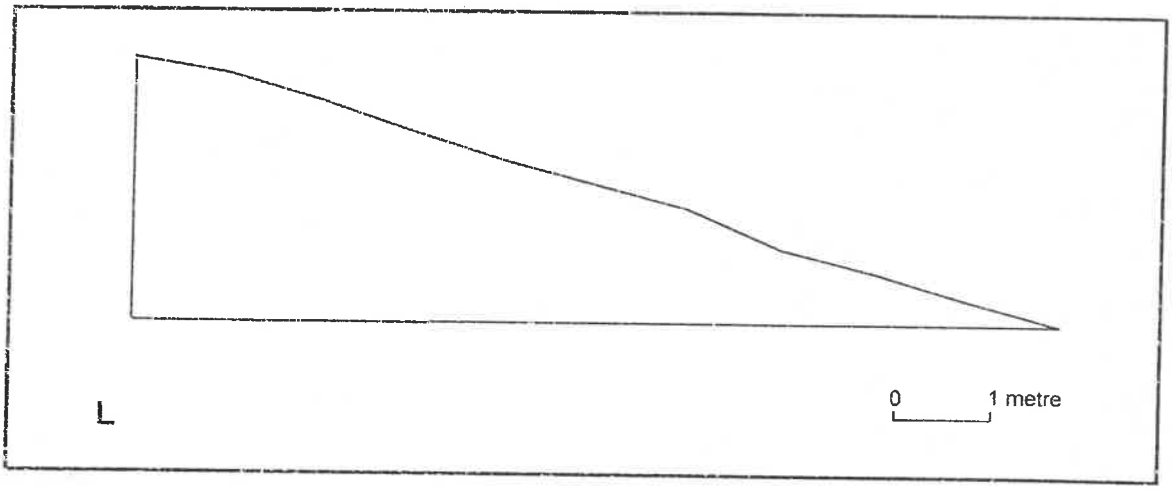

Figure 3.3l: Longitudinal profile of plot L.

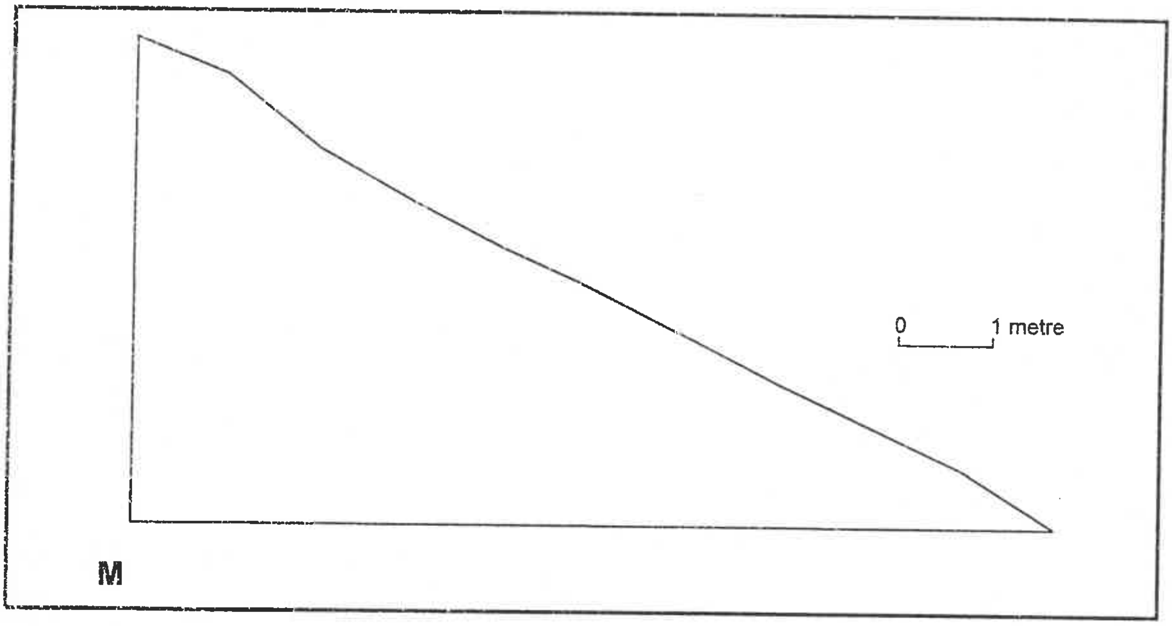

Figure 3.3m: Longitudinal profile of plot M.

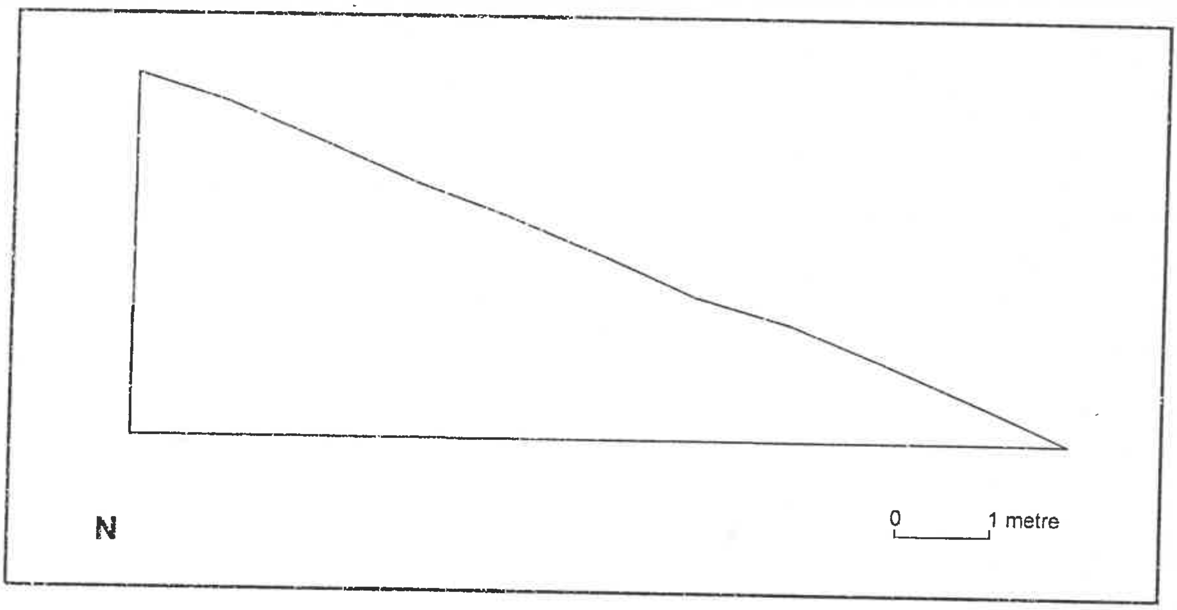

Figure 3.3n: Longitudinal profile of plot N.

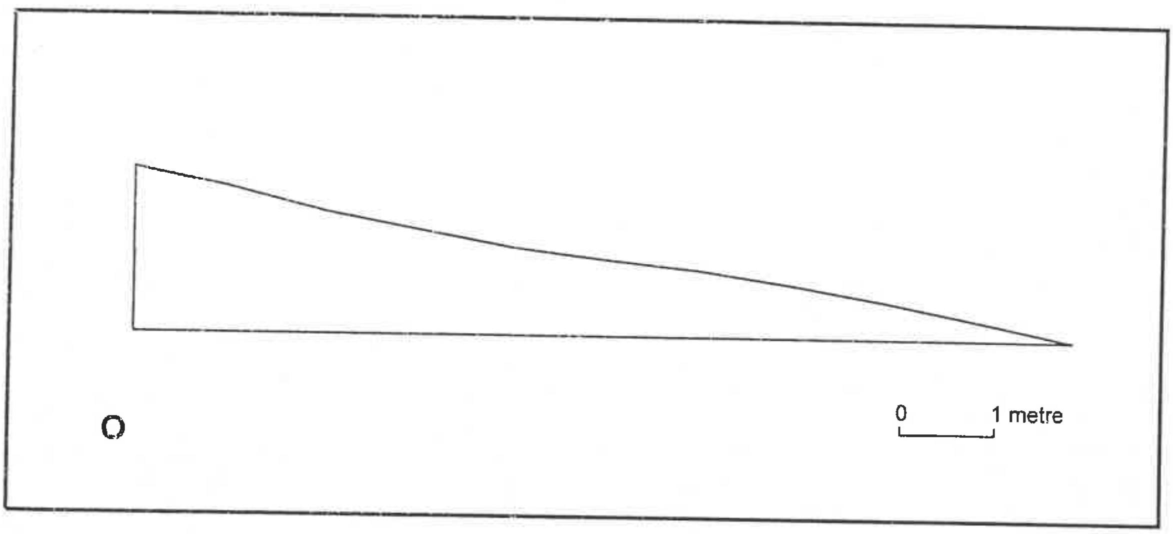

Figure 3.3o: Longitudinal profile of plot O.

3.3 Monitoring

3.3.1 Sediment yield and runoff

Sediment was to be collected on a weekly basis in one litre containers and the runoff counter readings taken after each rain event. The sediment was stored at GGHNP for later removal and analysis at the University of Natal laboratory.

The plots were checked regularly for disturbance and, although public cooperation was generally good, interference by baboons, horses and wind proved problematic. Animal disturbance decreased with time as they became used to the presence of the equipment.

Soil samples were analysed from the areas adjacent to the plots to act as controls, therby enabling comparisons with the sediment collected after rain events..

3.3.2 Rainfall monitoring

The effectiveness of rainfall as an erosive process is linked to its ability to detach the soil particles and to its capacity to generate runoff. Erosivity is dependent on the intensity and volume of precipitation suggesting a site-specific threshold value of rain intensity below which rain is not erosive (Wicherek, 1989). The weather station at GGHNP is not automated which necessitated the installation of a data logger to measure both the intensity and volume of the rain. However, technical malfunctions and moisture build-up in the circuitry of the logger caused significant data loss. Consequently data from the four surrounding automated weather stations namely, Ficksburg, Bethlehem, Tshiame and Van Reenen, were obtained and correlated with the total rainfall received at GGHNP, in an attempt to interpolate representative values for rainfall intensity during individual storm events.

3.3.3 Soil properties

The basic hypothesis that erodibility of the soil is dependent on two components - organic matter and particle size; and two properties - soil structure and infiltration (Wischmeier and Mannering, 1969); is still generally accepted (see for example Morgan, 1986). To determine if fire has any effect on the erodibility of the soil these components and properties had to be analysed. The effects of fire were determined at four stages; immediately before and after a fire, and subsequently two months and one year after burning.

All the burns analysed in this Section occurred in August and were classified as winter burns. The spring burns were not analysed with respect to soil properties as it is the temperature of the fire which is the important factor in this experiment rather than the timing of the fire. The effect of burn timing is discussed in Chapter 5. The review in Section 2.2 has also shown that even though the higher fuel load in spring would produce a higher fire temperature, and the greater soil moisture would conduct the temperature deeper into the soil profile, the temperatures produced by grassland fires are generally insufficient to cause structural changes in the soil. Most prescribed burning occurs during the winter months and therefore practically it was also seen as more valuable to use winter burns for this experiment. All of the monitored burns were classified as light to moderate fires.

A further field experiment on plots N and O was conducted on August 1, 1995 to determine the temperature profile of the soil during a prescribed fire-break burn. The burn was classified as very light (de Kock, *pers. comm.*, 1995) because of the low fuel load present on the plots as a result of the extremely dry summer growing season.

3.3.3.1 Particle size analysis

The texture of the oven dried sediment was analysed using a vibrating sieve stack. The general procedure for sieve stack analysis as outlined by Briggs (1977) was followed. Standard 200mm sieves at regular phi units from -3ϕ (8mm) to 4ϕ (63 μm) were used. Sumner (1994) points out that differences in particle size classification exist in the International, the United States Department of Agriculture and the Wentworth scale classification systems. The laboratory sieves used in this study corresponded to the Wentworth scale and therefore for practical purposes this was the classification system employed.

Mean, sorting and skewness values were obtained from the cumulative percentage graphs for cumulative particle size distribution using the classifications for skewness and sorting provided by Briggs (1977).

CHAPTER FOUR

The effect of fire on soil properties

"We hold the flame for the planet. The Earth's trial by fire is our own."

- S.J. Pyne (1993, p. 264)

The results and accompanying discussion presented in this chapter is an analysis of the effects of controlled winter burning on those soil properties which affect soil erodibility. The reasons for the exclusion of the spring burns for this analysis are outlined previously in Section 3.3.3. The burns under discussion in this Section ocurred during August on the south-facing Gladstone site under controlled conditions, with the exception of the Oorbietjiekom fire described in Section 4.2.

4.1 Fire temperature

The temperature of the prescribed burn applied on the south-facing slope near Gladstone (Figure 4.1) was measured using thermo-couples and temperature meters supplied by the Electronics Workshop of the University of Natal, Pietermaritzburg. Temperature was measured within a grass tuft (+2cm above soil surface), at the soil surface and at 5cm depth (root-depth). The results obtained are shown in Figure 4.2.

Figure 4.1: Prescribed burning on Plot N on the south-facing slope.

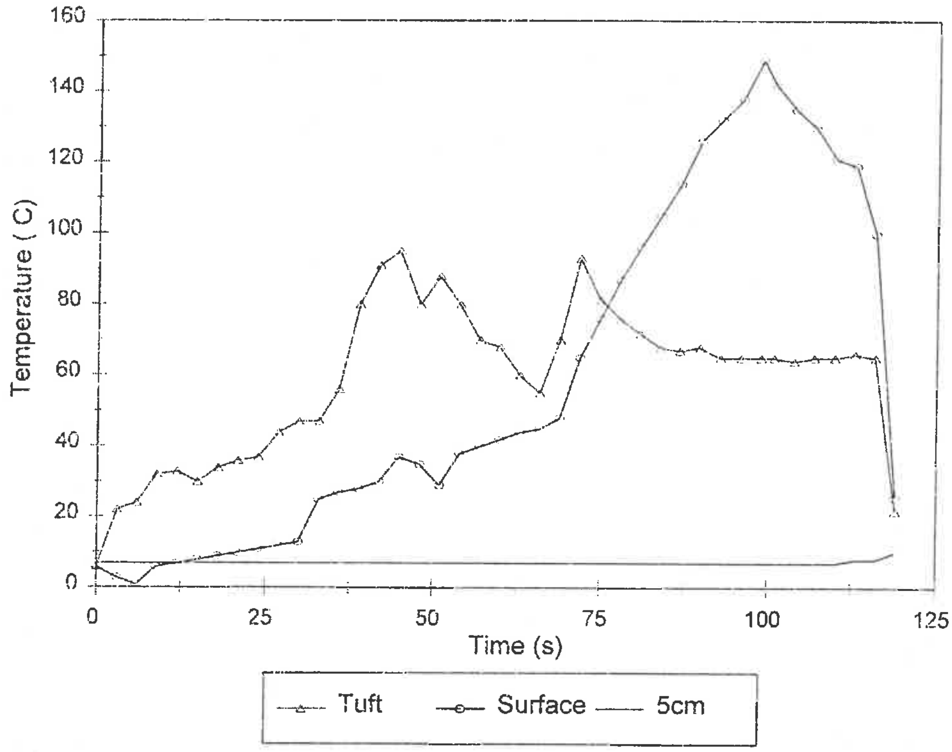

Figure 4.2: Soil temperature variations at different positions relative to soil surface.

The fire was short-lived because of the low fuel load and temperatures did not exceed 150°C. The highest temperature was recorded at the surface and temperature increase at depth was not recorded. The tuft temperature rose as the flames passed over the sensor and then remained constant, probably insulated to some extent by ash. The burn occurred during August when the soil moisture was very low (<10%) and thus the soil did not conduct the fire heat through the profile. The fire was also of a very short duration and this did not allow time for the heat to be conducted. The temperatures that were measured during the prescribed burn were insufficient to effect changes in clay mineralogy and soil structure. It is also unlikely that such a light intensity burn significantly affected the organic matter content. The slight increase in organic matter that was recorded can be attributed to the addition of ash as suggested by Trabaud (1983).

4.2 Infiltration

Infiltration capacity of the soil was measured immediately before; two hours, two months, and again at one year after the fire. Following the work of King (1981) two methods were employed. The first involved the use of a single ring infiltrometer inserted into the ground to a depth of 50mm. The water drop penetration time was the second method used, which is simply the average time taken for a drop of water to be absorbed by the soil. The latter method was found to be the most practical for a field test because it can be replicated a number of times without the need for large quantities of water to be carried to the field site.

Table 4.1: Results of the infiltrometer and drop test at different time intervals before and after burning.

METHOD	BEFORE	AFTER	2 MONTHS	1 YEAR
INFILTROMETER (mm/hr) *	378.01	383.28	231.08	204.08
DROP TEST (s)	0.84	1 73	1.45	1.12

* ml/hr converted to standard mm/hr (Finlayson and Statham, 1980)

A comparison of infiltration rates was made between the plots on the south-facing slope at of Gladstone, and in the area known as Oorbietjiekom (see Figure 1.1). Both fires were firebreak burns, but they differed in their intensities. Using standard veld management criteria the Gladstone fire was described as a cool burn, whereas the Oorbietjiekom fire was classified as a hot fire (de Kock, pers. comm., 1995). The fuel load for the Oorbietjiekom fire was high and the windspeed increased during the burn from negligible to gusting, creating adverse conditions for controlled burning.

Table 4.2: Comparison of the infiltration rates at Gladstone and Oorbietjiekom.

SITE	INFILTRATION RATE (mm/hr)		PERCENTAGE CHANGE
	BEFORE BURN	AFTER BURN	
Gladstone	378.01	383.28	-1.4%
Oorbietjiekom	978.20	455.50	+53.4%

(By convention, -ve denotes a decrease and *vice versa*)

The small change in infiltration rate at the Gladstone site is less than the 5% fluctuation that may be attributed to local variation during replication and can thus be ignored. In contrast, the more intense fire at Oorbietjiekom resulted in a significant reduction in infiltration rates.

For the water drop test, results below 10 seconds are indicative of insignificant to very low water repellence (King, 1981). Infiltration rate can be correlated to the percentage of organic matter, particularly an unincorporated litter layer (Scott, 1994). In grasslands the litter layer is usually removed by regular burning, and at GGHNP the percentage of organic matter within the soil appears to have a negative effect on the infiltration of water. This is contrary to the theory that infiltration is improved by a high organic matter content (Evans, 1980). It is possible that some form of hydrophobicity has developed, but the frequency of fires in this area does tend to negate the possibility of fire-induced repellency resulting from hydrophobic organic substances as discussed in Section 2.2.1.4. The levels of organic matter content found for the soils in GGHNP in this study are indicative of a stable soil with good structural condition (Hazelton and Murphy, 1992) and therefore theoretically should have good infiltration. There was little evidence of heat-induced crusting, probably because of the low temperatures of the prescribed burn. Surface sealing may be responsible for the decreasing infiltration rates as the season progresses. The poor rains at the beginning of the season imply that the effects of surface sealing would have only become apparent later in the year, and thus the anomolous infiltration rates may be more a function of the contrary rain season than a negative correlation between organic matter and infiltration rate.

The 50% decrease in infiltration rate recorded at Oorbietjiekom is probably related to the higher fire temperatures that would have been generated by the greater fuel load and adverse burning conditions. A more intense fire would have evaporated the surface soil moisture resulting in a hydrophobic surface soil layer, as described in Section 2.2.1.4.

