CAUSES OF WETLAND EROSION AT CRAIGIEBURN, MPUMALANGA PROVINCE, SOUTH AFRICA

By

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As the candidate's supervisor I have/have not approved this thesis/dissertation for submission.

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ABSTRACT

Wetland degradation, which includes deterioration in functional performance and erosion, is a problem around the world. This has engendered a quest for causes and attempts to prevent the problem or to rehabilitate wetlands already degraded or undergoing degradation. The Craigieburn wetland system in Mpumalanga Province, South Africa has undergone erosion due to two downstream discontinuous gullies that have drained and considerably reduced the size of the wetland system. Measurements from 1954 to 1997 aerial photographs showed that over 40 years, the upper gully migrated headward over a distance of 30 m, while the lower gully eroded 522 m headward raising the question as to what caused their erosion? Prior to this study, the predominant view was that human activities, namely poor land use management within the wetland system, increased human occupation, and overgrazing on the adjacent catchment that caused a reduction in vegetation cover, were responsible for this wetland erosion.

Detailed field observation, aerial photograph interpretation, soil analyses for mineralogy, chemistry and particle size distribution, landscape mapping, dumpy level survey of the wetland valley and statistical analysis were undertaken to establish the relationships between gullying and possible contributing factors. Human impacts on wetland gully development between 1954 and 1997 were estimated using the number of individual homes, and total lengths of footpaths, animal tracks and dirt roads. Agricultural activities and the stocking rate of livestock were excluded due to the poor quality of aerial photographs and lack of historical records. Results of multiple regression correlating lengths of the two gullies (upper and lower gullies) and the sum of these human factors gave a high correlation (adjusted $R^2 = 0.92$ and 0.90, respectively) but a low significance ($p = 0.18$ and 0.21, respectively). However, time has played a significant role in the erosion of both the upper gully ($R^2 = 0.82$, $p = 0.02$) and the lower gully ($R^2 = 0.98$, $p = 0.02$) at Craigieburn.

X-ray diffraction and X-ray fluorescence spectrometry of weathered parent materials showed that the area has undergone deep weathering, supplying sediments to the wetland valley through surface run-off. The accumulation of these sediments resulted in localized over-steepening of certain sections of the valley floor with raised gradients of 0.0336 and 0.0337 at the two headcuts relative to the upper and lower non-eroding sections with lower gradients. These localized steep sections increased flow velocity and stream power and therefore stream erosivity thus triggering gully erosion. In addition to localized areas of raised valley floor, results from multiple regression showed a significant relationship ($p = 0.002$) between areas of earthflow scars and gully length, especially at the lower gully, thus further suggesting that physical factors are largely responsible for gully erosion at Craigieburn.

Long-term climate change has resulted in the formation of two terraces, an older, D1 (USU-760, 1.67 ± 0.89 ka) and a younger, D2 (USU 761, 0.32 ± 0.08 ka). The former probably eroded during the medieval warming around 1230 AD while the younger terrace, which likely formed during the last half of the Little Ice Age, has been eroding since the renewed warming thereafter. This erosion has been exacerbated by short-term periodic or seasonal climatic changes, especially episodic summer rainfall events, which have likely played a key role in the headward migration of the two gullies. The result has been shrinkage of the wetland system by about 15 m on both sides of the valley, leaving behind a greyish soil colour indicating wet and reducing conditions in the past. These, together with dried relict mottles left behind in the soil matrix at the margin of the shrunken wetland system suggest past seasonal fluctuation of the water table engendering the belief that the wetland system once extended beyond its present limit.

The overwhelming contribution of these physical factors, in addition to the fact that the two gullies predate human occupation of the study area catchment and environs, strongly argues for their responsibility in gully initiation and development at Craigieburn. Human presence and activities, which only became evident in the catchment from the 1950s onwards, may be secondary contributory factors.

This conclusion encourages a rethink of previous views that human occupation and activities are solely responsible for this wetland gully erosion at Craigieburn and provides a rationale for including physical processes and climate change as factors when investigating causes of wetland erosion elsewhere. Such an understanding should be used to inform any rehabilitation or conservation efforts that are related to wetland ecosystems.

PREFACE

The work described in this thesis was carried out in the School of Environmental Sciences, University of KwaZulu-Natal from 2005 to 2009 firstly under the supervision of Professors G Garland and WN Ellery and then Professor JC Hughes.

This study represents original work by the author and has not otherwise been submitted in any form for any degree of diploma to any tertiary institution. Where use has been made of the work of others, it is acknowledged in the text.

DECLARATION – PLAGARISM

I...declare that

1. The research reported in this thesis, except where otherwise indicated, is my original research.

2. This thesis has not been submitted for any degree or examination at any other university.

3. This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.

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   a. Their words have been re-written but the general information attributed to them has been referenced.
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5. This thesis does not contain text, graphics or tables copied and pasted from the internet, unless specifically acknowledged, and the source being detailed in the thesis and in the References section.

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Other funds for this study were provided by the Water Research Commision of South Africa and the University of KwaZulu-Natal Doctoral Research Grant, to whom I am enormously thankful.

Kerry Philp played the crucial role not only of financially organizing all my field trips including among others, car hire and accommodation but provided timely moral encouragement. I am deeply grateful and will always remember her for her kindness.

Various laboratories played a crucial role in analyzing different aspects of this study. At the soil science laboratory, University of KwaZulu-Natal, Pietermaritzburg, exchangeable bases were analyzed by Mr. Veeramuthoo Dorasamy. Mr. Pradeep Suthan and Mr Roy Seyambu performed X-ray fluorescence in the geology laboratory at the Westville campus of the same University; Mr. Isaac Abboy helped a great deal in providing equipment for particle size analysis, allowing me to use the soil laboratory of the same University, Durban campus and in planning optically stimulated luminescence (OSL) sampling. Tammy Rittenour performed the OSL analysis at Utah State University. My hearty thanks go to all of them.

I am grateful to the School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, for providing me with rainfall data.

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I will always remember Melusi Shezi for his vigorous assistance in manually collecting OSL sample in the field and Big Boy, my research assistant for sticking with me and working long hours under harsh conditions during my field work in Mpumalanga, sometimes even acting as my technician when field equipment failed. I owe him a lot, thanks.