4.3 Aggregate stability and Organic matter content

Soil samples for the determination of organic matter content and aggregate stability were taken from areas adjacent to the plots to minimise plot disturbance. Aggregate stability was determined by wet sieving as outlined in Grieve (1979) and using the percentage water stable aggregate classes recommended by Bryan (1971). Results are presented in Figure 4.3.

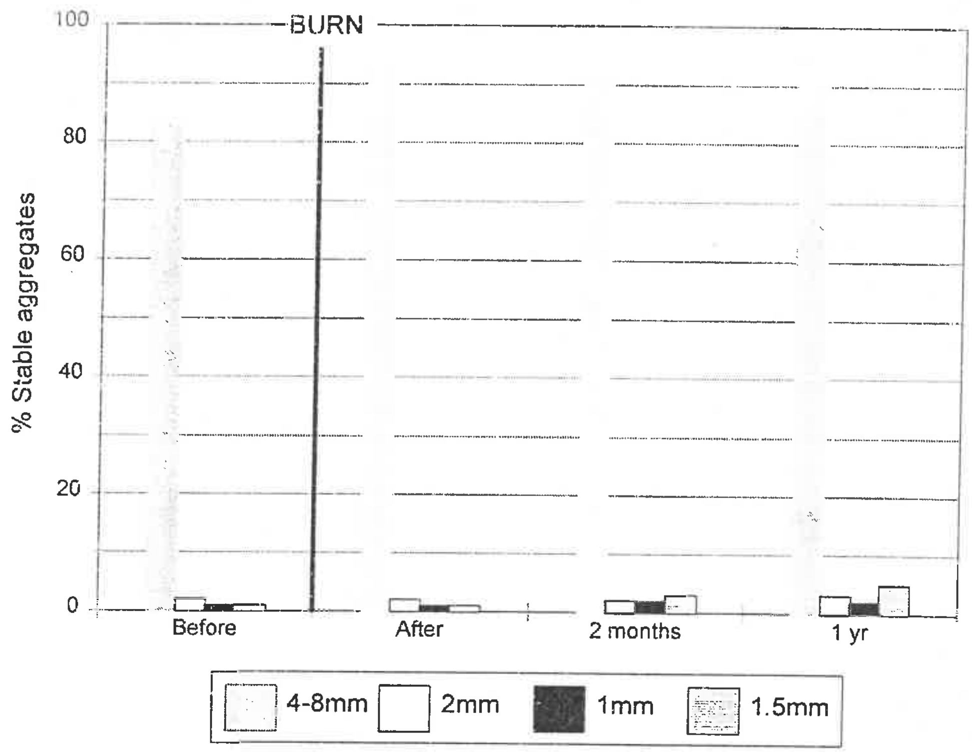

Figure 4.3: Percentage stable aggregates in relation to controlled burning as determined by wet sieving for the Gladstone site.

GGHNP has soil with large, stable aggregates, and in the case of the Gladstone burn, the fire had very little effect on the stability of the soil aggregates. This is a consequence of the low intensity of the burn where temperatures were insufficient to effect changes in soil structure. The soil in GGHNP is dominated by sand associated with the weathering of the Clarens Formation, and therefore aggregates in the smaller size classes are not expected. Thus the result obtained from wet sieving should be seen as site-specific and cannot be extrapolated to other mountainous areas e.g. KwaZulu-Natal Drakensberg, where clays, derived from the basalt weathering in association with higher moisture levels, form a greater percentage of the soil texture.

Organic matter content of the samples was determined before and after the burn and at two months and a year (Figure 4.4). The percentage organic matter increased after burning in association with the recovery of the vegetation. It decreased again after a year as the winter die-back of vegetation occurred. This increase and subsequent decrease appears to have very little to do with burning practices and is rather a consequence of the naturally occurring growth cycle within the grassland.

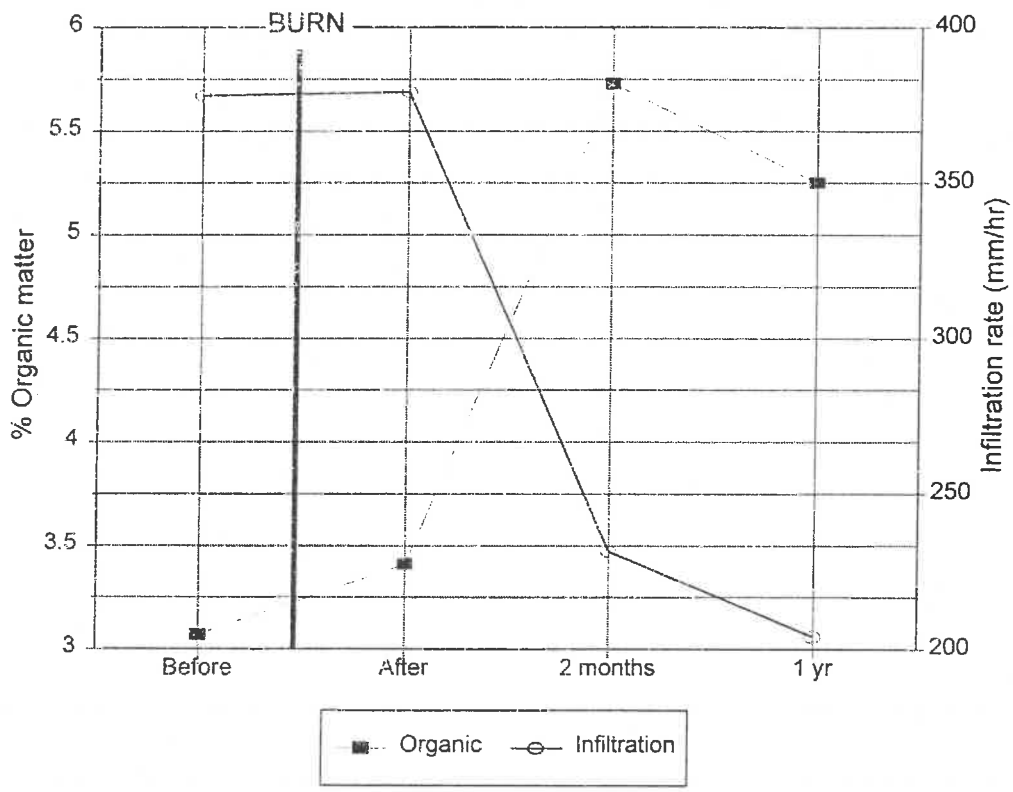

Figure 4.4: Relationship observed at Golden Gate Highlands National Park between organic matter content and infiltration rate.

According to Kirkby (1980) infiltration rate increases with increasing organic matter. Figure 4.4 clearly shows that in the present case, a negative relationship exists, with infiltration rate decreasing over time as organic matter increases. This suggests that some factor other than organic matter is controlling infiltration rate in this locality.

The soils at GGHNP are erodible in nature because of their high sand content. K-values (Wischmeier *et al.*, 1971) were not calculated because of the inaccuracies which occur when the nomograph is used outside of the United States (Bergsma and Valenzuela, 1981). The nomograph also does not account for the mulching effect of stones (Wischmeier, 1977) which is believed to play a role in improving infiltration on the upper stony slopes of GGHNP. The soils owe their aggregate stability almost entirely to the high organic matter content. Research elsewhere has shown a significant positive correlation between soil organic matter and aggregate stability against water forces (Chaney and Swift, 1984; Mbagwu and Piccolo, 1989). It is in this regard that the frequency of burn events becomes critical. The prescribed burns in this study were of light intensity and therefore had a minimal impact on the organic matter content. By comparison a wildfire, occurring under adverse weather conditions in an area with a high fuel load, will have a detrimental effect on the organic matter content and therefore aggregate stability.

The intensity of fires can be largely controlled by a burn frequency which prevents a dangerous build-up of fuel without impacting too severely on organic matter content of the soil. Conversely, if the organic matter content is allowed to build up to too high a level, the possibilities of fire-induced hydrophobicity developing will increase associated with a subsequent increase in runoff.

CHAPTER FIVE

The effect of fire on sediment yield, runoff and vegetation cover

"Fire is a good servant but a poor master"

-Finnish proverb (Kozlowski and Ahlgren, 1974 p. 7)

The data and subsequent discussion presented in this chapter are the results from fieldwork and laboratory procedures to determine the relationship between runoff, sediment yield and vegetation and their response to different burn regimes.

5.1 Sediment yield and runoff

The total sediment yield and runoff received from each plot is presented in Table 5.1 . These data do not include the extra sediment that was collected at the end of the monitoring period. An Analysis of Variance using factorial design (Gregory, 1978) of the data for the north-facing slope, contrasting the time of burn, the gradient of the plot and the sediment yield resulted in a statistically non-significant relationship between all the factors. The result of a multiple range analysis, contrasting the sediment yield and gradient for the south-facing slope, denotes a statistically significant difference between the sediment yield of the lower plots and the plot at the steepest gradient.

There is a good correlation between the sediment yield and runoff (Table 5.2). The exception is plot B. This plot, however, yielded only one sample of sediment during the study period and the accuracy of this plot's data is therefore difficult to assess.

Sumner (1995) found the I_{60} (maximum rainfall recorded in any 60 minute period) and I_{60}^2 (the square of the maximum 60 minute intensity) erosivity indices to be the most useful for high energy mountain environments. As a result of the failure of the data logger, an attempt was made to use the rainfall intensity data from the surrounding stations as discussed in Section 3.3.2. Total rainfall records were analysed and this showed a corresponding pattern of rainfall between stations in this area (Figure 5.1). It was decided to use those two stations (Bethlehem and Ficksburg) whose total rainfall was closest to GGHNP.

Table 5.1: Summary of the runoff and sediment yield from the plots during the study period.

Date	Rainfall	Plot	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	Ave
4/2	22mm	Sediment (g/m^{-2})	5.08	0	1.43	3.79	1.57	0.47	0.25	0.68	0.57	0	0.8	0.9	0	0.23	2.97	1.25
		Runoff (l/m^{-2})	0.82	0	0.89	0.54	0.5	0.58	0.25	0.35	0.25	1.67	2.78	3.1	1.35	0.3	1.21	0.97
9/2	8mm	Sediment (g/m^{-2})	14.08	0	2.73	30.35	8.2	2.47	4.23	1.05	18.73	4.46	15.87	12.91	38.89	13.12	4.74	7.25
		Runoff (l/m^{-2})	5.15	0	0.44	8.67	4.72	1.21	1.8	0.59	3.95	0.91	1.75	2.19	4.4	4.35	0.9	2.74
27/2	3.2mm	Sediment (g/m^{-2})	1.62	0	0	0	3.77	1.76	0	0	0	0	0	0	0	0	0	0.48
		Runoff (l/m^{-2})	0.26	0	0	0	0.7	0.39	0	0	0	0	0	0	0	0	0	0.09
10/3	nd	Sediment (g/m^{-2})	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1.17	0.08
		Runoff (l/m^{-2})	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0.01
27/3	nd	Sediment (g/m^{-2})	0	1.38	2.1	0.41	0	0	0	0	0	0.92	6.29	2.01	3.42	1.17	0	1.18
		Runoff (l/m^{-2})	0.1	0.16	0.1	0.2	0.15	0.24	0.2	0.1	0.3	0.27	0.57	0.16	0.16	0.15	0.2	0.2
30/3	nd	Sediment (g/m^{-2})	0	0	0	1	0	1.68	0	0	0.98	1.54	0	1.17	1.67	1.36	1.66	0.71
		Runoff (l/m^{-2})	0.31	0.57	0.34	0.99	0.9	0.72	0.8	0.5	0.6	1.02	0	0.21	0.83	0.95	0.7	0.63
9/4	6mm	Sediment (g/m^{-2})	0	0	0	0	0	0	1.73	0	0	0	0	0	0	0	0	0.12
		Runoff (l/m^{-2})	0	0	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0.03
10/4	6.4mm	Sediment (g/m^{-2})	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0.07
		Runoff (l/m^{-2})	0.26	0.38	0.2	0.15	0.1	0.1	0.25	0.2	0.25	0.11	0.21	0.16	0.62	0.15	0.25	0.22
23/4	7mm	Sediment (g/m^{-2})	2.8	0	0	3.21	0.28	0.58	0	0	0	8.16	3.6	5.2	14.89	3.1	0	2.79
		Runoff (l/m^{-2})	1.84	0.1	0.15	1.77	1.71	0.58	0.5	0.4	0.3	1.34	1.24	1.12	1.76	0.85	0.3	0.93
7/5	nd	Sediment (g/m^{-2})	0	0	0	3	1.4	3.53	0	0	0.76	0	1.47	3.9	0	2.84	0	1.13
		Runoff (l/m^{-2})	0	0	0	1.13	0.85	1.16	0	0	0.35	0	1.19	1.75	0	1.05	0	0.5
Ave		Sediment g/m^{-2})	2.36	0.14	0.63	4.18	1.52	1.05	0.62	0.17	2.1	1.51	2.8	2.61	5.89	2.23	1.05	
		Runoff (l/m^{-2})	0.87	0.12	0.21	1.36	0.96	0.5	0.43	0.21	0.6	0.53	0.77	0.87	0.91	0.78	0.38	

Table 5.2: Correlation values for sediment yield and three erosion indices.

	FICKSBURG		BETHLEHEM		GGHNP
PLOT	I_{60}	I_{60}^2	I_{60}	I_{60}^2	Plot runoff
A	-0.23	-0.26	0.1	0.14	0.95
B	-0.29	-0.23	0.05	-0.07	-0.18
C	-0.44	-0.41	0.3	0.26	0.68
D	-0.16	-0.2	-0.05	-0.04	0.95
E	-0.24	-0.32	-0.1	-0.05	0.8
F	-0.06	-0.21	-0.09	-0.14	0.45
G	-0.24	-0.26	-0.16	-0.14	0.85
H	-0.3	-0.31	0.39	0.44	0.88
I	-0.16	-0.2	-0.11	-0.11	0.92
J	0.41	0.37	-0.15	-0.19	0.57
K	-0.19	-0.21	-0.12	-0.16	0.86
L	-0.04	-0.1	-0.14	-0.17	0.93
M	0.01	-0.03	-0.18	-0.2	0.92
N	-0.07	-0.13	-0.15	-0.2	0.96
O	-0.05	-0.1	0.41	0.43	0.85
AVE	-0.14	-0.17	0	-0.01	0.7

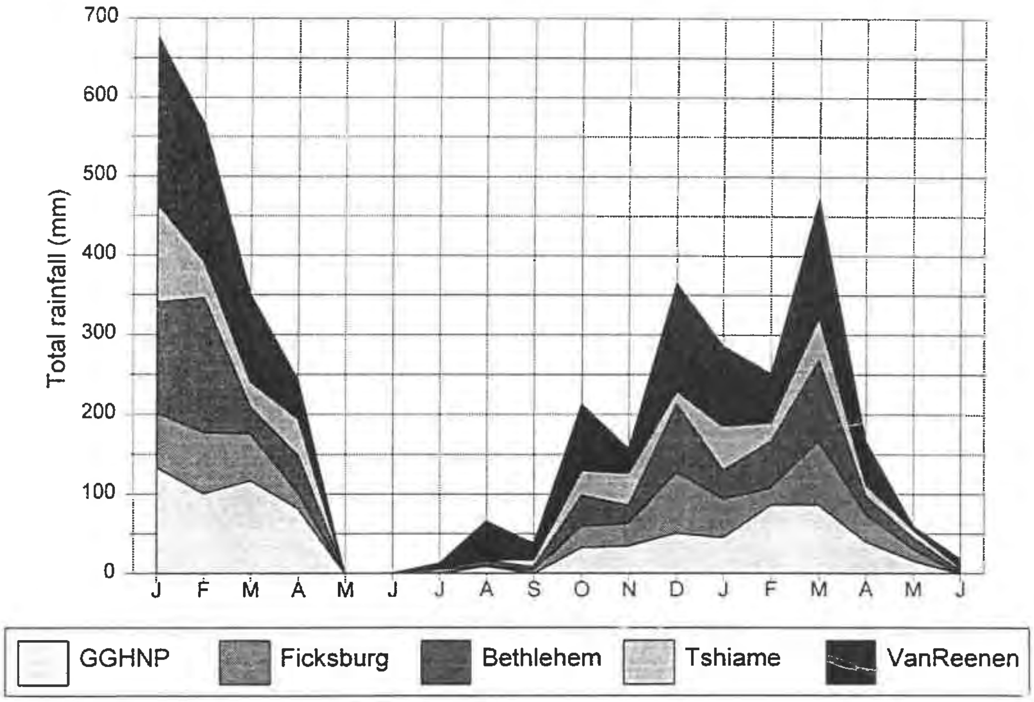

Figure 5.1: Total rainfall for GGHNP and surrounding stations for 1994 and up until June 1995.

A strong correlation is generally considered to be represented by values between ±0.7 and ±1 and weak correlations between ±0.3 and 0 (Steel and Torrie, 1980). Table 4.6 shows that all the values for I_{60} and I_{60}^2 represent weak correlations and are of little value to this study. Interpolation of the intensity values for GGHNP, using the intensity values for Ficksburg and Bethlehem, was not possible because although the total rainfalls have a similar pattern, in many cases the rainfall days did not correspond with observed runoff events.

5.1.1 Sediment particle size analysis

The sediment was analysed in the laboratory to determine particle size distribution (texture) using a vibrating sieve stack. The fine fraction, smaller than 0.063mm was asumed to be lost as a consequence of the plot design (Section 3.2.). The particle size distributions of the sediment obtained from the plots for the monitored period are given in Figures 5.2 a-f. The plots are presented in the three slope classes in order of in increasing gradient. All the figures show that the sediment derived from the plots was predominantly sandy. The sediment would have a bias towards the coarse fraction because of the 4ϕ (0.063mm) mesh used on the collecting buckets. Notwithstanding this, the underlying sandstone geology would contribute significantly to the predominance of the sand fraction.

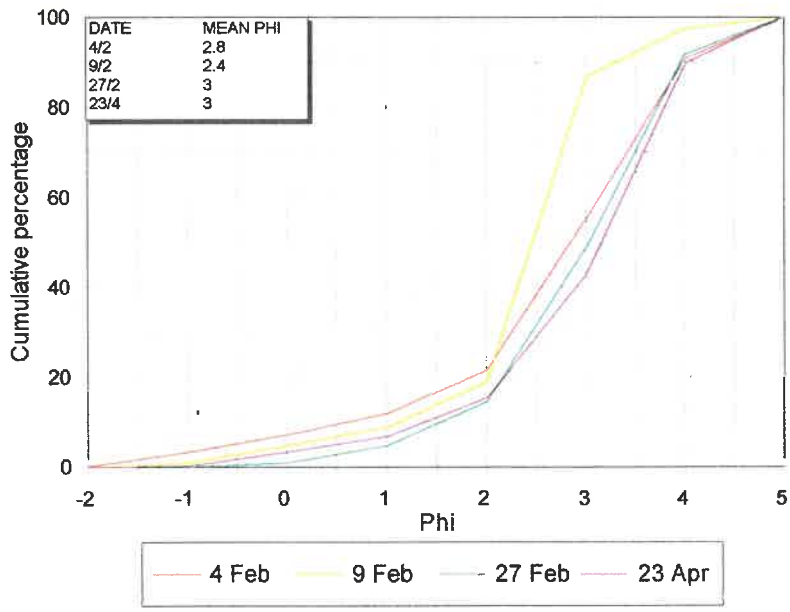

Figure 5.2a: Runoff plot A sediment yield characteristics.