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Thank you Jenny Guest for doing a final proof-reading.

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CHAPTER ONE

INTRODUCTION

1.1. Background

Wetlands have been defined as “those areas that are saturated or inundated by surface or groundwater at a frequency and duration sufficient to support, and under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions” (USACE, 1987). The South African National Water Act, 1998 adopts a somewhat narrow definition referring to wetlands as “lands which are transitional between terrestrial and aquatic systems where the water table is usually at or near the surface, or the land is periodically covered with shallow water, and which land in normal circumstances supports or would support vegetation typically adapted to life in saturated soil” (National Water Act, 1998 p.18). However, a more expanded definition is provided by the Department of Water Affairs and Forestry (DWAF), maintaining that “The word “wetland” is a family name given to a variety of ecosystems, ranging from rivers, springs, seeps and mires in the upper catchment, to midlands marshes, pans and floodplains, to coastal lakes, mangrove swamps and estuaries at the bottom of the catchment” (DWAF, 2005 p.4). Therefore, wetlands include among others, swamps, marshes, bogs, (Begg, 1986a; Begg, 1986b; USACE, 1987), and similar areas such as pans and vleis (Begg, 1986b). Whatever the definition and type, DWAF (2005) emphasizes that a common primary driving force in all wetlands is water. Despite the numerous functions and value of wetlands to humanity and biodiversity (Mitsch & Gosselink, 1993; Ramsar Convention Bureau, 2001), their wide scale degradation around the world particularly by erosion remains a reality. Of all processes and activities related to wetland erosion, human induced causes related to poor land use management, grazing, farming, deforestation and drainage are often cited as the major precursors, with much less attention on possible natural causes like climate change and geomorphic thresholds. For example, at the international level, Milne and Hartley (2001), Moeyersons (2003), Morgan and Mngomezulu (2003), and Usher (2001) all agree that human factors, especially poor land use practices related to agricultural development are largely responsible for wetland erosion in the world. For example, they contribute 87% of wetland loss in the USA (Walmsley, 1988) and 60% in Spain (Gallego-Fernandez et al., 1999).

In South Africa, many researchers have endorsed this model of wetland erosion suggesting that agricultural practices (farming and grazing) are largely responsible (Begg, 1988; Fowler, 1999; Kotze & Breen, 1994; Kotze et al., 1995). For example Begg (1988) attributes 58% of wetland loss in the Umfolozi catchment to human activities.

From this widely accepted school of erosion, a model can be developed which commences with a healthy wetland, followed by human occupation and poor land use practices. These human interventions are seen as the precursors creating the propensity for wetland erosion, which is then exacerbated by physical factors such as high rainfall erosivity, oversteepened valley floor and soil erodibility (Figure 1.1).

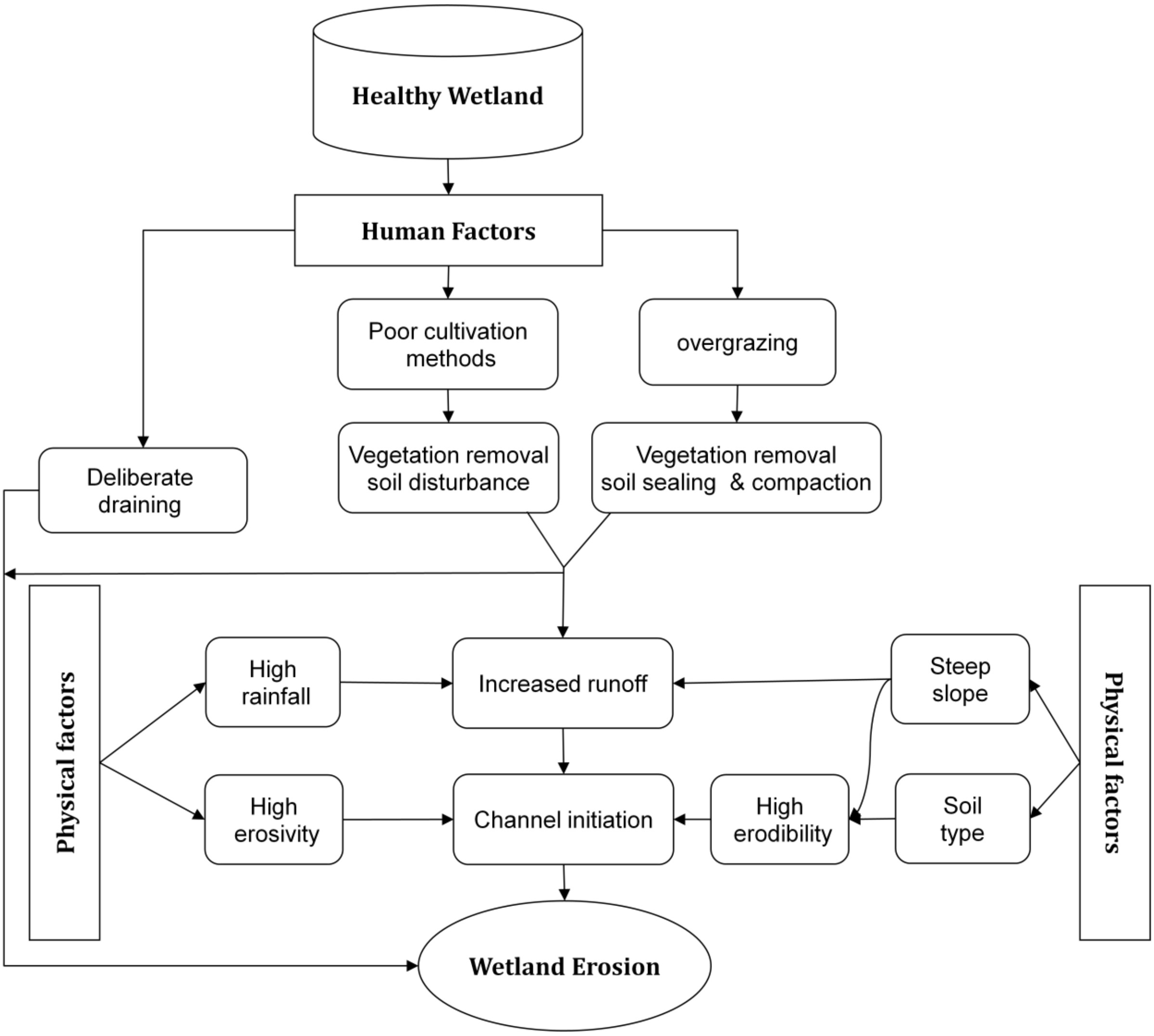


Figure 1.1 A conceptual anthropological model of the causes of wetland erosion.

This model (Figure 1.1), though presenting physical factors as contributory causes of wetland erosion is short of other key factors like incipient instability related to geomorphic thresholds and long term climate change; natural (physical) factors which generally do not appear in the discourses of those advocating anthropological causes of wetland erosion. Moreover, this model assumes that wetland erosion only occurs with the intervention of human activities and does not consider the possibility that wetland erosion can result from natural geomorphic processes irrespective of human intervention and that it occurs in diverse environments irrespective of landownership and land use.

These natural causes of gully initiation and erosion include localized valley floor steepening above a threshold gradient (Schumm, 1973; Schumm & Hadley, 1957) and climate change (Thornthwaite et al., 1942), factors which constitute subjects of considerable research in geomorphology (Gabris & Nador, 2007; Hanson et al., 2006; Schumm, 1973; Schumm, 1980; Wells & Andriamihaja, 1993). These physical factors in addition to those in Figure 1.1 constitute the alternative model which argues that gully initiation and erosion is primarily a function of natural causes which may or may not be exacerbated by human activities. Despite this well established alternative model of gully erosion, there has been little investigation of its applicability in South African wetlands. Even where attempts have been made, as in the work of King (1972) in Natal and Transkei, Meadows and Sugden (1988) in the Karoo region of South Africa and Botha (1996) in northern KwaZulu-Natal, these concepts have only rarely been applied to wetlands (Raw, 2003).

Related to the natural model of the causes of wetland erosion in South Africa, is the dating of events. Kotze et al. (1995) maintain that wetland loss in South Africa (including wetland erosion) has been occurring insidiously over the last century. However, while palaeoclimatic records of erosion and deposition exist for some South African river channels notably the Olifants, the Vaal (Deacon & Lancaster, 1988) and the Sundays (Hattingh & Rust, 1999) Rivers, the paucity of such records related to wetland erosion and the controversies surrounding existing dates present an opportunity to study and date this process at Craigieburn in Mpumalanga Province, South Africa.

1.2. The research problem

The Craigieburn wetland system plays a vital role in the livelihood of adjacent communities and is an important water source to users further downstream. However, the system sustains two unstabilized, downstream, discontinuous gullies that until recently have drained and considerably reduced the size of the wetland system, limiting its ability to effectively perform normal wetland functions.

The prevailing view (AWARD (Association for Water and Rural Development), 2004), is that human activities, namely poor farming within the wetlands, increased human occupation, and grazing on the adjacent catchment are the factors responsible for the erosion of this wetland system. However, the possibility exists that geomorphic processes are also responsible thus raising the question of what caused this erosion, human or natural factors? Such a study is critical not only to understanding the Craigieburn wetland system but also to informing and guiding any future remediation and conservation measures that may be undertaken at Craigieburn.

1.3. Aim, objectives and key research questions

The main aim of this study was to survey the wetland system at Craigieburn and to examine the relative importance of natural versus anthropogenic causes of the erosion that has affected it. The study had a number of objectives.

- To survey cross-sections and longitudinal profiles of the wetland system in order to reveal any existing gullies, terraces and evidence of over-steepened reaches.
- To identify and explain the past and present geomorphological processes in and around the wetland system, its characteristics and its catchment processes and materials.
- To describe the past and present human occupation of the wetland catchment and its impact on the wetland.
- To develop a conceptual model for the origin and evolution of the Craigieburn wetland system.
- To document the findings of this study in order to prevent future duplication of research and to inform any subsequent studies on existing gaps in knowledge.

Key research questions guiding this study were: How did the wetland system at Craigieburn originate? What factors are responsible for wetland erosion at Craigieburn? To what degree have human or geomorphic factors, including climate change, contributed to wetland erosion at Craigieburn?

1.4. Structure of the thesis

Chapter Two is a survey of selected literature on geomorphic processes, gully erosion and various techniques of erosion study. It demonstrates the global contribution of past and current discourses on the subject matter and reveals research gaps in the Southern African context.

Chapter Three describes the study area including its physical and socio-economic characteristics, while Chapter Four reviews the desktop, field and laboratory methods and techniques employed to achieve the aims and objectives of the study.

Chapters Five to Seven present the results of the study as follows. Chapter Five discusses the socio-economic variables influencing wetland erosion at Craigieburn; Chapter Six describes the geomorphological processes of weathering and soil development; and Chapter Seven discusses the geomorphic processes responsible for wetland erosion at Craigieburn. Chapter Eight summarizes the major findings of the study and its contribution to the existing debate on the causes of wetland erosion.

CHAPTER THREE

BACKGROUND TO THE STUDY AREA

3.1. Location of the study area

The study area at Craigieburn is a small catchment of about 1.64 km^2, located in the eastern foothills of the Northern Escarpment in Mpumalanga Province (Figure 3.1). This area accommodates two main wetlands. The first is a valley-head wetland (upper wetland) without a channel located at 24^0 39' 56.45"S and 30^0 58' 30.11"E. This upper wetland occupies a saucer-like depression with a sub-catchment size of about 0.26 km^2. The second (lower) wetland about 300 m downstream is found at 24^0 40' 2.94"S and 30^0 59' 1.66"E. It is elongated in shape and flanks the drainage line with a catchment size of about 1.42 km^2 (upper sub-catchment inclusive). Another 0.22 km^2 lies below the lower wetland and while, this later area may not directly affect the upstream wetland system by all its physical surface processes due to its location downstream towards the catchment mouth, it is probable that the wetland system is affected by residents living within the entire catchment. Both wetlands are located on the Manalana, a minor tributary of the Sand River which drains through the Kruger National Park. These wetlands have undergone erosion by unstabilized, downstream, discontinuous gullies that have drained and considerably reduced the size of the wetlands.