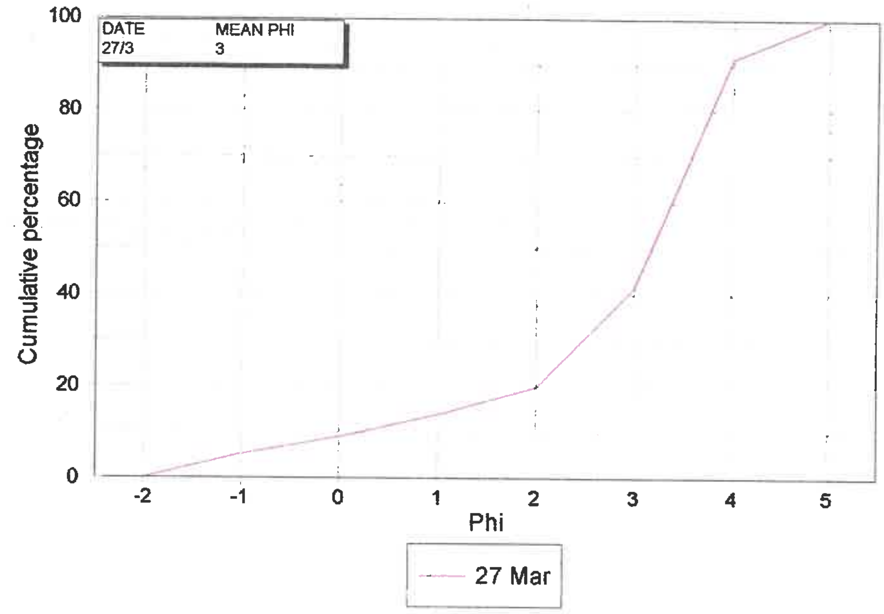

Figure 5.2b: Runoff plot B sediment yield characteristics.

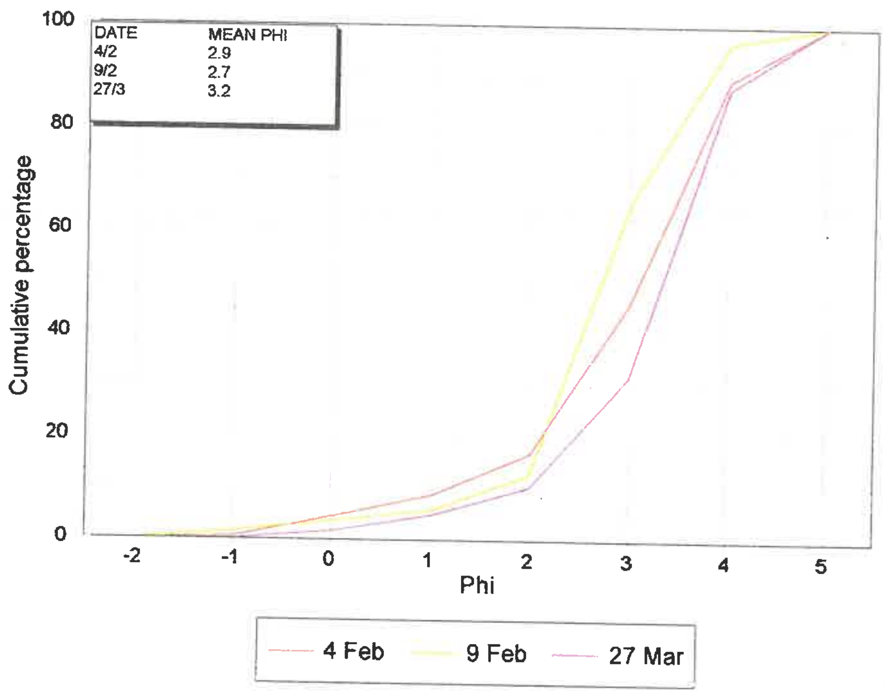

Figure 5.2c: Runoff plot C sediment yield characteristics.

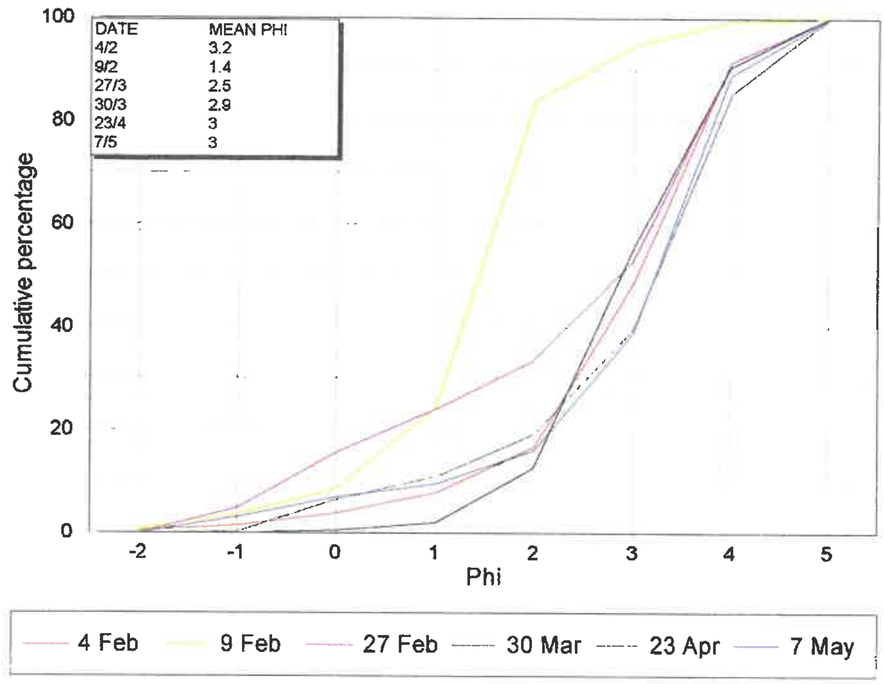

Figure 5.2d: Runoff plot D sediment yield characteristics

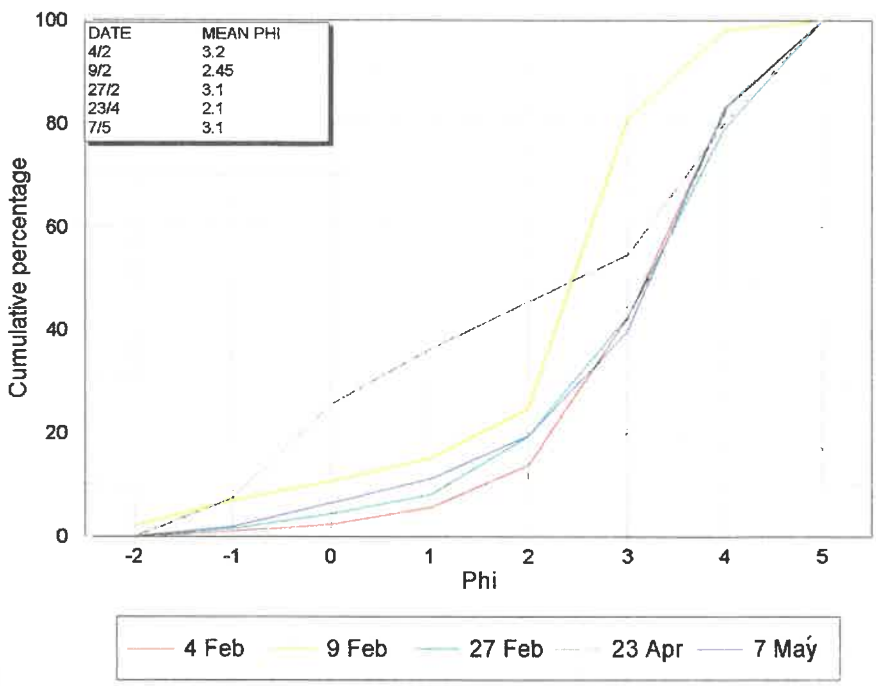

Figure 5.2e: Runoff plot E sediment yield characteristics.

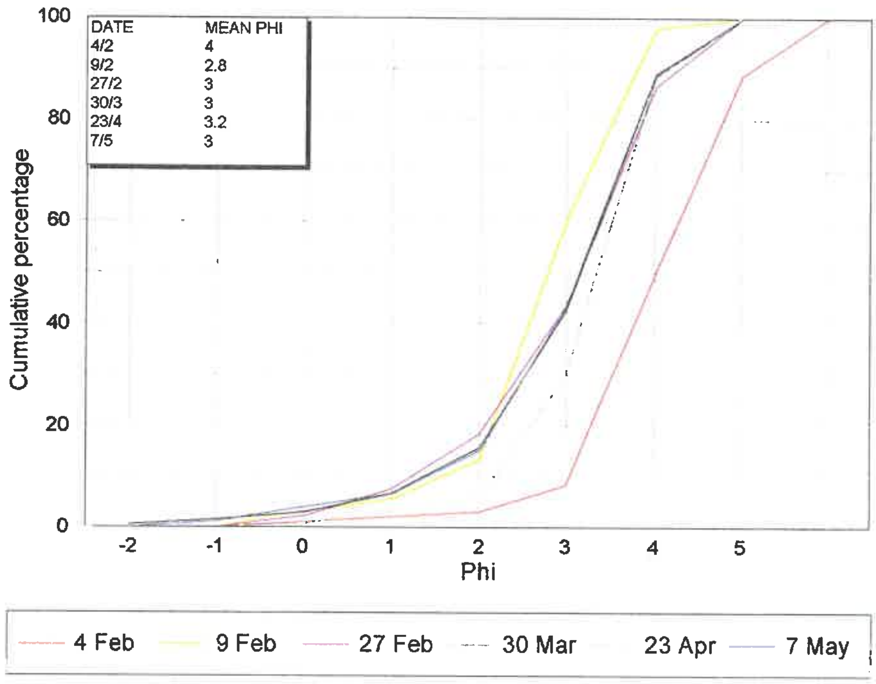

Figure 5.2f: Runoff plot F sediment yield characteristics.

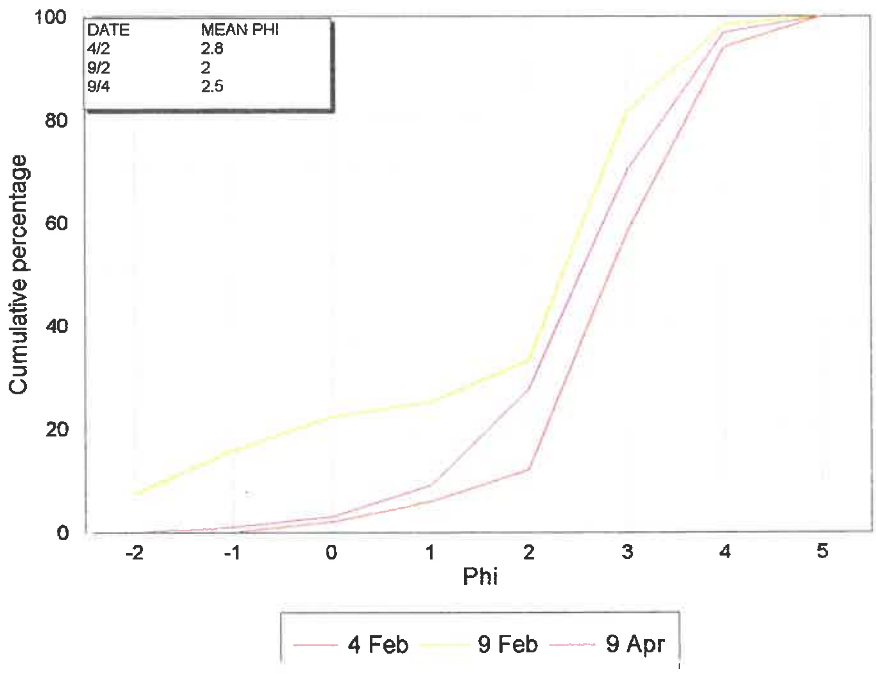

Figure 5.2g: Runoff plot G sediment yield characteristics.

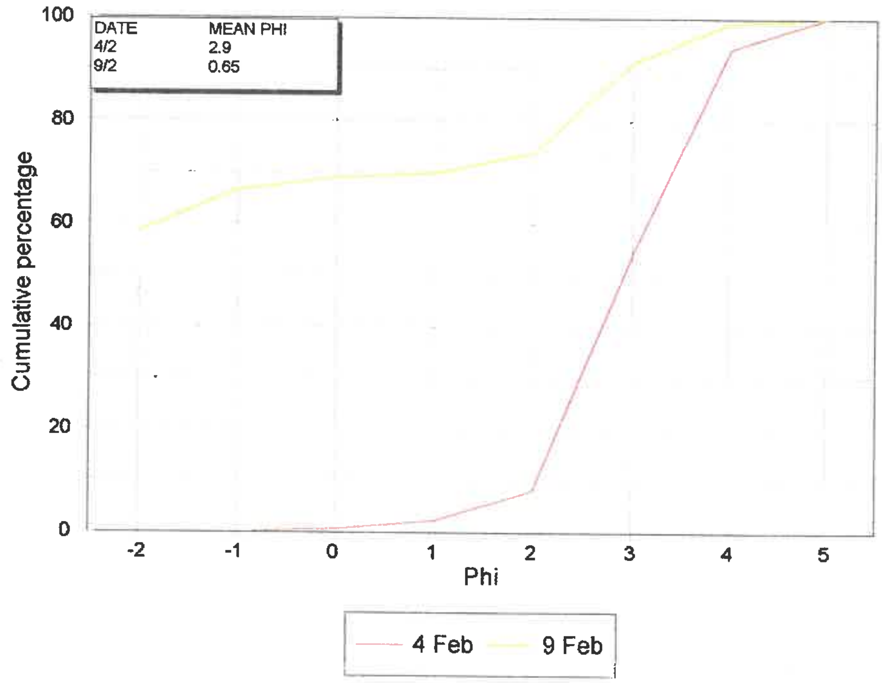

Figure 5.2h: Runoff plot H sediment yield characteristics.

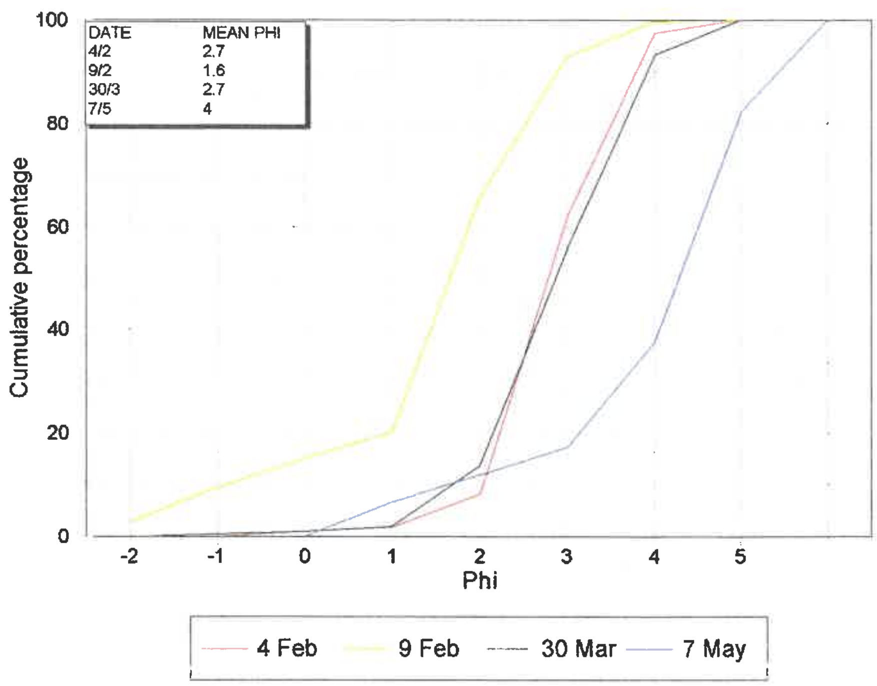

Figure 5.2i: Runoff plot I sediment yield characteristics.

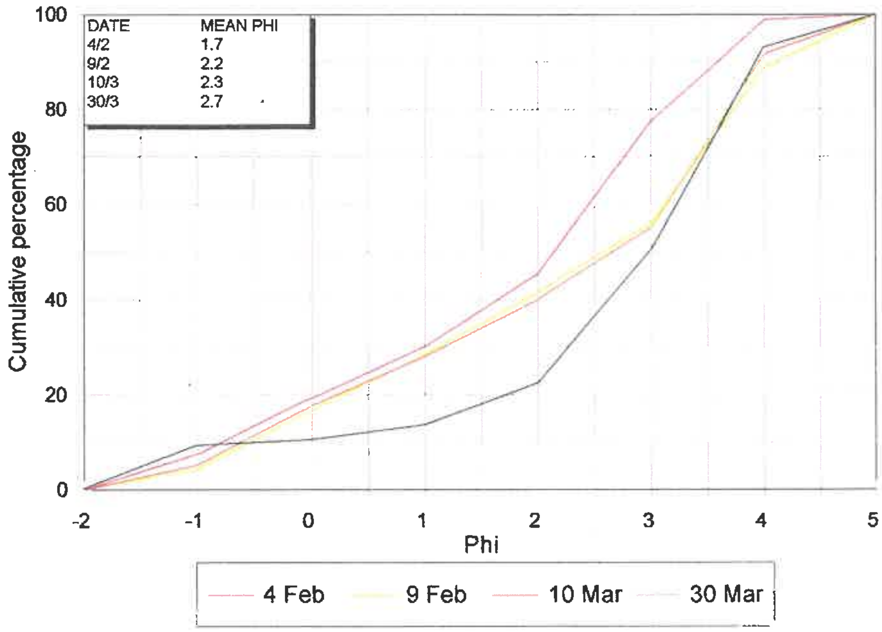

Figure 5.2j: Runoff plot O sediment yield characteristics.

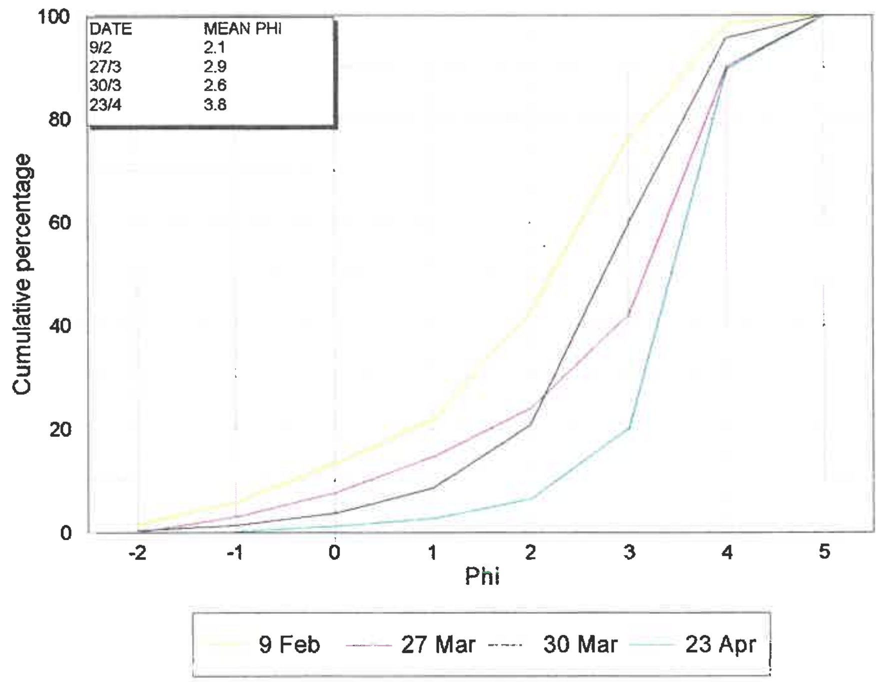

Figure 5.2k: Runoff plot J sediment yield characteristics.