3.2. Human settlement

Craigieburn is a rural suburb of Acornhoek, which is a semi-urban area close to the border between Mpumalanga and Limpopo Provinces. A brief human occupational history of the study area is provided by the Association for Water and Rural Development (AWARD, 2004), who relate that the anthropological activities of the region have been influenced by the political history of the country. Various apartheid laws segregated the African population into the less economically viable rural areas. These areas, known as Bantustans (AWARD, 2004), later became communal lands after the fall of the apartheid government in 1994. As Pollard et al. (1998) point out; huge populations had been forced into these areas exerting pressure on the scarce resources for their livelihood. Craigieburn, one of these communal areas, is juxtaposed by community residences, subsistence farming and community grazing land. Apart from open grazing land, the catchment of the upper wetland is less marked by the presence of homesteads while the lower slopes and part of the valley bottom enclosing the wetland are occasionally farmed by the local community. Further down the valley, the second wetland maintains some anthropological characteristics of the upper wetland but is flanked on the slopes by more residential homes accompanied by household gardens within homesteads (Figure 3.1). This human settlement history, and the geomorphological setting that follows, provide the framework for analysing the human and geomorphic processes that have shaped the Craigieburn wetland system.

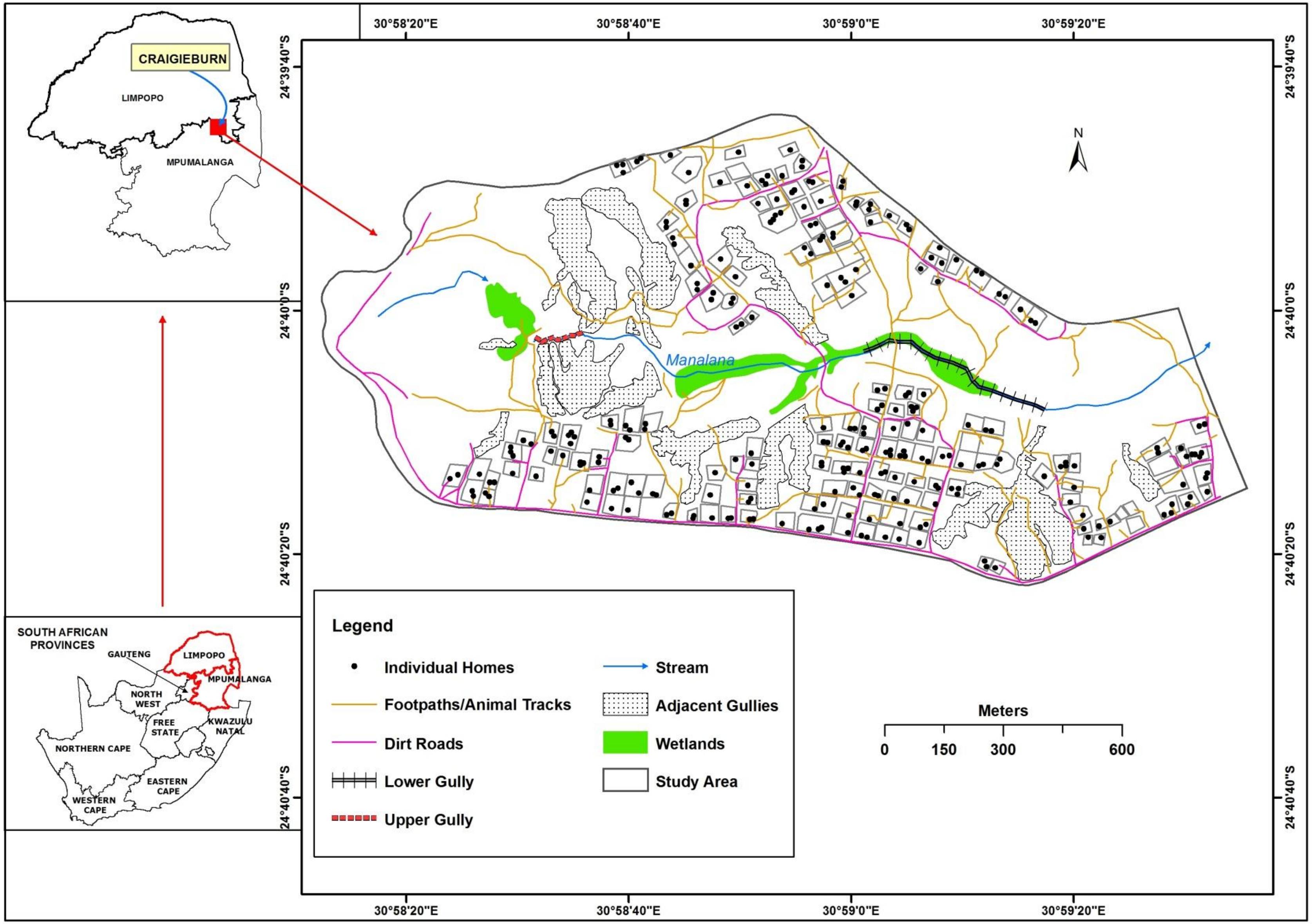


Figure 3.1 Location of the study area in Mpumalanga Province, South Africa and some features of the Craigieburn catchment (Modified from Chief Surveyor General, 2000).

3.3. Geomorphological setting

The study area is situated between 640 and 766 m above sea-level, with the highest point on the north-west side of the catchment (Figures 3.2 and 3.3). The catchment varies in topographical gradient, being steeper on the upper part of concave slopes (20^0 to 29^0), while the footslope gradients range from 9^0 to 10^0. Topslopes of the upper catchment are convex, while the lower part of the catchment is characterized by spurs protruding into the valley. Scars of earthflow characterize the catchment slopes together with a series of abandoned or active gullies, dry valleys and exposed bedrock or soil surfaces (earth banks). The earthflow scars are evidence of deep weathering and mass movement which have further contributed material into the valley. The mechanics of this movement is related to the loss of cohesive strength within the deeply weathered mass and its susceptibility to downslope pull by gravity especially in areas of steep slopes (Hamblin & Christiansen, 1995; Strahler & Strahler, 1989).