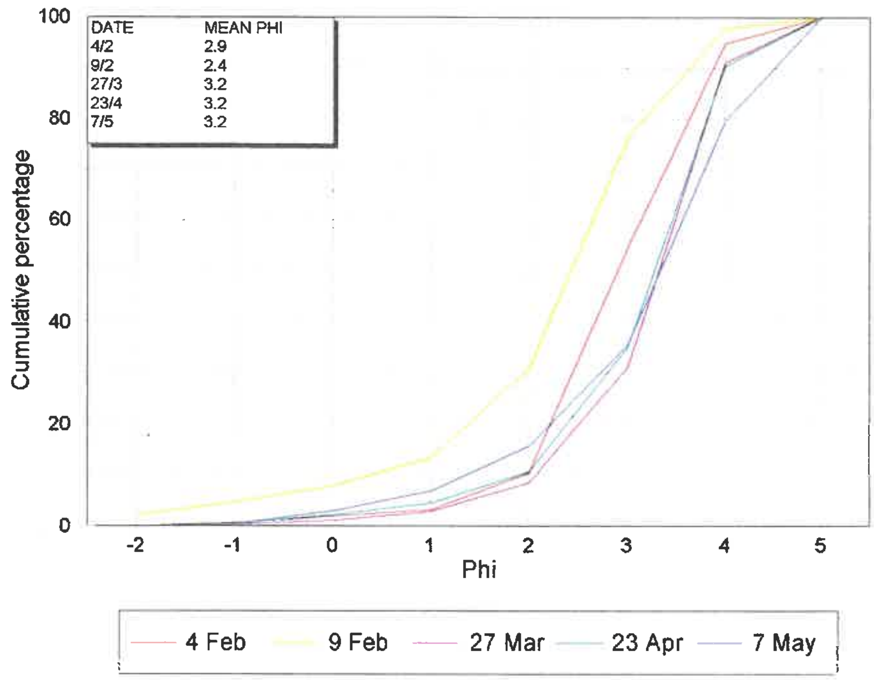

Figure 5.2l: Runoff plot K sediment yield characteristics.

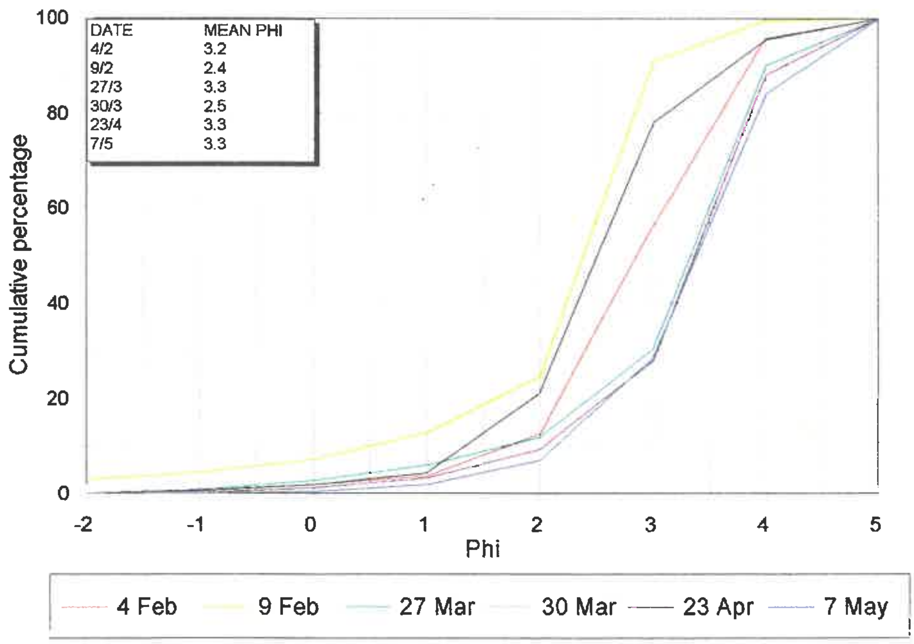

Figure 5.2m: Runoff plot L sediment yield characteristics.

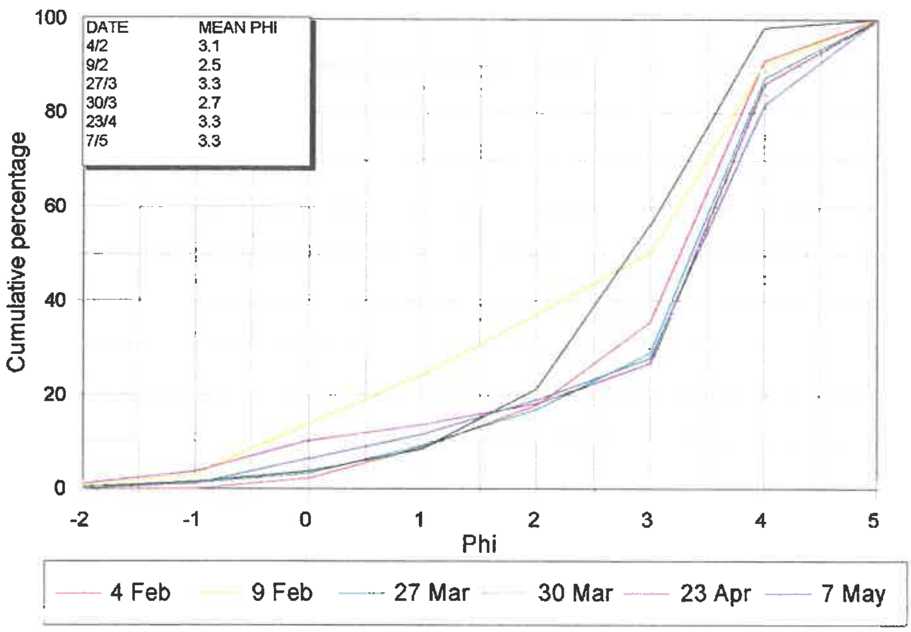

Figure 5.2n: Runoff plot N sediment yield characteristics.

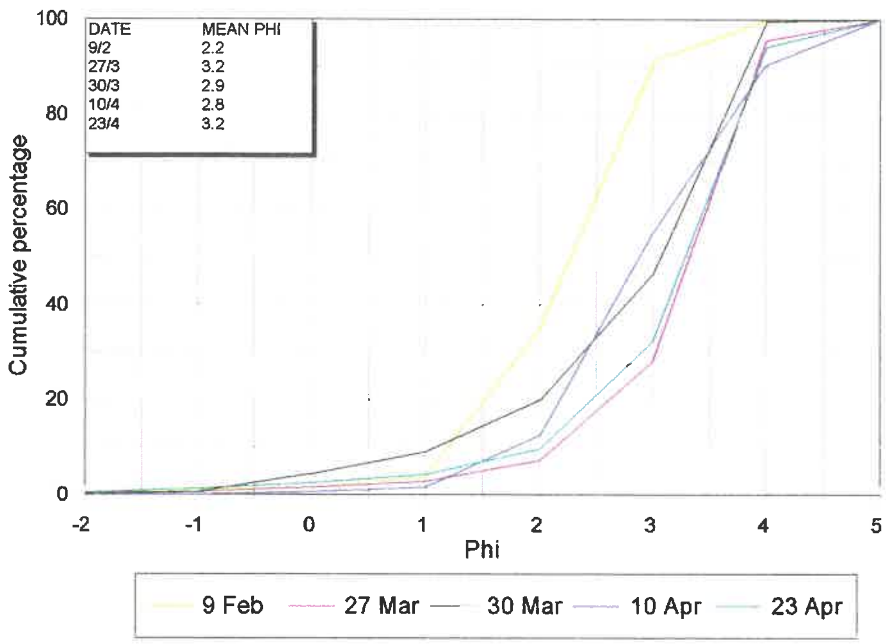

Figure 5.2o: Runoff plot M sediment yield characteristics.

Figures 5.2a-o show that the particle size distribution for February 9, 1995 differed from the other recorded rain events. The highest average sediment yield was also recorded on this day (Table 5.1). Although the total rainfall for this event was only 8mm, a mean runoff of 2.74l/m^2 was generated, suggesting that this event was of high intensity with the capability to transport more sediment of greater mean size than the other events. Gradient did not appear to significantly affect the mean size of the collected sediment. This can be attributed to the inherently sandy nature of the residual soil which is independent of any gradient effects. The characteristics of the sediment obtained from the plots over the monitoring period are displayed in Tables 5.3 - 5.8.

Table 5.3: Characteristics of the sediment yield averaged for all events recorded per plot from the north-facing plots in the <15^0 slope class compared with the residual soil

PLOT	%GRAVEL	%SAND	%SILT	MEAN(ϕ)	SORTING	SKEWNESS
A	1.4	91	7.6	2.8	0.9	-0.3
B	5	86	9	3.0	1.4	-0.5
C	0.7	91	8.3	2.9	0.9	-0.52
Residual	8.9	84.9	6.2	2.1	3.2	-0.49

Table 5.4 : Characteristics of the sediment yield averaged for all events recorded per plot from the north-facing plots in the slope class 15-25^0 compared with the residual soil.

PLOT	%GRAVEL	%SAND	%SILT	MEAN(ϕ)	SORTING	SKEWNESS
D	3	89	8	2.7	2.1	-0.3
E	3.8	81	15.2	2.8	1.5	-0.2
F	0.4	90	9.6	3.2	1.0	-0.3
Residual	9.3	84.3	6.4	2.2	3.15	-0.48

Table 5.5: Characteristics of the sediment yield averaged for all events recorded per plot from the north-facing plots in the slope class >25^0 compared with the residual soil.

PLOT	%GRAVEL	%SAND	%SILT	MEAN(ϕ)	SORTING	SKEWNESS
G	7.5	89	3.5	2.4	1.3	-0.2
H	32.5	64	3.5	1.8	1.0	0.1
I	3	90	7	2.8	0.9	0.1
Residual	14	83	3	2.5	2.6	-0.48

Table 5.6: Characteristics of the sediment yield averaged for all events recorded per plot from the south-facing plots in the slope class <15^0 compared with the residual soil.

PLOT	%GRAVEL	%SAND	%SILT	MEAN(ϕ)	SORTING	SKEWNESS
O	5.3	88	6.7	2.2	1.7	-0.4
J	3	90	7	2.9	1.2	-0.3
Residual	6.9	85.6	7.5	2.6	3	-0.3

Table 5.7: Characteristics of the sediment yield averaged for all events recorded per plot from the south-facing plots in the slope class 15-25^0 compared with the residual soil.

PLOT	%GRAVEL	%SAND	%SILT	MEAN(ϕ)	SORTING	SKEWNESS
K	0.7	90	9.3	3.0	1.0	-0.2
L	1.4	90	8.6	3.0	0.9	-0.4
N	1.6	86	12.4	3.0	1.3	-0.3
Residual	7.1	85.5	7.4	2.6	3	-0.31

Table 5.8: Characteristics of the sediment yield averaged for all events recorded per plot from the south-facing plot in the >25^0 slope class compared with the residual soil.

PLOT	%GRAVEL	%SAND	%SILT	MEAN(ϕ)	SORTING	SKEWNESS
M	0.5	96	3.5	2.9	0.6	-0.2
Residual	7.4	86	6.6	2.7	3	-0.3

Tables 5.3-5.8 show that the skewness values are generally negatively to very negatively skewed, representing a coarse tail to the distribution (Briggs, 1977). The exceptions are plots H and I (Table 5.5) which have a tendency towards a more symmetrical distribution. The sorting values vary between moderately sorted to poorly sorted but the collected sediment sorting values show better sorting than the parent material on all plots. The sediment from control plots (C, F and I) is better sorted than the corresponding burnt plots because of the filtering effect of the vegetation. There is a shift towards the fines in the collected sediment when compared to the parent material although

the percentage of fine material collected is still low as would be expected from a soil derived from sandstone. The low percentages of fine material in the collected sediment concur with Garland's (1988) findings. Garland maintains that this could be explained by a slower weathering rate for the fine fraction than for the coarse component of the soil. It is possible that the fine material had already been removed in previous rain seasons but in time will be replenished, otherwise a soil consisting entirely of sand would develop. The exposed nature of many of the plots particularly those on steep slopes (G, H. I and M) and those on the firebreak (N and O) suggests the possibility of removal of fines by wind erosion as well as water. The only plots which showed an increase in the production of fines as the season progressed were G and H. The runoff from these two plots was less than the control plot on the same gradient for reasons discussed above. It is possible therefore that there was simply not the energy available to remove any particles larger than fines.

Another possible explanation is offered by Le Roux and Roos (1986), who showed that low intensity rainfall, as occurred during this study, is more likely to erode the sand and silt fractions than clay sized particles. Le Roux and Roos suggest that if only rainfall amount is considered the cohesion of clay particles resists erosion to a certain extent and that the silt and sand fraction are relatively more easily removed by surface wash. The good correlation which exists between runoff and sediment yield seems to lend support to this possibility and to Garland's (1988) contention that the surface roughness of burnt plots renders rainfall kinetic energy increasingly impotent and increases the importance of runoff as an agent of erosion. Thornes (1980) explains that the energy contained in runoff is translated into boundary shear stress at the soil-water interface, which results in particle movement by creating differential pressure on the up-and downstream sides of particles, promoting the Bernoulli lift effects. Future research should investigate the contribution of splash erosion to total sediment loss in burnt areas compared to that produced by runoff.

5.2 Vegetation cover

While this study is essentially a geomorphological examination of the effects of veld burning, vegetation is a primary control of erosion processes and therefore cannot be ignored. Burning has an immediate and drastic effect on vegetation, reducing the protective canopy cover to zero. Two techniques for the assessment of vegetation cover were employed in this study. Canopy cover (CC) was estimated by dividing the plot into three sections and photographing each section. A grid was then laid over the photograph and the cover in each grid square calculated. Basal cover (BC), defined as the area of the actual ground surface taken up by vegetation stalks and grass tufts (Stocking, 1994), was calculated using the technique proposed by Hardy and Tainton (1993) for tufted grassland which uses spaces between grass tufts as a measure of tuft density. The results of these two techniques are presented in Table 5.9.

Table 5.9 : Canopy cover (CC) and basal cover (BC) for each runoff plot.

PLOT	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
CC (%)	68	74	96	74	76	94	72	66	92	90	77	79	77	82	70
BC (%)	20	18	18	22	16	17	17	15	14	20	20	22	20	18	20

Canopy and basal cover are compared graphically with respect to burn treatments, gradient and aspect.

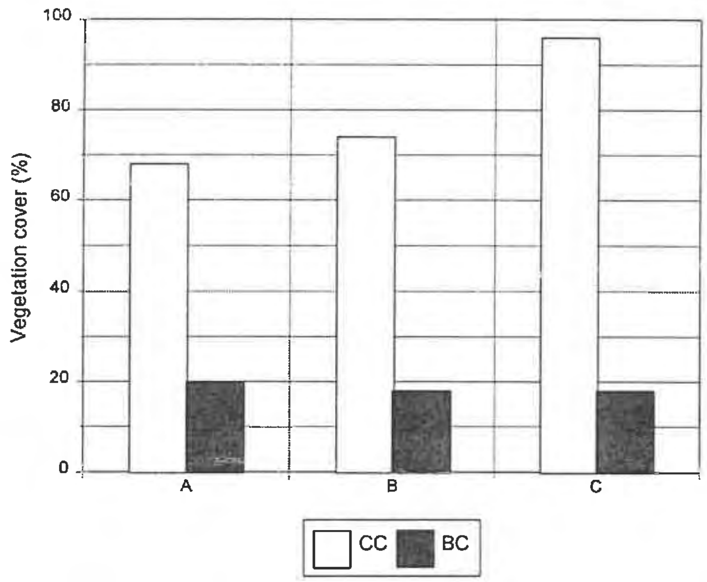

Figure 5.3: Comparison of basal cover (BC) and canopy cover (CC) for the north-facing plots of <15^0 gradient.

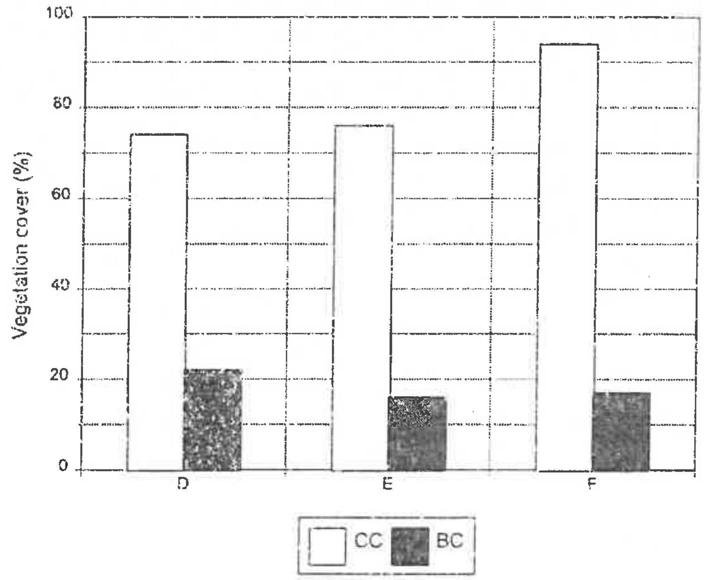

Figure 5.4: Comparison of basal cover (BC) and canopy cover (CC) for the north-facing plots of 15-25^0 gradient.

Figure 5.3 shows that in the slope class <15^0, the BC for the winter burn plot (A) is marginally higher than the other two plots. The canopy cover is, as expected, greatest in the control plot. The canopy cover appears to have recovered more successfully after the spring burn than after the winter burn. A similar pattern of vegetation cover is shown in Figure 5.4 for the plots in the slope class 15 - 25^0. On the steepest gradient, > 25^0, the winter burn plot had a higher BC and CC than the spring burn plot. The canopy cover was again highest for the control plot (I). It would be premature to make lengthy comment on the response of BC and CC to different burning regimes as shown in Figures 5.3 - 5.5 . Monitoring over the longer term will reveal changes in the patterns shown here and allow for comment on burning effects on grassland vigour.

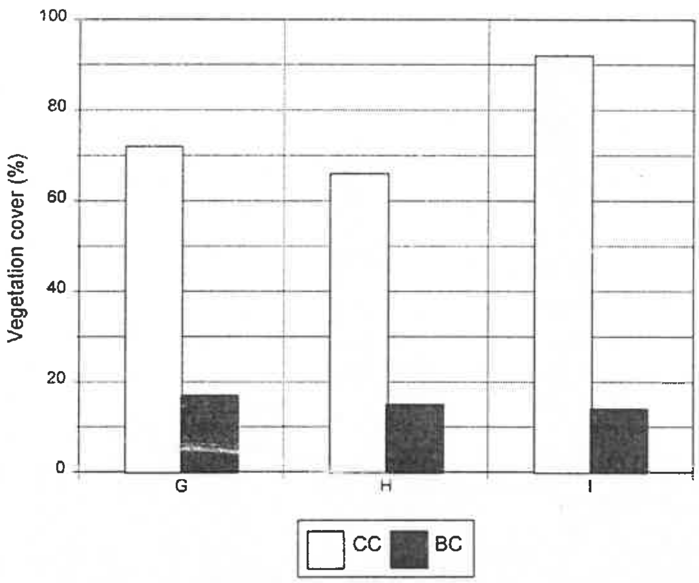

Figure 5.5: Comparison of basal cover (BC) and canopy cover (CC) for the north-facing plots of >25^0.