The saucer-like, valley head depression begins with a channel and later fans out into the upper wetland area in the absence of a channel. The valley then constricts just below the wetland after which it widens again further downstream, occupied by the lower wetland and then a secondary valley constriction below. The main valley and the wetland system are marked by alluvial and colluvial clastic sediments forming valley fill deposits that have been incised by gully erosion. Adjacent side valleys contain fills characterized by stabilized and vegetated head cuts, while the slopes and valley bottoms display a terrace-like morphology intermittent in occurrence. In some places an upper and lower terrace can be found but elsewhere only the lower terrace is present.

Two discontinuous gullies occupy the main valley bottom, incising into the two wetlands through the process of knickpoint, headward erosion. The catchment topography is further compounded by a ramified network of animal tracks and footpaths, evidence of human presence.

3.4. Geology and soils

The geological map (Geological Survey, 1986) identifies two main rock types in the study area, namely granitoid (Barbarin, 1999; Rizaoglu et al., 2009) a white, coarse-grained, porphyritic, biotite-granite; and green, fine to medium-grained, diabase (dolerite) (Figure 3.4). Raw (2003), also maintains that the dominant geology of the area is granite, overlain by scattered boulders of dolerite. This was verified by field observation of rock outcrops which showed that both sides of the catchment are dominated by granite except in the north-west of the study area where corestones of dolerite occur. Downstream in the study area, partially weathered dolerite occurs in the valley with isolated granite outcrops on nearby hills.

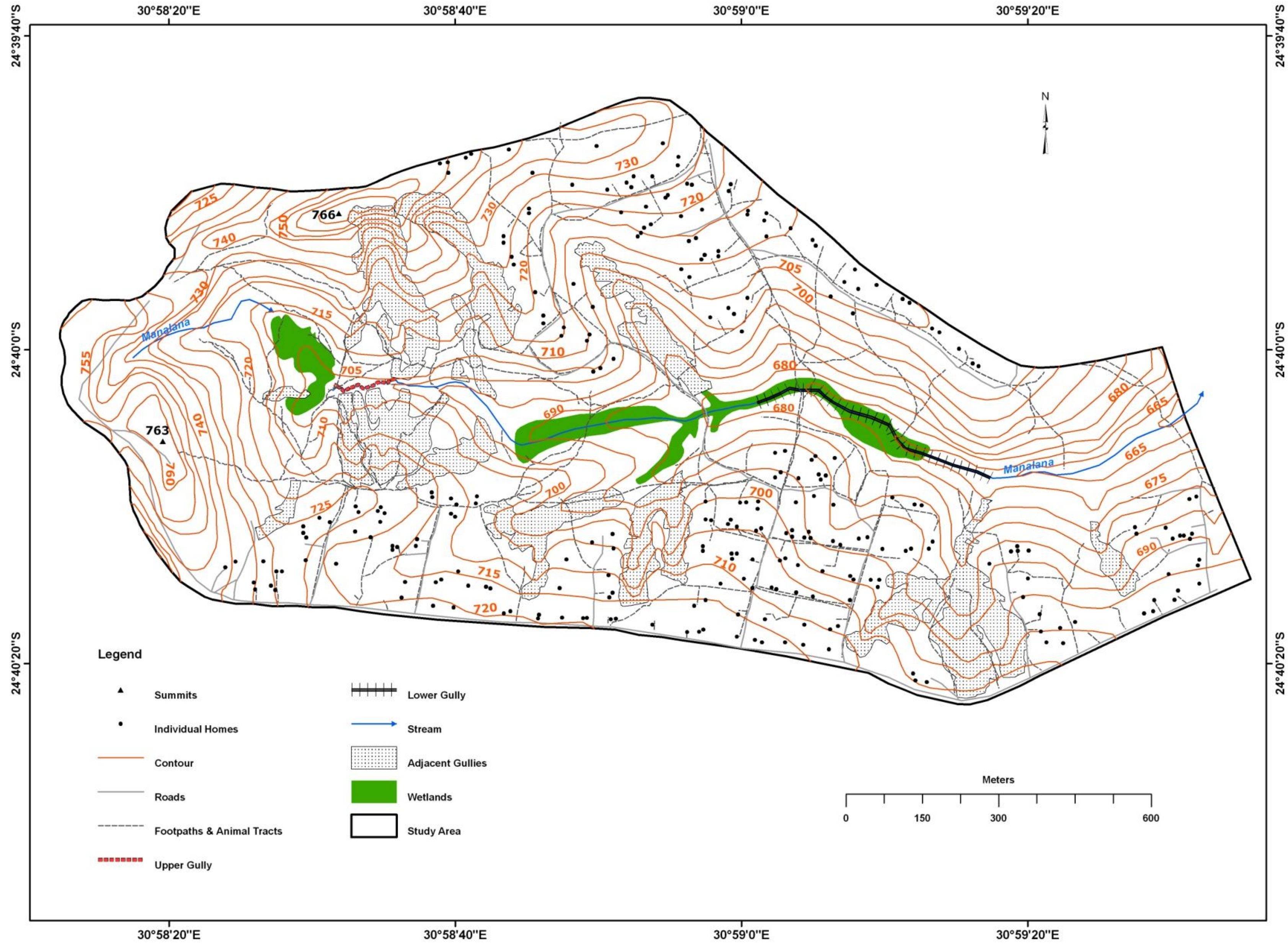


Figure 3.2 Contour map of Craigieburn (Modified from Chief Surveyor General, 2000).