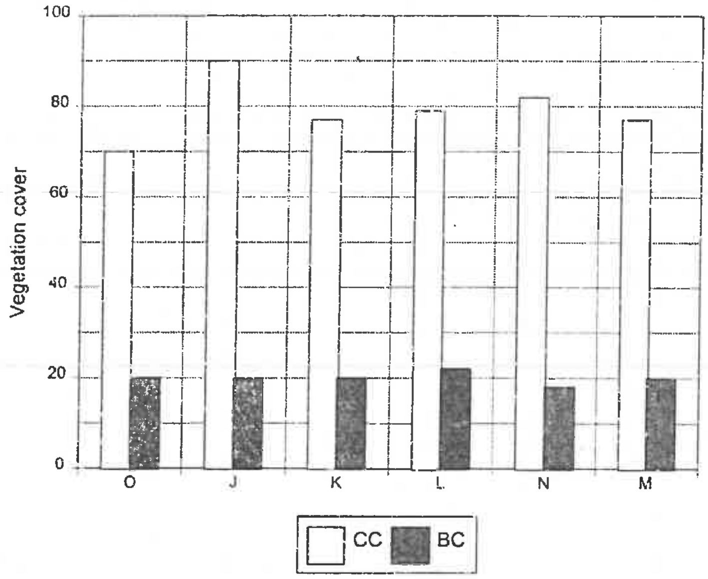

Figure 5.6: Comparison of the basal cover (BC) and canopy cover (CC) for the south-facing plots.

The plots for the south-facing slope are represented in Figure 5.6 in order of increasing gradient. Basal cover does not appear to vary significantly over the different gradients. Plot J has the highest CC because its protected position combined with shallow gradient have created better soil moisture conditions and protection from high winds.

A comparison of the north- and south-facing plots of similar gradients and burn treatment is shown in Figures 5.7 and 5.8. In the slope class 15^0-25^0 (Figure 5.7a) basal cover does not vary with respect to aspect but canopy cover is greater for the south-facing plots, K, L, and N, than for the north-facing plot D. In the lower slope class a similar pattern is shown (Figure 5.7b) with higher canopy cover for the south-facing plots O and J, and similar BC for all three plots regardless of aspect.

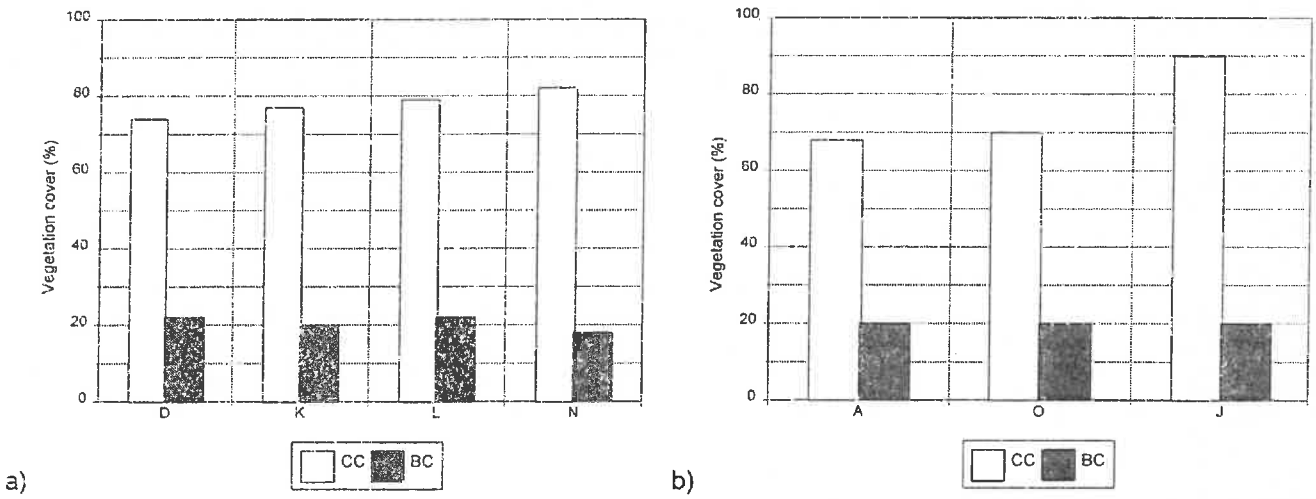

Figure 5.7: Comparison of the canopy cover (CC) and basal cover (BC) of the winter burn plots on the north- and south-facing plots of gradients 15-25^0 (a) and <15^0 (b).

Figure 5.8 shows that for steeper gradients (>25^0) both basal cover and canopy cover are higher on the south-facing plot. This can be attributed to the deeper soil profile on plot M than on plot G, and therefore improved soil moisture conditions.

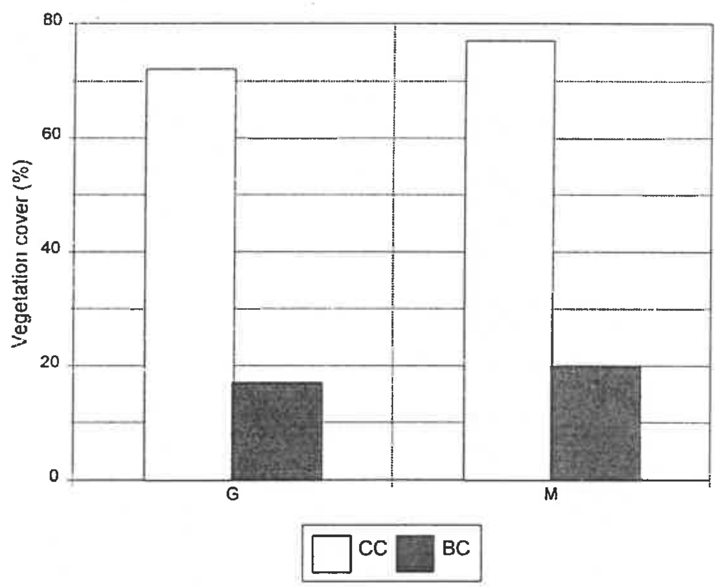

Figure 5.8 : Comparison of basal cover (BC) and canopy cover (CC) for north- and south-facing plots of >25^0 gradient.

A comparison of the basal and canopy cover of all the plots at the end of the growing season showed that the canopy cover of all the lower plots and those on the South-facing slope had recovered to the greatest extent of all the plots. This was probably because of the better soil moisture conditions in these areas which allowed some growth under the drought conditions which prevailed. The basal cover however did not differ significantly with respect to aspect or gradient.

Stocking (1994) states that for the purpose of erosion research, canopy cover is the more important vegetation cover parameter, as it gives a measure of the efficiency of the vegetation to intercept raindrops or, alternatively, the proportion of the ground vulnerable to rainsplash. In this study however, basal cover was deemed the more valuable, because it is basal cover that will be the determining vegetation factor immediately after a burn when the canopy has been removed and the soil is the most vulnerable to the rainsplash. Under normal soil moisture conditions the canopy will recover quickly and should attain full canopy cover within two months of the start of the growing season (Everson *et al.*, 1989). It can be seen from Figure 5.9 that extremely dry conditions prevailed at GGHNP during the time of this study. Thus the rate of canopy recovery following burning was not as rapid nor as complete as had been expected, emphasising the importance of basal cover as a variable in this particular research. By the end of the season none of the burnt plots had recovered to the percentage canopy cover of the control plots.

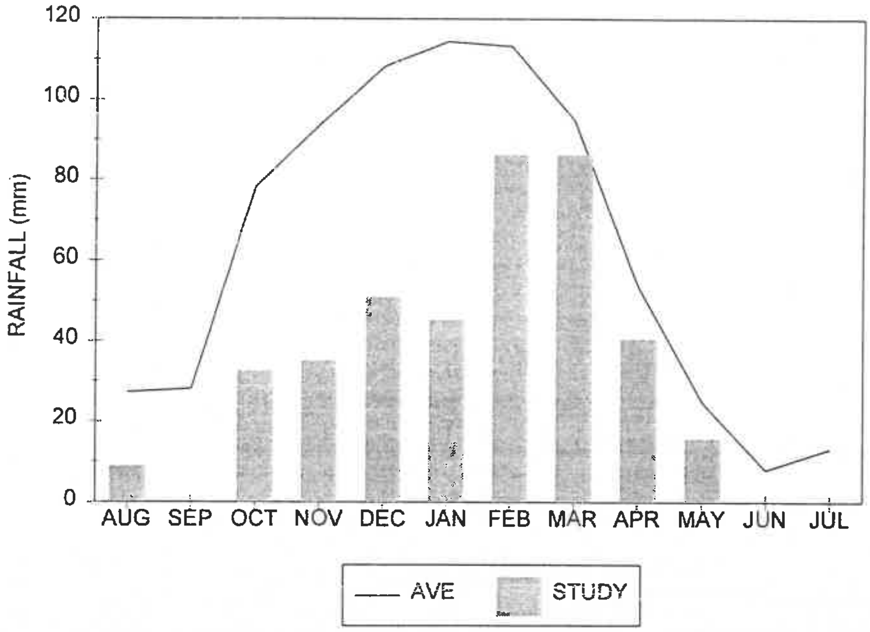

Figure 5.9 : Comparison of the average annual rainfall received at Golden Gate Highlands National Park with that received during the study period.

The basal cover is such that there are spaces between grass tufts. Overland flow is not likely to develop because of the surface roughness presented by these tufts. It is more likely that flow will be concentrated into rills. Garland (1988) notes that the rough surfaces common to burnt plots retard runoff and cause small pools to develop. These pools would act to dissipate the kinetic energy of impacting raindrops, effectively protecting the soil (Thornes, 1980). Deposition of any detached material will take place in these pools. In the case of this study, this process will be exacerbated by the small changes in gradient which occur along the length of the plot (Figures 3.3a-o). Observations of deposition at these sites of gradient change were made on all the burnt plots (Figure 5.10).

Figure 5.10: Deposition of sediment at site of gradient change on plot D.

5.3 The relationship between basal cover, runoff and sediment yield

It is expected that basal cover (BC) will be negatively correlated with sediment yield and runoff from the plots. At the end of the monitoring period uncollected sediment was found in some of the nose cones of the runoff plots and in the gutters. This was removed and added to the total weight of sediment for that plot. It was impossible to determine from which rain event the sediment had originated and therefore for the purpose of this comparison the mean sediment was divided out over the known dates. The results from the plots are graphically represented, and compared with respect to burn treatment, gradient and aspect.

5.3.1. Comparison of burn treatments

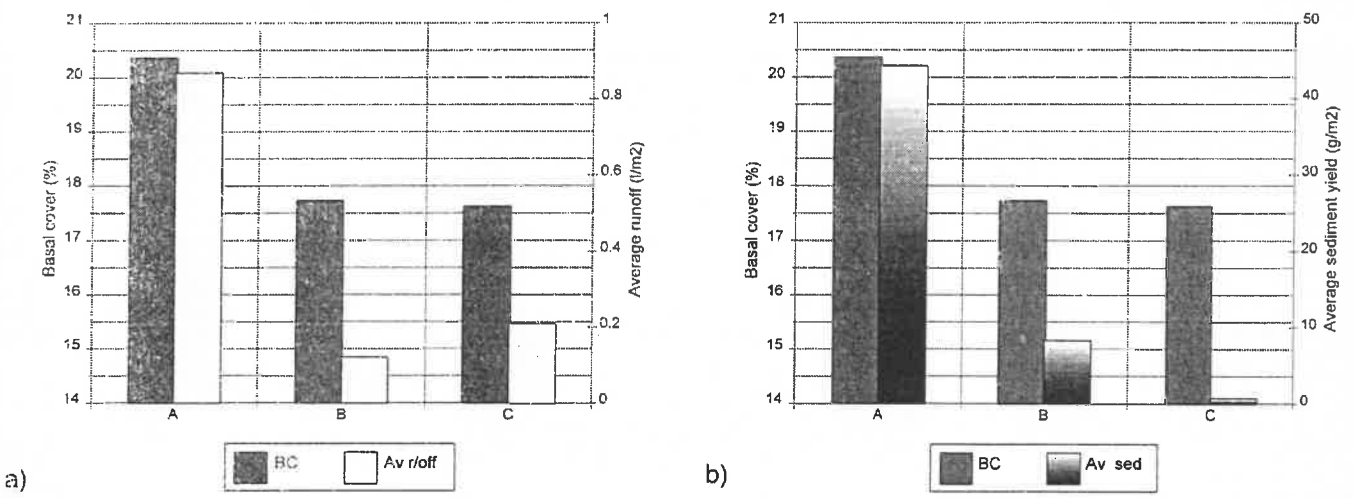

Figure 5.11 : The runoff (a) and sediment yield (b) compared to basal cover for the north-facing plots <15^0.

The north-facing plots did not show a clear pattern of relationships between season of burn and runoff and sediment yield at the slope level. This suggest that the effects are site specific. Figures 5.11a and b show that in the slope class <15^0 the winter burn plot (A) produced the highest sediment yield and runoff, despite having the highest BC of the three plots in this slope class. This can be attributed to the slow recovery of the vegetation canopy. The addition of the extra sediment found in the plots after the monitoring period had ended, boosted the sediment yield of the spring burn plot (B) to above that of the control (C). The runoff generated from plot C was higher than plot B but the litter layer in plot C would have helped to minimise the movement of soil. It is suggested that the maintenance of a good canopy and litter layer resulted in the control plot yielding less sediment and runoff.

Figure 5.12 reveals a similar pattern for plots in the slope class 15-25^0. Although the winter burn plot (D) has the greater percentage of BC, it has the highest runoff and sediment yield. Basal cover was higher for the control plot (F) than for the spring burn plot (E) and this may have been a significant factor in restricting runoff and sediment movment in plot F. The spring burn was applied under conditions of greater soil moisture than the winter burn. It is possible that the moisture in the surface was converted to steam by the heat of the fire which opened pore spaces in the soil. This would lead to improved infiltration and consequently lower runoff and sediment yield. The evaporation rates would be higher from the burnt plots because of the differences in albedo and the absence of the mulching effects of vegetative cover. This may promote the formation of a surface layer of dry hydrophobic soil resulting in lower infiltration rates when compared to the control plot.

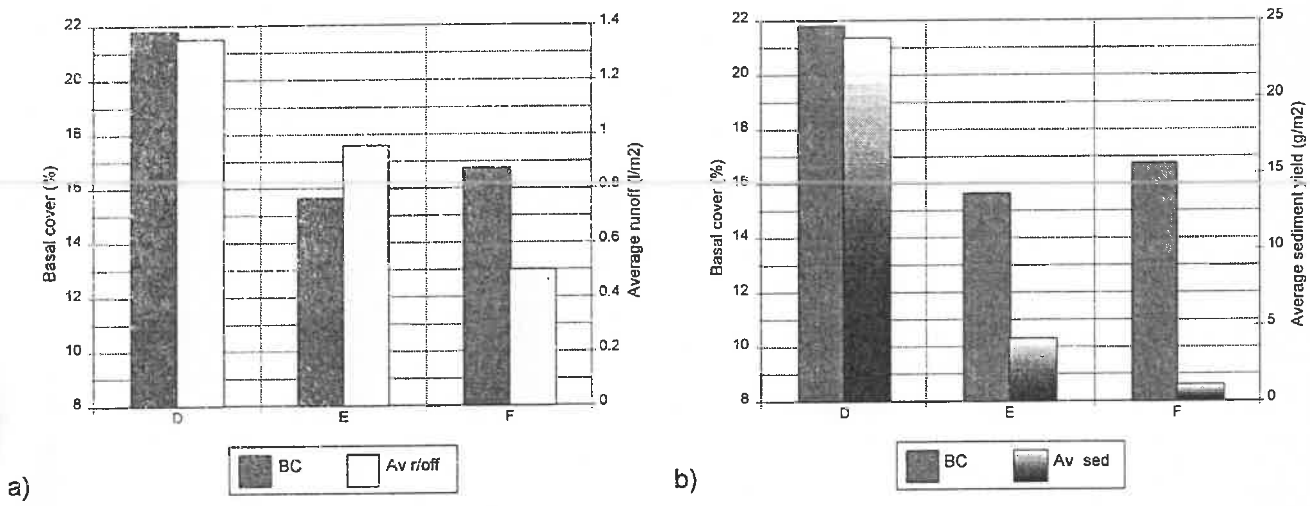

Figure 5.12 : The runoff (a) and sediment yield (b) compared to basal cover (BC) for the north-facing plots 15-25^0.

The plots on the >25^0 slope class produced an unexpected result with the control plot (I) having the highest runoff and sediment yield of the three plots (Figures 5.13a and b) despite having a high percentage of BC and CC suggesting a controlling variable other than vegetation cover. A steeper slope causes higher boundary shear stresses and associated increase in potential for particle entrainment. However the combined effects of surface roughness and slight gradient changes will act to obviate the effective steepness of the slope. Together they generate runoff conditions which dissipate energy without causing erosion, while simultaneously creating a mode of runoff which requires more energy merely to sustain motion, leaving less available for entrainment and transportation (Garland, 1988).

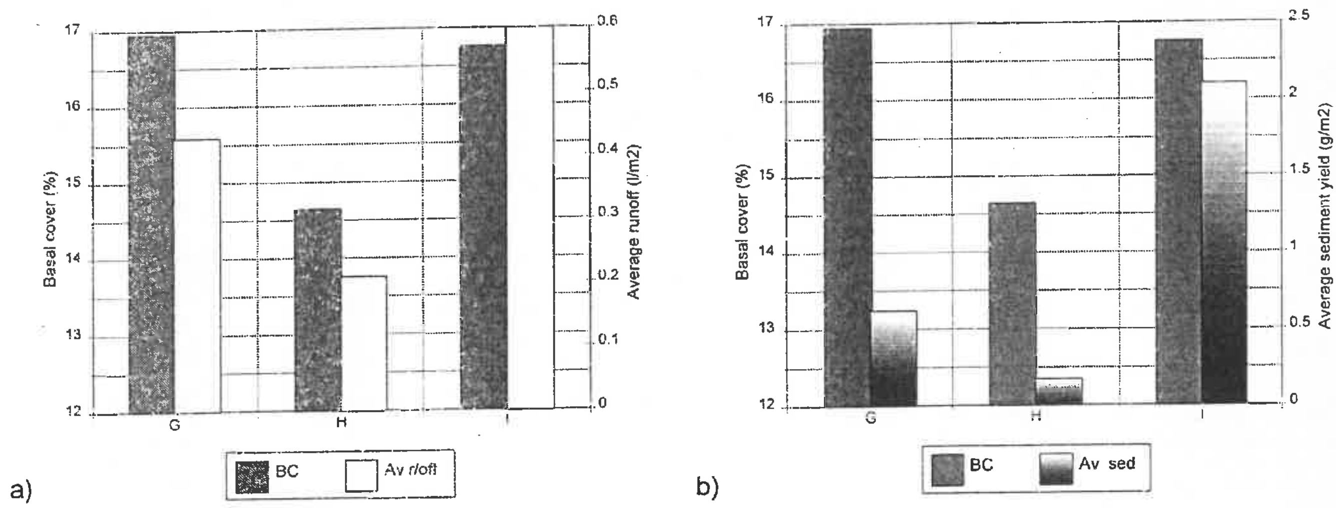

Figure 5.13: The runoff (a) and sediment yield (b) compared to the basal cover (BC) for the north-facing plots >25°.