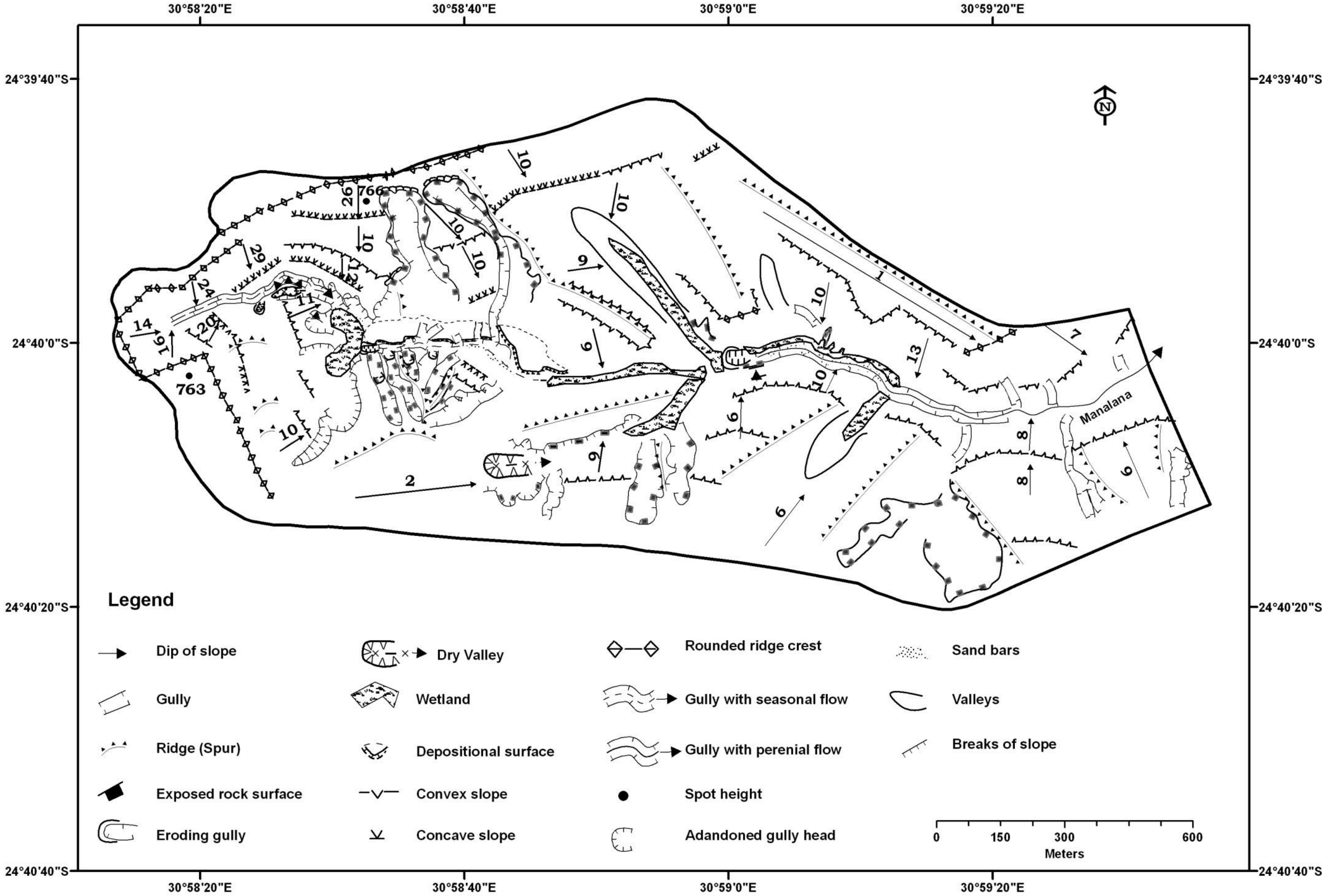


Figure 3.3 Geomorphological map of Craigieburn.