Of the burn plots, the winter burn plot again produced more sediment and runoff than the spring burn plot. The steep slopes yielded the least sediment, contrary to the expectation that increased gradient would produce increased soil loss. This can be attributed to the thin soil profile at that gradient which suggests that much of the sediment has already been removed. The steepest slope produced a different relationship between burn and no-burn treatments, with the control yielding the highest runoff and sediment. This is in spite of the 92% canopy cover and slightly lower gradient. Observations show that the no-burn plot is the least stony of the three and therefore would not benefit from the beneficial effects of surface armouring and improved infiltration outlined by Evans (1980). These results concur with the findings of Kutiel and Inbar (1993) and Kutiel *et al.* (1995) who found that fire, in a mediterranean ecosystem, resulted in a slight decrease in runoff and erosion in comparison to unburnt areas. They argue in favour of fire aiding the development of a mosaic of runoff generating and runoff accepting patches which is controlled largely by surafce roughness (Lavee *et al.*, 1995). Steep stony slopes are also less likely to develop surface sealing (Poesen, 1986) resulting in improved infiltration.

The steep section of this slope was prone to much stronger winds than the lower plots and it is possible that sediment was removed from the unprotected burnt plots by wind erosion prior to the onset of the summer rains, resulting in a lower sediment yield from these plots in comparison to the control plot. The potentially important role which wind erosion plays in the removal of sediment from burnt areas is an area of research that requires further investigation.

5.3.2. Comparison of the effect of gradient

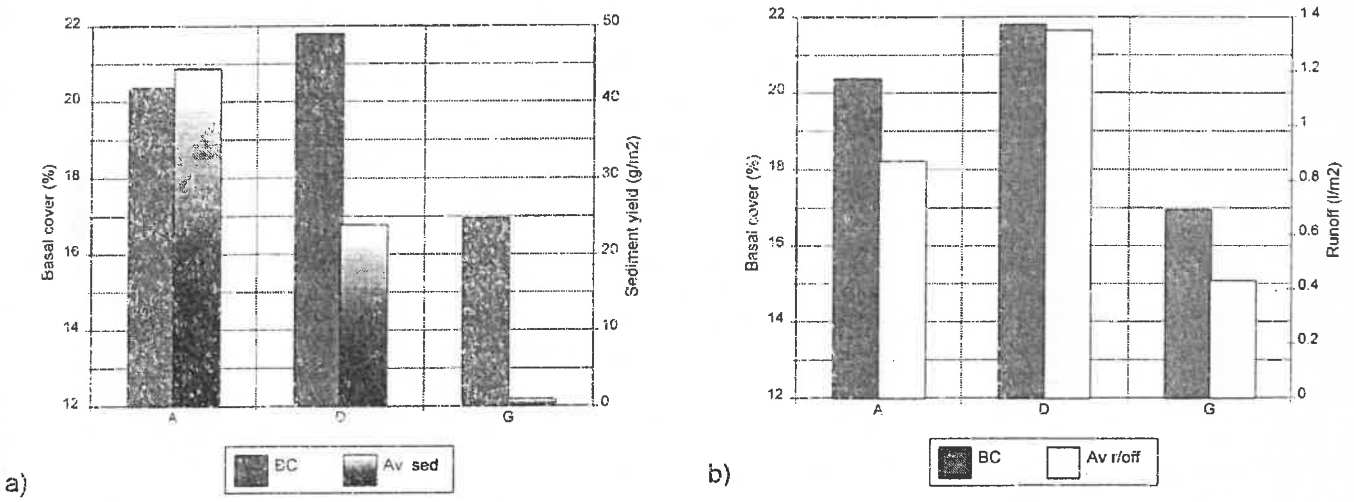

Figure 5.14: The runoff (a) and sediment yield (b) compared to the basal cover (BC) for the winter burn plots on the north-facing slope.

Figure 5.14 show that runoff and sediment loss decrease with increasing gradient for the winter and spring burn plots on the north-facing slope. BC decreases upslope, probably in response to decreasing soil moisture conditions. The runoff and sediment loss do not increase correspondingly, suggesting that, in this case, BC is not the dominant factor in controlling runoff and erosion.

The results for plot B, as shown in Figure 5.15, must be viewed with caution because the runoff counter was inoperative for some of the monitoring period. If plot B is ignored then the spring burn plots show a similar trend to the winter burn plots (Figure 5.14) with decreasing sediment yield as gradient increases.

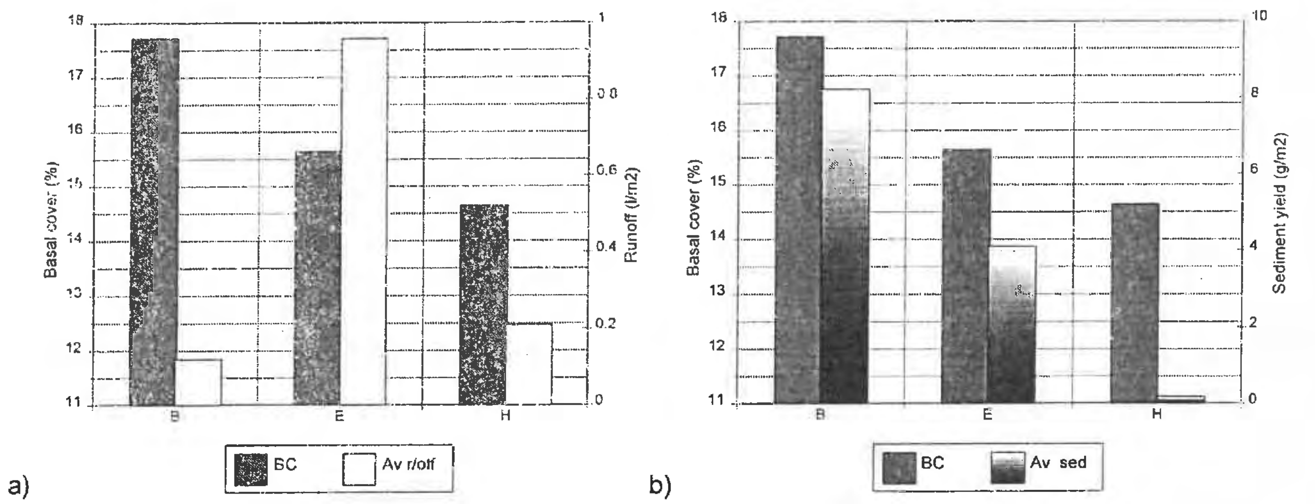

Figure 5.15: The runoff (a) and sediment yield (b) compared to the basal cover (BC) for the spring burn plots on the north-facing slope.

The sediment yield and runoff for the control plots, C, F and I , increase with increasing gradient (Figure 5.16) suggesting that under natural conditions there is better infiltration downslope. Thus at low gradients a high BC results in improved infiltration and decreased runoff and sediment yield. It must be remembered however that regardless of BC, under natural conditions, steeper slopes will produce more runoff simply because gravity does not allow rain the time to collect on the surface.

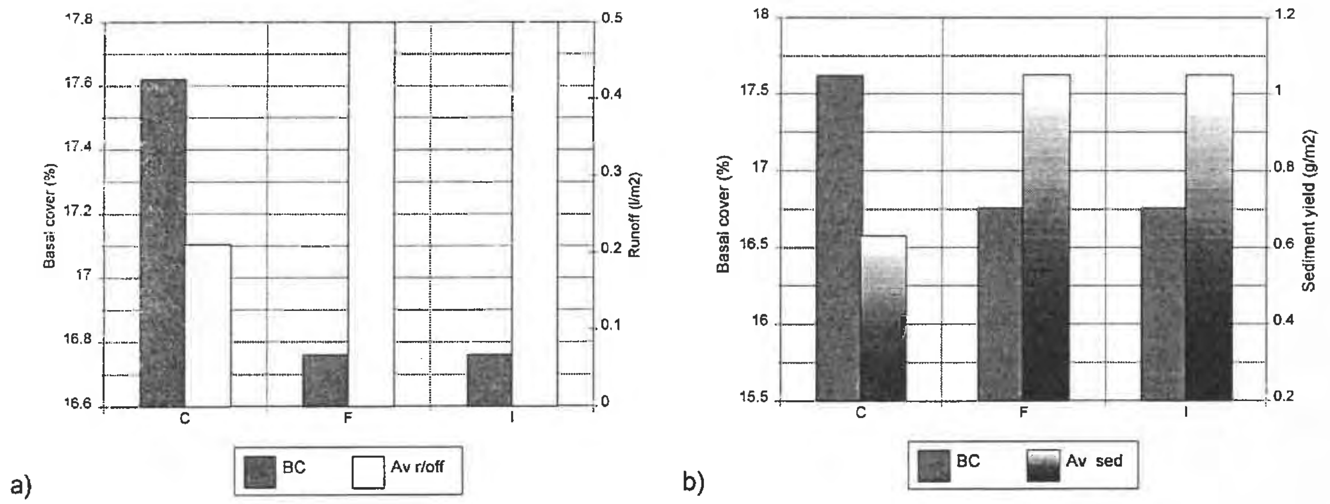

Figure 5.16: The runoff (a) and sediment yield (b) compared to the basal cover (BC) for the control plots on the north-facing slope.

There is no clear trend for BC on the South-facing slope as gradient increases (Figure 5.17). Both runoff and sediment loss generally increase with increasing gradient. A comparison of all the winter burn plots of similar gradients irrespective of aspect (Figures 5.18 - 5.19) shows a common pattern between BC and runoff and sediment yield.

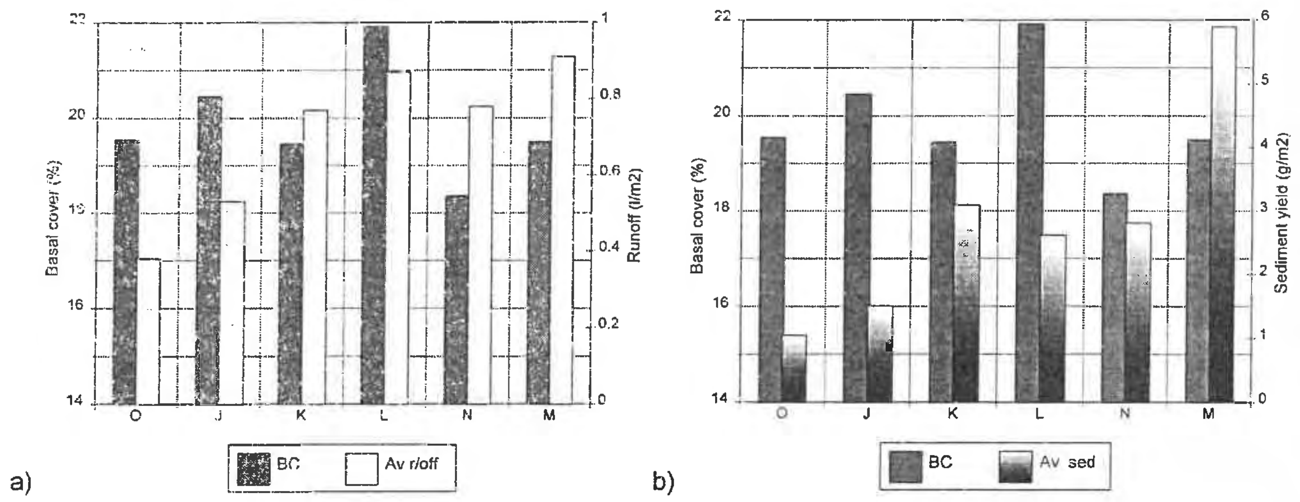

Figure 5.17: The runoff (a) and sediment yield (b) for the plots on the south-facing slope.

5.3.3. Comparison of the effect of aspect

All the plots on this slope received the same treatment in terms of season of burn so there was very little difference in canopy cover between the plots. The only plot which had substantially more vegetation was plot J which is on a low gradient and therefore higher soil moisture. Although O is also shallow in gradient it did not recover to the same extent because of it's more exposed position and the detrimental effect of grazing horses. The grazing did not increase the sediment yield, in fact plots O and N which are exposed to occasional grazing yielded less sediment and runoff than the other plots in the same slope classes. Both O and N are more exposed to wind than the other plots and are positioned on a firebreak. Annual burning does not allow the build up of organic matter content within the soil. The organic matter is responsible for the stability of the aggregates in what is essentially a sandy soil. The detrimental effects of annual burning and their exposed position could be responsible for the plots having already lost much of their transportable sediment. They also have a slightly more southwesterly orientation and therefore receive sunlight for longer periods than the other plots which are well shaded by the cliff above them. Evaporation rates are thus assumed to be higher resulting higher infiltration rates because of a lower soil moisture.

With the exception of O and N, the plots were burnt in a wildfire, rather than planned prescribed burns. Vegetation is obviously more lush on the south-facing slopes because of the more favourable moisture conditions and therefore it was assumed that the intensity of burn was greater than that experienced on the north-facing slope because of the higher fuel load.

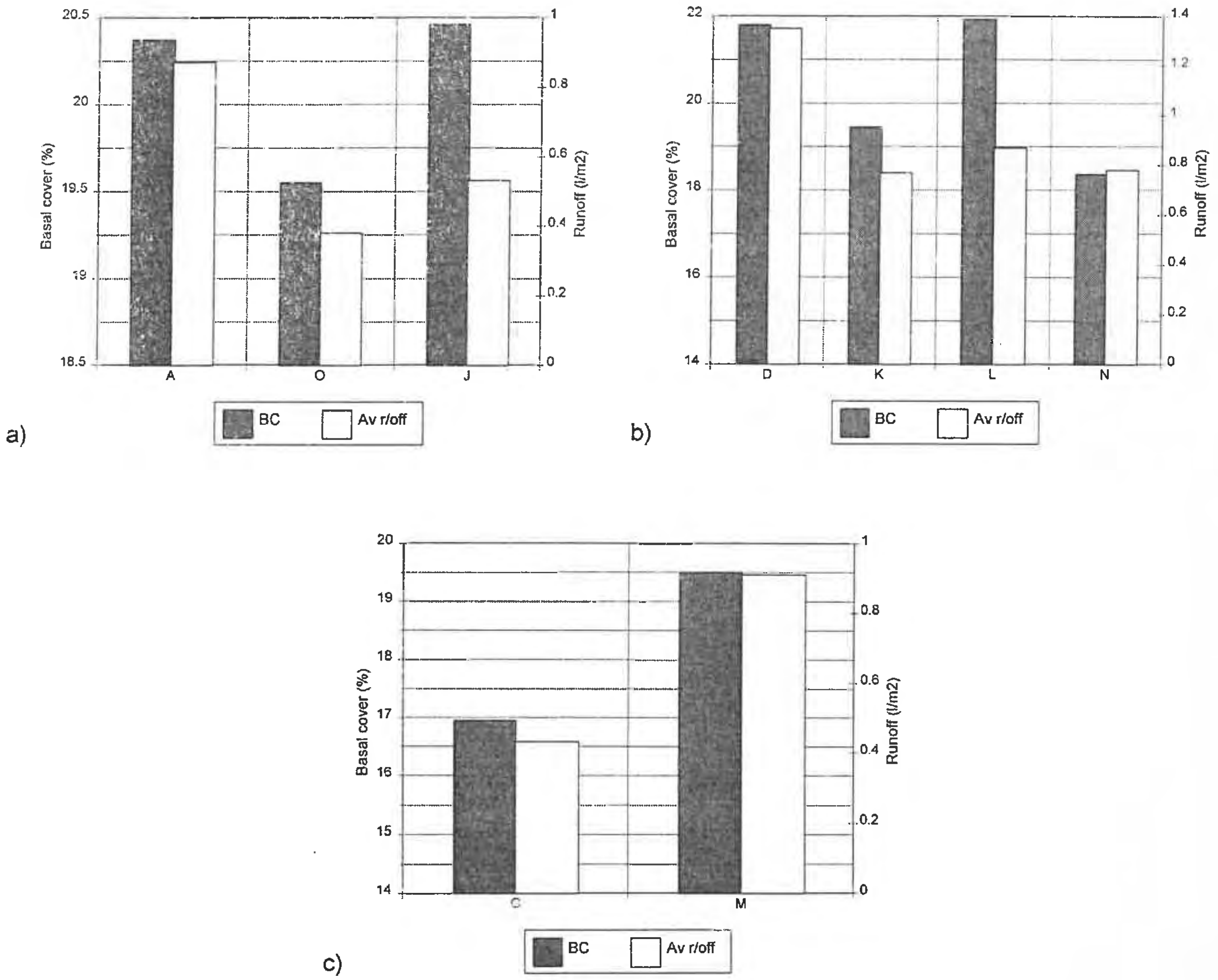

Figure 5.18 : Comparison of the runoff from the winter burn plots on (a)<15^0, (b)15-25^0 and (c)>25^0 slopes.

This comparison also shows that soil loss for the plots on the north-facing slope (A, D, and G) was generally greater, with the exception of the steepest plots, G and M. This exception can be explained by the lack of sediment available for removal on the north-facing plot when compared to the thicker soil profile resulting from the effects of aspect, as shown by plot M. The trend for the plots on the lower gradient is probably a result of the protection of the higher canopy cover for the south-facing plots.

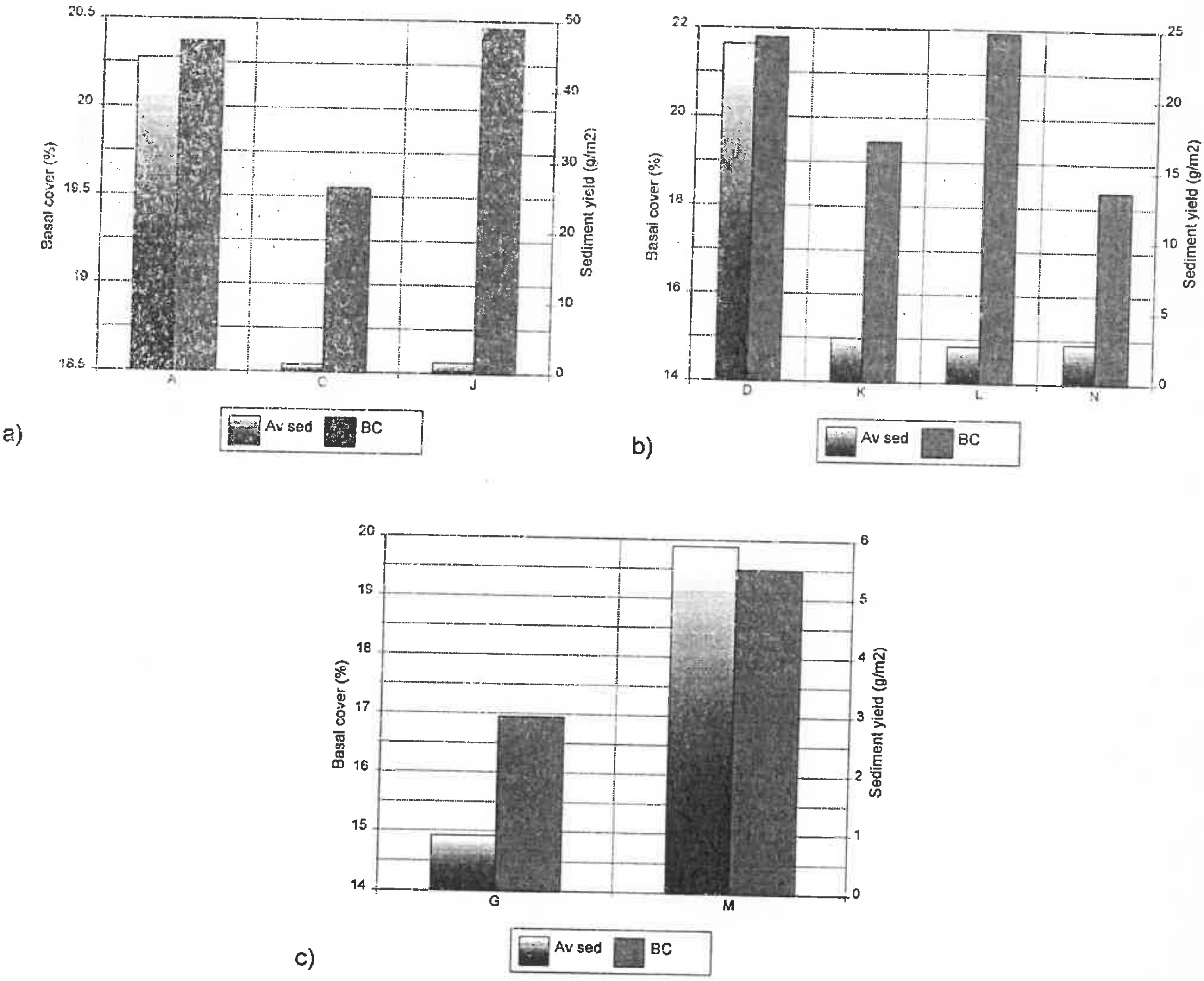

Figure 5.19: Comparison of the sediment yield and basal cover (BC) from the winter burn plots on <15^0 (a), 15-25^0 (b) and >25^0 (c) slopes.