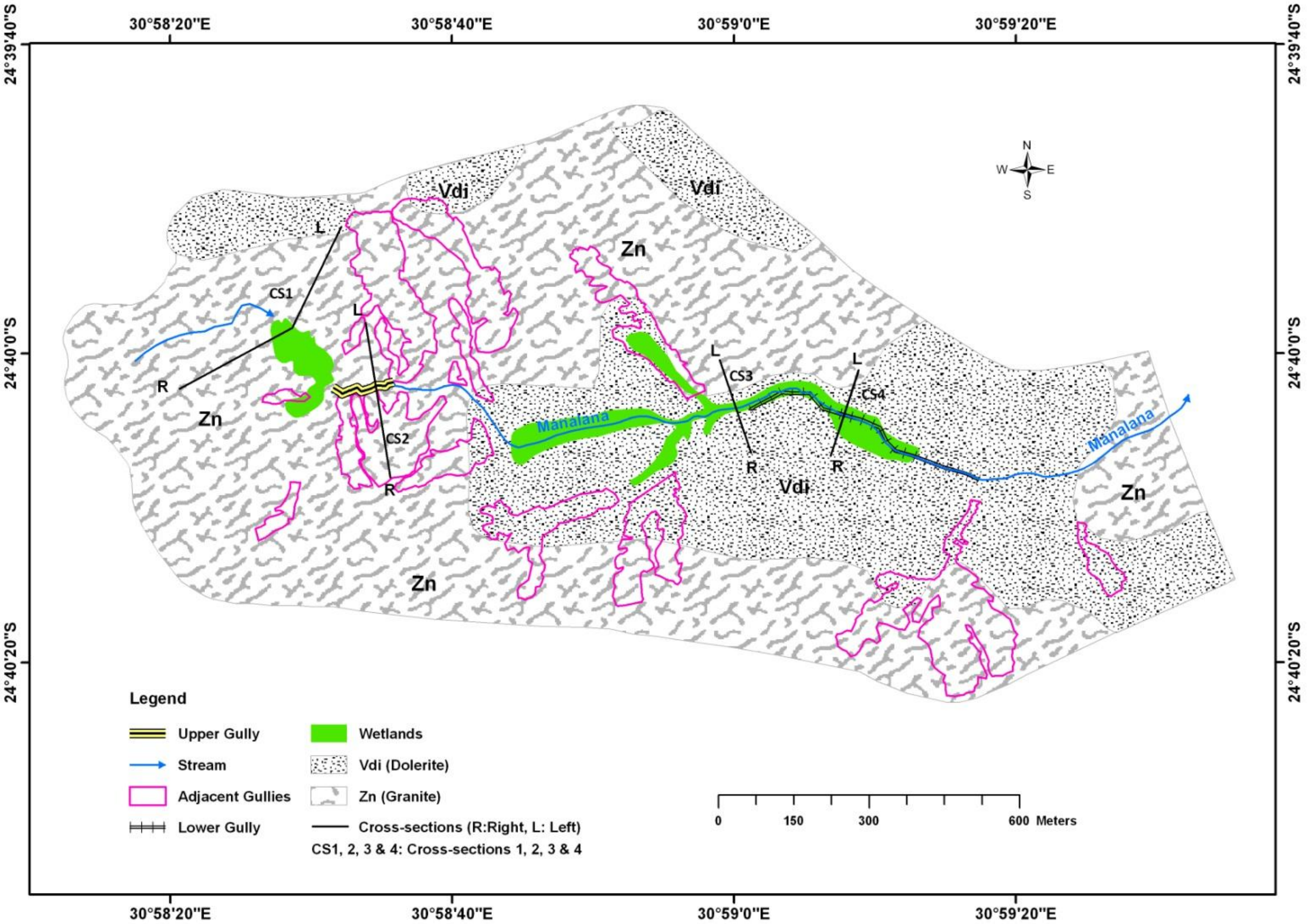


Figure 3.4 The geology of Craigieburn (adapted from Geological Survey, 1986).

According to the land type information (ARC, 2006), the study area is dominated by freely drained red and yellow dystrophic/mesotrophic apedal soils, although wetter soils will occur in the valley. Cross-sections of the study area derived from field observation show a stratified geological structure, where dolerite sills alternate with granite (Figures 3.5a and 3.5b).

The study area’s environs bear imprints of tectonic uplift which shed light on the geological history of the region as a whole and provide a background for understanding the geomorphic history of the area. An example lies west of the study area where part of the South African Great Escarpment (Figure 3.6) stands as a remnant of two post Gondwana uplifts, the greatest said to have occurred in the Miocene (20 million years ago) followed by a lesser one 5 million years ago in the Pliocene (King, 1963; McCarthy, 2005; Moon & Dardis, 1988; Ollier & Marker, 1985; Partridge & Maud, 2000). Each of these uplifts was subsequently followed by tilting which resulted in steeper slopes and steep stream gradients with the tendency to erode (Dardis et al., 1988; King, 1963, McCarthy & Rubidge, 2005; Ollier & Marker, 1985).

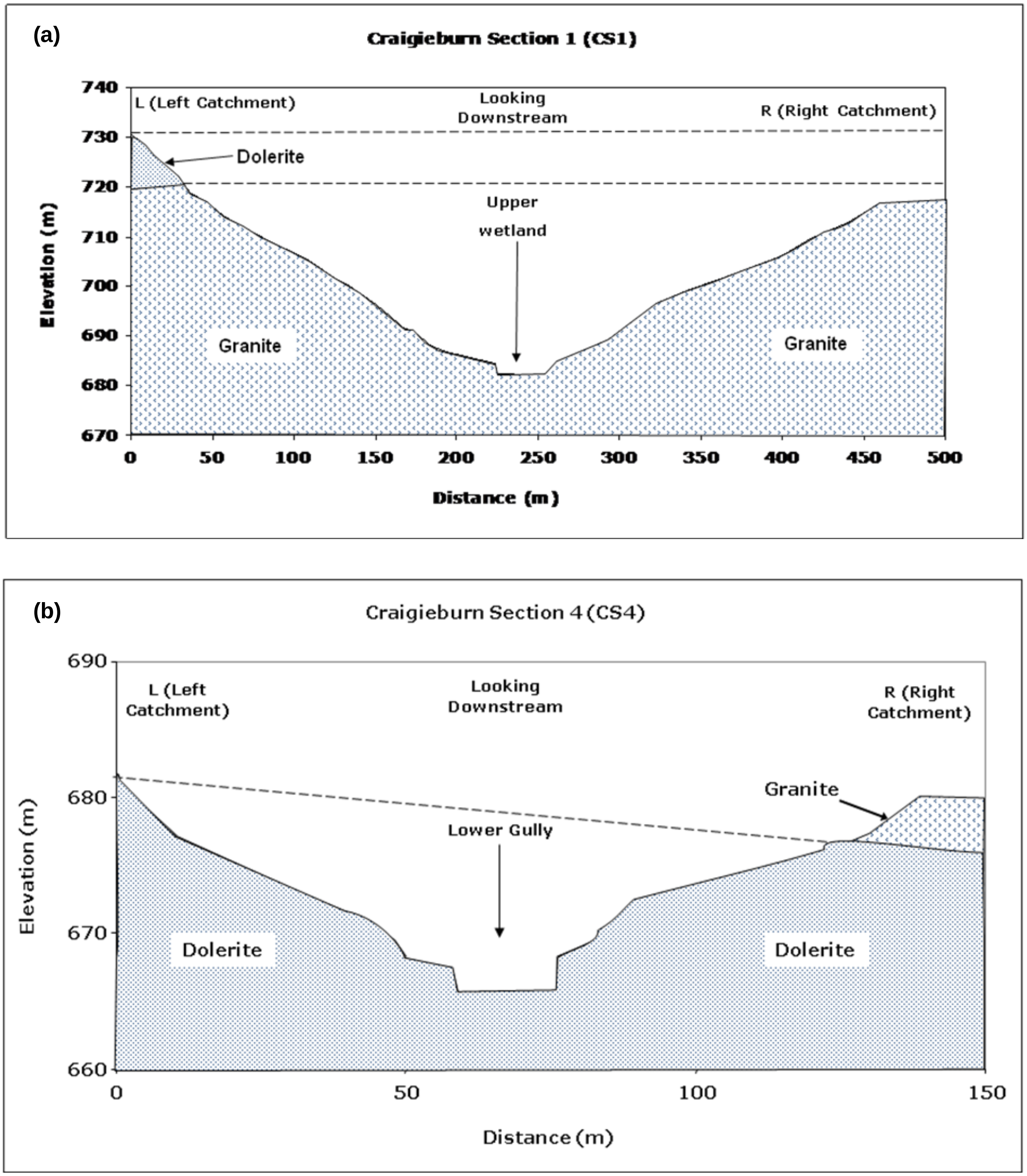


Figure 3.5 Cross-sectional geology at Craigieburn (a) upper wetland; (b) lower gully just below the lower headcut at the lower wetland.