5.3.4. Summary

Basal cover did not have the same influence on soil loss and runoff which was found by Snyman and Van Rensburg (1986). They found that slopes covered with climax vegetation had a higher canopy and basal cover and produced less runoff and soil loss than slopes consisting of sub-climax and pioneer vegetation. The grassland at GGHNP is in the climax successional stage but generally basal cover did not prove to be the controlling variable expected. It appears as if the site conditions i.e. degree of stoniness or surface roughness, and the timing of the burn are more important factors in this study than the existing basal cover. It is recommended however that continued monitoring of the canopy and basal cover under wetter conditions is necessary to give a more complete picture of the relationship of vegetation cover and soil loss in GGHNP.

Burning at different seasons results in exposure to erosive forces at different times of the year. Winter burning exposes the soil for an extended period during the dry season but, under normal rainfall conditions, recovery is rapid in the spring. Spring burning exposes the soil to the first summer rains and according to Everson *et al.* (1985), results in higher predicted sediment losses. However, Garland (1988) showed that in the Drakensberg winter burns yielded greater sediment than spring burning. The findings of this study are in agreement with Garland in that generally winter burning produces greater sediment yield than spring burning, although site conditions exert an influence on the significance of this difference.

Similar winter burn treatment on north and south aspect slopes resulted in greater sediment and runoff yield from the north-facing plots. The exception was the steepest plots which could be attributed to differences in sediment availability because of varying soil depth.

CHAPTER SIX

Conclusion

"...the ideal burning regime will probably never be settled - indeed there cannot be one to suit all species and vegetation types simultaneously."

- U.W. Nänni, 1969 (in Granger, 1976 p. vi)

The addition of geomorphological aspects to Nänni's statement, quoted above, has made the search for the perfect burning policy something of a Holy Grail. It would be inadvisable to offer a definitive statement on the geomorphological effects of burning based on the results of this research because it was essentially a short term preliminary investigation conducted during an abnormal rainfall season. The study was aimed at evaluating the effect of burning on soil properties and analysing the effect of fire on soil erosion processes in terms of slope aspect, gradient and the timing of the burn.

6.1 The effect of fire on soil properties

- The temperature of the fire was not conducted to root depth (5cm below the soil surface), and was too low to cause changes in soil structure or clay mineralogy.
- High fire temperatures have a negative effect on infiltration rate but if burning occurs under favourable controlled burning conditions this is unlikely to occur.
- Low intensity controlled burning has little effect on soil aggregate stability. Changes in organic matter content were related to the grassland growth cycle rather than to burning.
- The soils of GGHNP are essentially sandy and their aggregate stability is due almost entirely to high organic matter content. High intensity frequent burning will reduce organic matter and act to increase soil erodibility.

6.2 The effect of gradient

- Canopy cover is generally higher on areas of low gradient because of improved soil moisture conditions.

- Gradient did not play a significant role in determining the particle size characteristics of the sediment yielded from the runoff plots.
- Sediment yield and runoff from burnt plots decreased with increasing gradient in contrast to the control plots where the opposite trend was observed.

6.3 The effect of aspect

- The soil particle size was similar for north- and south-facing slopes.
- Soil moisture is higher for the south-facing slope and this is shown by the greater canopy cover. This results in diminished sediment yield from the south-facing plots compared to those on the opposite slope.

6.4 The effect of timing of burn

- Winter burning tends to cause greater sediment losses than spring burning, although site-specific conditions, particularly on the steep upper slopes, exert a considerable influence.
- Spring burning is preferred in spite of the fact that a higher soil moisture will result in better conduction of the heat of the fire to deeper in the soil profile. If the burn is conducted under suitable meteorological conditions the heat intensity produced can be minimised. The heat produced in grassland fires is usually not of an intensity that will result in changes to soil structure.

Field managers cannot wait for academic certainty in the answers which they seek. This research has provided some burn programme guidelines from which to operate and opened up some avenues for further investigation. The study has certainly highlighted the need for management decisions of this nature to be made on the basis of multi-disciplinary research results.

6.5 Towards a revised burn policy

The findings of various researchers on the effect of fire are contradictory and site specific, making the formulation of a burn policy difficult. While fire is a part of the grassland ecosystem and does pose an extreme risk during the dry season, it is not necessarily a natural feature of the winter landscape. Although GGHNP falls within the area of 4 lightning strikes $km^{-2}yr^{-1}$, lightning induced fires are more likely to occur during the wetter months when soil and fuel moisture are higher. Burning has been used as a tool for improving grazing and grass palatability since primitive times, however Golden Gate is a scenic National Park and not a farm and the management aims should reflect this. The area is adapted to fire and fire exclusion will result in veld succession to include woodier vegetation. Woody vegetation presents a higher fire risk and possibility of decreased water yield. It is therefore desirable that the area is regularly burnt. Botanists will be responsible for ensuring that the fire regime implemented at GGHNP will maximise biodiversity in accordance with the stated policy of the National Parks Board. Such a burn policy should simultaneously keep the erosion risk to a minimum if the biodiversity objectives are to be sustained in the long term.

A largely undocumented body of knowledge has been gained by managers through field experience and generally pertains to the safe application of controlled burns rather than to the achievement of pre-determined management goals. If implementation of management recommendations is to occur they must not only be scientifically based, but also practical and cost effective. Rather than formulate a rigid prescriptive policy, it seems more environmentally sensitive to apply burns to those areas where the build-up of fuel is such that it poses an unacceptable fire hazard. For this purpose the Park needs to be divided into management units. These units should be identified using features such as ridges and roads, yet still with due regard to the criterion of botanical diversity. Cognisance must be taken of the needs of some of the rarer indigenous fauna which occur in the Park and are restricted to certain areas because of specific habitat requirements e.g. Oribi.

It is suggested that the Park be divided into blocks taking into account slope steepness, vegetation and critical animal habitat. These blocks must also be practically accessible to the field management staff. The firebreaks which delineate the blocks cannot be fixed so that the same area is burnt year after year. The divisions should therefore be broad to allow fluctuation. Thus it seems almost inevitable that the Park boundaries will be burnt in successive years. It would be ideal if firebreaks could be rotated on a biennial or triennial basis, however it is recognised that this could prove impractical especially around infrastructure such as the camps and offices. It can be argued that these areas are already largely disturbed and therefore annual burning of these strategic firebreaks could be justified. The borders of the Park present a unique problem. It is not possible to leave the borders unprotected as there are legal and financial considerations should a fire within the Park spread to a neighbouring property. It is also not desirable to spend excessive time and effort fighting wildfires that come into the Park from outside the Park boundaries.

It is proposed that the blocks are assessed at the beginning of the burn season to determine both the fuel load (and therefore fire risk) and the erosion risk which the area poses. If the manager deems the area to be a danger the area should be burnt in a controlled burn, the results of which are not nearly as devastating as those associated with a wildfire. If a block is burnt in a wildfire, the area should be allowed to burn out but the fire should be prevented from entering other blocks, hence the need for suitably sited firebreaks to divide the blocks. Any detrimental effects of burning are that much worse in a wildfire because by it's very nature it is uncontrolled and usually of a much greater intensity than prescribed burns. The manager therefore must weigh the economic advantages of not fighting the fire against the possible environmental damage which may occur.

The following preliminary conclusions can be drawn based on the results from this and other South African research.

- Controlled burns should be applied as head fires as they may cause the least damage to the grass sward (Trollope, 1984).
- When burning to remove moribund, unacceptable grass material a low intensity fire is required. This can be achieved by burning when the air temperature is <20°C and the relative humidity is >50%. These conditions frequently prevail between 15h30 and 11h00 (Trollope, 1984).

- The present study has shown that winter burning produces a greater sediment yield than does spring burning. This suggests that controlled burns should be applied in the spring from late August to the beginning of October.
- In all cases the grass must be fully cured and the wind speed not exceed $5.6 m.s^{-1}$ for safety reasons (Trollope, 1984). Spring is unfortunately also the time of maximum windspeeds. The windspeeds are lowest between midnight and 06h00 and therefore burns should be conducted as early as possible in the morning.

It would be worthless for management to apply preventive burning such as firebreaks in the spring when much of the fire danger has passed. This emphasises the importance of rotating firebreaks and thus allowing the burnt area time to recover.

There is a fine balance between burning too much too often and allowing a dangerous build-up of fuel that will result in catastrophic effects if burnt during a wildfire.

6.6 Further research

If this project is continued for a longer period, a greater understanding of the complexities of the fire and soil erosion relationship will develop. The botanical or grassland aspects of this study can be taken further in an attempt to identify how the grassland species composition of GGHNP reacts to the frequency and timing of burns, as well as the continued monitoring of the vegetation cover in response to different burn treatments.

More detailed investigation is required into the effect of fire temperature on infiltration rate in grassland areas. The factors which control post-burn infiltration rate also need to be identified.

The contribution of rainsplash erosion to total sediment loss in burnt areas compared to that resulting from runoff requires further study.

REFERENCES

Acocks, J.P.H., 1975: Veld types of South Africa, Second edition, *Memoirs of the Botanical Survey of South Africa* No. 40.

Anderson, H.W., 1976: Fire effects on water supply, floods and sedimentation, *Proceedings Annual Tall Timbers Fire Ecology Conference*, 15, 249-260.

Andreu, V., Rubio, J.L., Forteza, J. and Cerni, R., 1994: Long term effects of forest fires on soil erosion and nutrient losses, in: Sala, M. and Rubio, J.L. (Eds), *Soil erosion as a consequence of forest fires*, Geoforma Ediciones, Logroño, 79-90.

Bergsma, E. and Valenzuela, C.R., 1981: Drop testing aggregate stability of some soils near Mérida, Spain, *Earth Surface Processes and Landforms*, 6, 309-318.

Blong, R.J., Riley, S.J. and Crozier, P.J., 1982: Sediment yield from runoff plots following a bushfire near Narrabeen Lagoon, NSW, *Search*, 13, 36-38.

Bosch, J.M., 1980: ŉ Ontleiding van die hidrologiese eksperiemente in die Cathedral Peak opvangebiede, unpublished M.Sc thesis, Faculty of Forestry, University of Stellenbosch.

Bosch, J.M., Schulze, R.E. and Kruger, F.J., 1984: The effect of fire on water yield, in: Booysen, P. de V. and Tainton, N.M. (Eds), *Ecological effects of fire in South African ecosystems*, Springer-Verlag, Berlin, 327-349.

Brady, H.M., 1993: An investigation into the nature of gully erosion at Golden Gate Highlands National Park, unpublished M.Sc thesis, Department of Geography, University of Natal, Pietermaritzburg.

Briggs, D., 1977: *Sediments*, Butterworths, London.

Britton, C.M. and Wright, H.A., 1971: Correlation of weather variables to mesquite damage by fire, *Journal of Range Management*, 24, 136-141.

Bronowski, J., 1973: *The ascent of man*, British Broadcasting Corporation, London.

Brown, J.A.H., 1972: Hydrologic effects of a bushfire in a catchment in south-eastern New South Wales, *Journal of Hydrology*, 15, 77-96.

Bryan, R.B., 1971: Efficiency of aggregation indices in the comparison of some English and Canadian soils, *Journal of Soil Science*, 22, 166-178.

Bryden, H.B. and de Vos, V., 1994: Scientific bibliography on the National Parks of South Africa, *Koedoe supplement*, 1-3.

Calvo-Cases, A. and Cerdá-Bolinches, A., 1994: An example of the changes in the hydrological and erosional response of soil after a forest fire, Pedralba (Valencia), Spain, in: Sala, M. and Rubio, J.L. (Eds), *Soil erosion as a consequence of forest fires*, Geoforma Ediciones, Logroño, 99-110.

Campbell, R.E., Baker, M.B.J., Ffolliott, P.F., Larson, L.R. and Avery C.C., 1977: *Wildfire effects on a ponderosa pine ecosystem: an Arizona case study*, USDA Forest Service, Research Paper RM-191, Rocky mountain Forest and Range Experiment Station, Fort Collins, Colorado, USA.

Cass, A., 1978: Chemical characteristics of selected plots at the Ukulinga long-term burning trials, unpublished report, Department of Soil Science and Agrometeorology, University of Natal, Pietermaritzburg.

Cass, A., Savage, M.J. and Wallis, F.M., 1984: The effect of fire on soil and microclimate, in: Booysen, P. de V. and Tainton, N.M. (Eds), *Ecological effects of fire in South African ecosystems*, Springer-Verlag, Berlin, 311-326.

Chandler, C., Cheney, P., Thomas, P., Trabaud, L. and Williams, D., 1983: *Fire in forestry, Volume 1-Forest fire behaviour and effects*, John Wiley and Sons, New York.

Chaney, K and Swift, R.S., 1984: The influence of organic matter on aggregate stability in some British soils, *Journal of Soil Science*, 35, 223-230.

Coelho, C.O., Shakesby, R.A., Walsh, R.D.P., Terry, J.P. and Ferreira, A.D., 1990: Responses of surface and sub-surface soil water movement and soil ersion to forest fires in *Eucalyptus globulus* and *Pinus pinaster*, Agueda Basin, Portugal, in: Domingos Xavier, V. (Ed.), *Proceedings of the International Conference on Forest Fire Research*, Coimbra, C.08-1.

Daubenmire, R., 1968: Ecology of fire in grasslands, in: Cragg, J.B. (Ed.), *Advances in Ecological Research,* volume 5, Academic Press, London.

Davies, B.R., O'Keefe, J.H. and Snaddon, C.D., 1993: *A synthesis of the ecological functioning, conservation and management of South African ecosystems*, Water Research Council Report TT62/93.

Day, K.D., Sumner, P.D. and Beckedahl, H.R., 1994: Compaction and soil loss from a footpath in Royal Natal National Park, South Africa, paper presented at the GERTEC/SAAG Conference, University of Natal, Pietermaritzburg, 23-27 January, 1994.

DeBano, L.F., 1966: *Formation of non-wettable soils...involves heat transfer mechanism*, USDA Forestry Service, Research Note PSW-132, Pacific Southwestern Forest and Range Experiment Station, Berkeley, California, USA.

DeBano, L.F., 1969: The relationship between heat treatment and water repellency in soils, in: DeBano, L.F. and Letey, J. (Eds), *Proceedings symposium water-repellent soils*, University of California, Riverside, 265-279.

DeBano, L.F., 1971: The effect of hydrophobic substances on water movment in soil during infiltration, *Soil Science Society of America Proceedings*, 35, 340-343.

DeBano, L.F., 1981: *Water repellent soils; a state-of-the-art*, USDA Forest Service, General Technical Report PSW-46, Pacific Southwestern Forest and Range Experiment Station, Berkeley, California, USA.

DeBano, L.F. and Krammes, J.S, 1966: Water repellent soils and their relation to wildfire temperatures, *International Association of Scientific Hydrologists Bulletin*, XI Annee 2, 14-19.

DeBano, L.F., Osborn, J.F., Krammes, J.S. and Letey, J., 1967: *Soil wettability and wetting agents...our current knowledge of the problem*, USDA Forest Service, Research Paper PSW-43, Pacific Southwestern Forest and Rang Experiment Station, Berkeley, California, USA.

DeBano, L.F., Savage, S.M. and Hamilton, D.A., 1976: The transfer of heat and hydrophobic substances during burning, *Soil Science Society American Journal*, 40, 779-782.

De Kock, G., 1995: Head Ranger, Golden Gate Highlands National Park, Private Bag Clarens, 9708.

Díaz-Fierros, F., Benito, E., Vega, J.A., Castelao, A., Soto, B., Pérez, R. and Taboada, T., 1990: Solute loss and soil erosion in burned soil from Galicia (NW Spain), in: Goldammer, J.G. and Jenkins, M.J. (Eds), *Fire in ecosystem dynamics: Mediterranean and Northern perspectives*, SPB Publishing, The Hague, 103-116.

Díaz-Fierros, F., Benito, E. and Soto, B., 1994: Action of forest fires on vegetation and soil erodibility, in: Sala, M. and Rubio, J.L. (Eds), *Soil erosion as a consequence of forest fires*, Geoforma Ediciones, Logroño, 163-176.

Dimitrakopoulos, A.P. and Martin, R.E., 1994: Effect of moisture content on soil heating during simulated wildland fire conditions, in: Sala, M. and Rubio, J.L. (Eds), *Soil erosion as a consequence of forest fires*, Geoforma Ediciones, Logroño, 207-216.

Dimitrakopoulos, A.P., Martin, R.E. and Papamichos, N.T., 1994: A simulated model of heating during wildland fires, in: Sala, M. and Rubio, J.L. (Eds), *Soil erosion as a consequence of forest fires*, Geoforma Ediciones, Logroño, 199-206.

Edwards, P.J., 1961: Studies in veld burning and mowing in the Tall Grassveld of Natal, unpublished M.Sc thesis, University of Natal, Pietermaritzburg.

Edwards, D., 1984: Fire Regimes in the biomes of southern Africa, in: Booysen, P. de V. and Tainton, N.M. (Eds), *Ecological effects of fire in South African ecosystems*, Springer-Verlag, Berlin, 19-38.

Edwards, P.J., 1984: The use of fire as a management tool, in: Booysen, P. de V. and Tainton, N.M. (Eds), *Ecological effects of fire in South African ecosystems*, Springer-Verlag, Berlin, 349-362.

Evans, R., 1980: Mechanics of water erosion and their spatial and temporal controls: an empirical viewpoint, in: Kirkby, M.J. and Morgan, R.P.C. (Eds), *Soil Erosion*, John Wiley and Sons, Chichester.

Everson, C.S., George, W.J. and Schulze, R.E., 1985: The effect of veld burning on canopy cover and sediment yield, in: Schulze, R.E. (Ed), *Proceedings Second South African National Hydrology Symposium*, Pietermaritzburg, September 1985, Agricultural Research Unit Report no. 22, 396-409.

Everson, C.S., George, W.J. and Schulze, R.E., 1989: Fire regime effects on canopy cover and sediment yield in the montane grasslands of Natal, *South African Journal of Science*, 85, 113-116.

Finlayson, B. and Statham, I., 1980: *Hillslope Analysis*, Butterworths, London.

Garland, G.G., 1987: *Erosion risk from footpaths and vegetation burning in the central Drakensberg*, Supplementary Report No. 20, Natal Town and Regional Planning Commission, Pietermaritzburg.

Garland,G.G., 1988: Experimental footpath losses and path erosion risk assessment in the Natal Drakensberg, unpublished Ph.D thesis, University of Natal, Durban.

Gilman, K. and Newson, M.D., 1980: *Soil pipes and pipeflows: A hydrological study in upland Wales*, British Geomorphological Research Group Monograph Series No. 1, Geobooks, Norwich.

Giovannini, G., 1994: The effect of fire on soil quality, in: Sala, M. and Rubio, J.L. (Eds), *Soil erosion as a consequence of forest fires*, Geoforma Ediciones, Logroño 15-28.

Giovannini, G. and Lucchesi, S., 1983: Effect of fire on hydrophobic and cementing substances of soil aggregates, *Soil Science*, 136, 231-236.

Giovannini, G., Lucchesi, S. and Giachetti, M., 1990: Efffects of heating on some chemical parameters related to soil fertility and plant growth, *Soil Science*, 149, 344-350.

Granger, J.E., 1976: The vegetation changes, some related factors and changes in the water balance following twenty years of fire exclusion in Catchment IX, Cathedral Peak Forestry Research Station, unpublished Ph.D. thesis, University of Natal, Pietermaritzburg.

Greene, R.S.B., Chartres, C.J. and Hodgkinson, K.C., 1990: The effects of fire on the soil in a degraded semi-arid land - 1. Cryptogam cover and physical and micromorphological properties, *Australian Journal of Soil Research*, 28, 755-775.

Gregory, S., 1978: *Statistical methods and the geographer*, Longman, London.

Grieve, I.C., 1979: *Soil aggregate stability tests for the geomorphologist*, BGRG Technical Bulletin No. 25, Geo Abstracts, Norwich.

Groenewald, G.H., 1985: List of interesting geological sites: Rhebuck Trail, Golden Gate Highlands National Park, unpublished internal report, National Parks Board, Golden Gate Highlands National Park.

Groenewald, S. and Groenewald, G.H., 1989: 'n Ekologiese en gedragsstudie van die Swartwildebees in die Golden Gate Hoogland Nasionale Park, Golden Gate Highlands National Park, unpublished internal report, National Parks Board, Golden Gate Highlands National Park.

Hall, M., 1984: Man's historical and traditional use of fire in southern Africa, in: Booysen, P de V. and Tainton, N.M. (Eds), *Ecological effects of fire in South African ecosystems*, Springer-Verlag, Berlin, 39-52.

Hardy, M.B. and Tainton, N.M., 1993: Towards a technique for determining basal cover in tufted grasslands, *African Journal of Range and Forage Science*, 10, 77-81.

Hazelton, P.A. and Murphy, B.W., (Ed), 1992: *What do all the numbers mean? A guide for the interpretation of soil test results*, Department of Conservation and Land Management (incorporating the Soil Conservation Service of NSW), Sydney.

Helvey, J.D., Tiedemann, A.R. and Fowler, W.B., 1976: Some climatic and hydrological effects of wildfire in Washington state, *Proceedings Annual Tall Timbers Fire Ecology Conference*, 15, 201-222.

Hosking, J.S., 1938: The ignition at low temperatures of the organic matter in soils, *Journal of Agricultural Science*, 38, 393-400.

Hudson, N.W., 1971: *Soil Conservation*, Batsford, London.

Hudson, J., Kellman, M., Sanmugadas, K. and Alvarado, C., 1983: Prescribed burning of *Pinus oocarpa* in Honduras - 1. Effects on surface runoff and sediment loss, *Forest Ecology and Management*, 5, 269-281.

Humphreys, F.R. and Craig, F.G., 1981: Effects of fire on soil chemical, structural and hydrological properties, in: Gill, A.M., Groves, R.H. and Noble, I.R. (Eds), *Fire and the Australian Biota*, Australian Academy of Science, Canberra, 177-200.

Imeson, A.C., Verstraten, J.M., Van Mulligen, E.J. and Sevink, J., 1992: The effect of fire and water repellency on infiltration and runoff under Mediterranean type forest, *Catena*, 19, 345-361.

Josá, R., Arias, X. and Solé, A, 1994: Effects of slashburning on some soil physical properties in an olm-oak coppice, in: Sala, M. and Rubio, J.L. (Eds) *Soil erosion as a consequencef forest fires*, Geoforma Ediciones, Logroño, 29-42.

Kay, C., Bredenkamp, G.J. and Theron. G.K., 1993: The plant communities of the Golden Gate Highlands National park in the northeastern Orange Free State, *South African Journal of Botany*, 59(4), 442-449.

King, P.M., 1981: Comparison of the methods for measuring the severity of water repellence of sandy soils and assessment of some factors that affect its measurement, *Australian Journal of Soil Research*, 19, 275-285.

Kirkby, M.J., 1980: Modelling soil ersoion processes, in: Kirkby, M.J. and Morgan, R.P.C.(Eds), *Soil Erosion*, John Wiley and Sons, Chichester.

Kozlowski, T.T. and Ahlgren, C.E., 1974: *Fire and ecosystems*, Academic Press Inc., New York.

Krammes, J.S. and Osborn, J., 1969: Water-repellent soils and wetting agents as factors influencing ersoion, in: DeBano, L.F. and Letey, J. (Eds) *Proceedings Symposium, Water-repellent soils*, University of California, Riverside, May 1968, 177-186.

Kutiel, P. and Inbar, M., 1993: Fire impacts on soil nutrients and soil erosion in a Mediterranean Pine Forest Plantation, *Catena*, 20, 129-139.

Kutiel, P., Lavee, H., Segev, M. and Benyamini, Y., 1995: The effect of fire-induced surface heterogeneity on rainfall-runoff-erosion relationships in an eastern Mediterranean ecosystem, Israel, *Catena*, 25, 77-87.

Lavee, H., Benyamini, Y., Kutiel, P. and Segev, M., 1991: Infiltration, runoff and erosion processes as influenced by forest fires in the Carmel Mountain, Israel, paper presented at the ESSC Conference on Soil Erosion and Degradation as a Consequence of Forest Fires, Barcelona and Valencia, Spain, September, 1991.

Lavee, H., Kutiel, P., Segev, M. and Benyamini, Y., 1995: Effect of surface roughness on runoff and erosion in a Mediterranean ecosystem: the role of fire, *Geomorphology*, 11, 227-234.

Le Roux, J.S. and Roos, Z.N., 1986: The relationship between the size of particles in surface wash sediment and rainfall characteristics on a low angle slope in a semi-arid climate, *Zeitschrift für Geomophologie*, 30, 363-369.

Leitch, C.J., Finn, D.W. and van de Graaf, R.H.M., 1983: Erosion and nutrient loss resulting from Ash Wednesday (February 1983) wildfires: a case study, *Australian Forestry*, 46, 173-180.

Lindley, A.J., Bosch, J.M. and van Wyk, D.B., 1988: Changes in water yield after fire in fynbos catchments, *Water SA*, 14, 7-12.

Link, S.O., Gee, G.W., Thiede, M.E. and Beedlow, P.A., 1990: Response of a shrub-steppe ecosystem to fire: Soil water and vegetation change, *Arid Soil Research and Rehabilitation*, 4, 163-172.

Luke, R.H. and McArthur, A.G., 1977: Bushfires in Australia, Department of Primary Industry, Forestry and Timber Bureau, CSIRO Division of Forest Research, Austalian Government Publishing Service, Canberra.

Marker, M., 1989: Periglacial geomorphology at Golden Gate Highlands National Park: a note on its fieldwork potential, *South African Geographer*, 16, 147-153

Martínez-Fernández, J. and Díaz Pereira, E., 1994: Changes of the physical and chemical properties in a soil affected by forest fire in Sierra Larga (Murcia), in: Sala, M. and Rubio, J.L. (Eds), *Soil erosion as a consequence of forest fires*, Geoforma Ediciones, Logroño, 67-77.

May, T., 1990: Die entwicklung der Vegetationsstruktur nach Bränden im Mittelmeergebiet - Konsequenzen für die Bodenerosion und Landschaftsdegradation - Beispiele aus Hochandalusien, *GeoÖkodynamik*, 11, 43-64.

Mbagwu, J.S.C. and Piccolo, A., 1989: Changes in soil aggregate stability induced by amendment with humic substances, *Soil Technology*, 2, 49-57.

Molina, M.J. and Sanroque, P., 1991: Incendios forestales y desertificación: una revisión en torno a la erosionalidad del suelo, in: *Procesos de desertización en condiciones ambientales mediterráneas,* Universidad Internacional Menedez Pelayo, Valencia, 24-28 June, 1991.

Molina, M.J., García Fayos, P. and Sanroque, P., 1994: Short-term changes on aggregate stability and organic matter content after forest fire in a calcareous soil in Valencia, in: Sala, M. and Rubio, J.L. (Eds), *Soil erosion as a consequence of forest fires*, Geoforma Ediciones, Logroño, 43-52.

Morgan, R.P.C., 1986: *Soil erosion and conservation*, Longman Scientific and Technical, Harlow.

Moon, B.P. and Munro-Perry, P.M., 1988: Slope development on the Clarens Sandstone Formation in the northeastern Orange Free State, *South African Geographical Journal*, 70, 57-69.

Munro-Perry, P.M., 1990: Slope development in the Klerkspruit valley, Orange Free State, South Africa, *Zeitschrift für Geomorphologie*, 34, 409-421.

Mutchler, C.K., Murphree, C.E. and McGregor, K.C., 1994: Laboratory and field plots for erosion research, in: Lal, R (Ed.), *Soil erosion research methods*, St Lucie Press, Florida, 11-38.

Nänni, U.W., 1960: The immediate effects of veld-burning on stream flow in Cathedral Peak catchments, *Journal of the South African Forestry Association*, 34, 7-12.

Nicol, I.G., 1976: The geomorphology of the Little Caledon Valley, unpublished Ph.D thesis, Department of Geography, University of South Africa.

Packham, D.R., 1969: Heat transfer above a small ground fire, *Australian Forest Research*, 5, 19-24.

Pieterse, C., 1995: Director, Golden Gate Highlands National Park, Private Bag Clarens, 9708.

Poesen, J., 1986: Surface sealing as influenced by slope angle and position of simulated stones in the top layer of loose sediments, *Earth surface processes and landforms*, 11, 1-10.

Pyne, S.J., 1993: Keeper of the flame: a survey of anthropogenic fire, in: Crutzen, P.J. and Goldammer, J.G. (Eds), Fire in the environment: the ecological, atmospheric and climatic importance of vegetation fires, John Wiley and Sons, Chichester, 245-266.

Raison, R.J., 1979: Modification of the soil environment by vegetation fires, with particular reference to nitrogen transformations: a review, *Plant and Soil*, 51, 73-108.

Roberts, B.R., 1969: The vegetation of the Golden Gate Highlands National Park, *Koedoe*, 12, 15-28.

Sánchez, J.R., Mangas, V.J., Ortiz, C. and Bellot, J., 1994: Forest fire effect on soil chemical properties and runoff, in: Sala, M. and Rubio, J.L. (Eds), *Soil erosion as a consequence of forest fires*, Geoforma Ediciones, Logroño, 53-65.

Savage, S.M., Osborn, J., Letey, J. and Heaton, C., 1972: Substances contributing to fire-induced water repellency in soils, *Soil Science of America Proceedings*, 36, 674-678.

Scheidegger, A.E., 1995: Geojoints and geostresses, in: Rossmanith, H-P. (Ed.), *Mechanics of Jointed and Faulted Rock*, Balkema, Rotterdam, 3-35.

Schulze, B.R., 1947: The climates of South Africa according to the classification of Köppen and Thornwaite, *South African Geographical Journal*, 29, 32-42.

Scott, J.D.. 1951: A contribution to the study of the problems of the Drakensberg conservation area, *Science Bulletin* No. 324, Union of South Africa, Department of Agriculture.

Scott, D.F., 1991: The influence of eucalypts on soil wettability, *Proceedings of the Symposium on Intensive Forestry: the role of eucalypts*, 1044-1056.

Scott, D.F., 1994: The hydrological effects of fire in South African catchments, unpublished Ph.D thesis, Department of Agricultural Engineering, University of Natal, Pietermaritzburg.

Scott, D.F., 1995: CSIR; Forest Science and Technology, Jonkershoek Forestry Research Centre, Stellenbosch, South Africa.

Scott, V.H. and Burgy, R.H., 1955: Effects of heat and brush burning on the physical properties of certain upland soils that influence infiltration, *Soil Science*, 82, 63-70.

Scott, D.F. and Van Wyk, D.B., 1990: The effects of wildfire on soil wettability and hydrological behaviour of an afforested catchment, *Journal of Hydrology*, 121, 239-256.

Scott, D.F. and Van Wyk, D.B., 1992: The effects of fire on soil water repellency, catchment sediment yields and streamflow, in: Van Wilgen, B.W., Richardson, D.M., Kruger, F.J. and van Hensbergen, H.J. (Eds), *Fire in South African Mountain Fynbos: ecosystem, community and species reponse at Swartboskloof*, Ecological Series no. 93, Springer, Heidelberg.

Scotter, D.R., 1970: Soil temperatures under grass fires, *Austalian Journal of Soil Research*, 8, 273-279.

Shakesby, R.A., Coelho, C.O.A., Ferreira, A.D., Terry, J.P and Walsh, R.P.D., 1994: Fire, post-burn land management practice and soil erosion response curves in eucalyptus and pine forests, North-Central Portugal, in: Sala, M. and Rubio, J.L. (Eds), *Soil erosion as a consequence of forest fires*, Geoforma Ediciones, Logroño, 111-131.

Snyman, H.A. and Van Rensburg, W.L.J., 1986: Effect of slope and plant cover on run-off, soil loss and water use efficiency of natural veld, *Journal of the Grassland Society of southern Africa*, 3(4), 153-158.

Soler, M. and Sala, M., 1992: Effects of fire and of clearing in a Mediterranean *Quercus ilex* woodland: an experimental approach, *Catena*, 19, 321-332.

Soler, M., Sala, M. and Gallart, F., 1994: Post fire evolution of runoff and ersion during an eighteenth month period, in: Sala, M. and Rubio, J.L. (Eds), *Soil erosion as a consequence of forest fires*, Geoforma Ediciones, Logroño, 149-162.

Soto, B., Basanta, R., Benito, E., Pérez, R. and Díaz-Fierros, F., 1994: Runoff and erosion from burnt soils in northwest Spain, in: Sala, M. and Rubio, J.L. (Eds), *Soil erosion as a consequence of forest fires*, Geoforma Ediciones, Logroño, 91-98.

Steel, R.G.D. and Torrie, J.H., 1981: *Principles and procedures of statistics: A biometrical approach*, McGraw-Hill, Singapore.

Stocking, M., 1984: Rates of ersoion and sediment yield in the African Environment, in: *Challenges in African Hydrology and Water Resources*, 285-283, Proceedings of the Harare Symposium, July 1994, IAHS Publication no. 144.

Stocking, M., 1994: Assessing vegetative cover and managemet effects, in: Lal, R (Ed.), *Soil erosion research methods*, St Lucie Press, Florida, 211-232.

Sumner, P.D., 1994: Rates and controls of footpath erosion in Giant's Castle Game Reserve, KwaZulu/Natal Drakensberg, unpublished M.Sc thesis, Department of Geography, University of Natal, Pietermaritzburg.

Teramura, A.H., 1980: Relationship between stand age and water repellency of chaparral soils, *Bulletin of the Torrey Botanical Club*, 107, 42-46.

Terry, J.P., 1994: Soil loss from erosion plots of differing post fire forest cover, Portugal, in: Sala, M. and Rubio, J.L. (Eds), *Soil erosion as a consequence of forest fires*, Geoforma Ediciones, Logroño, 133-148.

Thornes, J.B., 1980: Erosional processes of running water and their spatial and temporal controls: a theoretical viewpoint, in: Kirkby, M.J. and Morgan, R.P.C. (Eds), *Soil ersoion*, John Wiley and Sons, Chichester.

Trabaud, L., 1983: The effects of different fire regimes on soil nutrients levels in *Quercus coccifera* garrigue, in: Kruger, F.J., Mitchel, D.T. and Jarvis, J.U.M. (Eds), *Mediterranean-type Ecosystems: the role of nutrients*, Springer-Verlag, Berlin, 233-242.

Trollope, W.S.W., 1984: Fire Behaviour, in: Booysen, P. de V. and Tainton, N.M. (Eds), *Ecological effects of fire in South African ecosystems*, Springer-Verlag, Berlin, 199-218.

Van Dam, J.C., Hendrickx, J.M.H., Van Ommen, H.C., Bannink, M.H., Van Genuchten, M.Th. and Dekker, L.W., 1990: Water and solute movement in a coarse-textured water repellent field soil, *Journal of Hydrology*, 120, 359-379.

Van der Walt, P.T. and Van Zyl, L.J., 1982: Die invloed van veldbrand op bewegings patrone van wildsbokke in die Golden Gate Highlands Nasionale Park, *Koedoe*, 25, 1-11.

Van Rensburg, A.P.J., 1968: Die geskiedenis van twee plase wat ŉ Nasionale Park geword het, *Koedoe*, 11, 83-131.

Van Wyk, D.B., 1985: The effects of catchment management on sediment and nutrient exports in the Natal Drakensberg, in: Schulze, R.E. (Ed.), *Proceedings Second South African National Hydrology Symposium*, Pietermaritzburg, September 1985, Agricultural Catchments Research Unit Report no. 22, 266-274.

Van Wyk, D.B. and Lesch, W., 1989: The effect of the Langrivier fire on water quality and sediment yield, in: Richardson, D.M. (Ed.), *The short-term effects of fire in Langrivier, Jonkershoek State Forest, Stellenbosch*, South Afrcian Forest Research Institute Report J.2/89, Jonkershoek Forestry research Centre, Stellenbosch, 78-88.

Watson, H.K., 1981: Firebreak treatment and sediment yield from small catchments at Cathedral Peak, unpublished M.Sc thesis, Department of Geography, University of Natal, Durban.

Watson, H.K. and Poulter, A., 1987: Erodibility of soils at Cathedral Peak in the Natal Drakensberg, unpublished poster paper presented at the 50 years of research in mountain catchments in South Africa Symposium, November 1987, Stellenbosch.

Wells, C.G., Campbell, R.E., DeBano, L.F., Lewis, C.E., Frederiksen, R.L., Franklin, E.C., Froelich, R.C. and Dunn, P.H., 1979: *Effects of Fire on Water: a state of knowledge review*, USDA Forest Service, General Technical Report WP-7, Washington DC, USA.

West, O., 1965: *Fire in vegetation and its use in pasture management with special reference to tropical and subtropical Africa*, Mimeographed Publication No 1, Commonwealth Bureau of Pastures and Field Crops, Hurley, Berkshire.

Wicherek, S., 1989: Impact of splash and aeolian transport on erosion case study: north of Parisian Basin, France, *Earth Surface Processes and Landforms*, 14. 461-467.

Williams, J.D. and Buckhouse, J.C., 1991: Surface runoff plot design for use in watershed research, *Journal of Range Management*, 44, 411-412.

Wischmeier, W.H., 1977: Soil erodibility by rainfall and runoff, in: Toy, T.J. (Ed), *Erosion: Research techniques, erodibility and sediment delivery*, Geo Abstracts Ltd, Norwich, 45-56.

Wischmeier, W.H. and Mannering, J.V., 1969: Relation of soil properties to its erodibility, *Soil Science Society of America Proceedings*, 33, 131-137.

Wischmeier, W.H., Johnson, C.B. and Cross, B.V., 1971: A soil erodibility nomograph for farmland and construction sites, *Journal of Soil and Water Conservation*, 26, 189-193.

Wright, H.A. and Bailey, A.W., 1982: *Fire Ecology, United States and southern Canada*, John Wiley and Sons, New York.