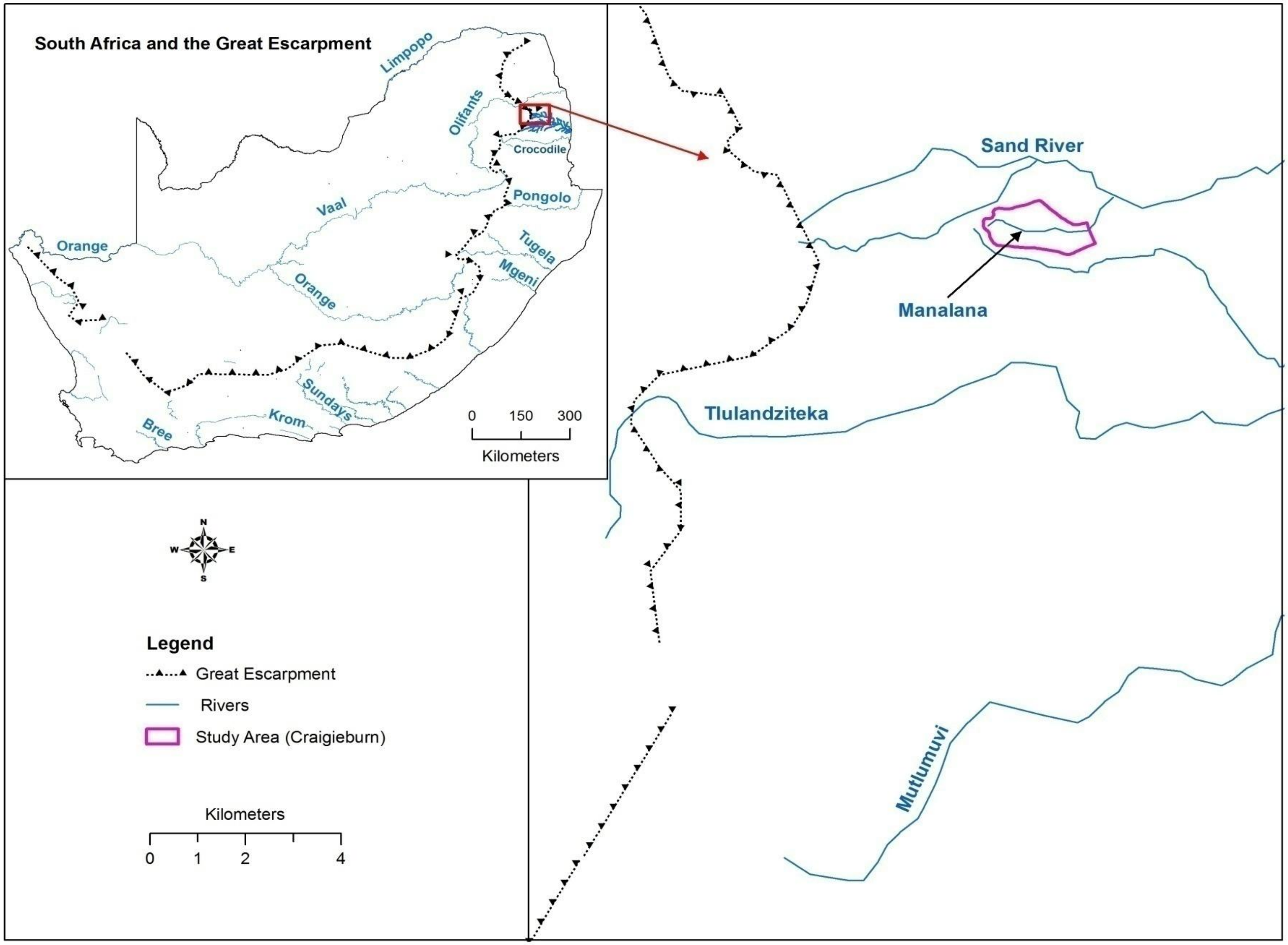


Figure 3.6 The Great Escarpment in relation to the study area.

3.5. Vegetation

A detailed vegetation survey within the wetland system and the immediate surroundings (Huyssteen, 2003) showed that *Phragmites mauritianus* and *Cyperus latifolius* occupy the permanently wet sections of the two wetlands, and elephant grass (*Miscanthus giganteus)* along portions of the downstream wetland. Away from the permanently wet zone are mostly *Centella asiatica* (semi-permanent wetland community), *Sporobolus pyramidalis* (moist grassland community) and *Cynodon dactylon*. Riddel (2011) has also classified the study area's vegetation and the most common species are thatching grass (*Hyparrhenia hirta* and *Hyperthelia dissoluta*), limpo grass (*Hemarthria altissima*) and *Parinari curatellifolia*. Banks close to the wetland and the valley have stands of some alien species such guava (*Psidium guajava)* and some indigenous tree species. Seasonally, the wetland and some parts of the catchment are cultivated with maize (*Zea mays*), madumbe (*Colocasia esculenta*), beans (*Phaseolus vulgaris)* and sweet potato (*Ipomoea batatas)*.

3.6. Drainage and climate

The Craigieburn wetland system is drained by the Manalana (AWARD, 2004), which rises about 2 km west of the Great Escarpment and forms part of a ramified network belonging to the Sabie and Sand Rivers secondary catchment. This secondary catchment is one of the four secondary catchments which make up the Crocodile River primary catchment in the northern part of South Africa (Figure 3.7).

Short term seasonal climate plays a very important role in the hydrology and geomorphic evolution of the study area. The area is situated in a semi-arid region with hot, humid summers, an average annual precipitation of about 1075 mm (1908-1999) and daily maximum temperatures ranging from 26^0C in winter to 33^0C in summer (Raw, 2003).

Analysis of rainfall measurements from the Wales Station (ICFR, 2005) (Appendix 7.1), situated about 2 km south of the study area, over a period of 91 years (1908-1999) shows not only monthly and seasonal variation but also long term periodic variation between years (Figures 3.8 and 3.9). Most of the rain falls during the summer months as high intensity storms (~November-March) and averages about 170 mm per month in contrast to 18 mm per month for winter (May-August). This rainfall regime greatly affects the Manalana, which is supplemented by channel and overland flow during summer when the water table rises to intersect the surface, and by occasional rainfall extreme events.

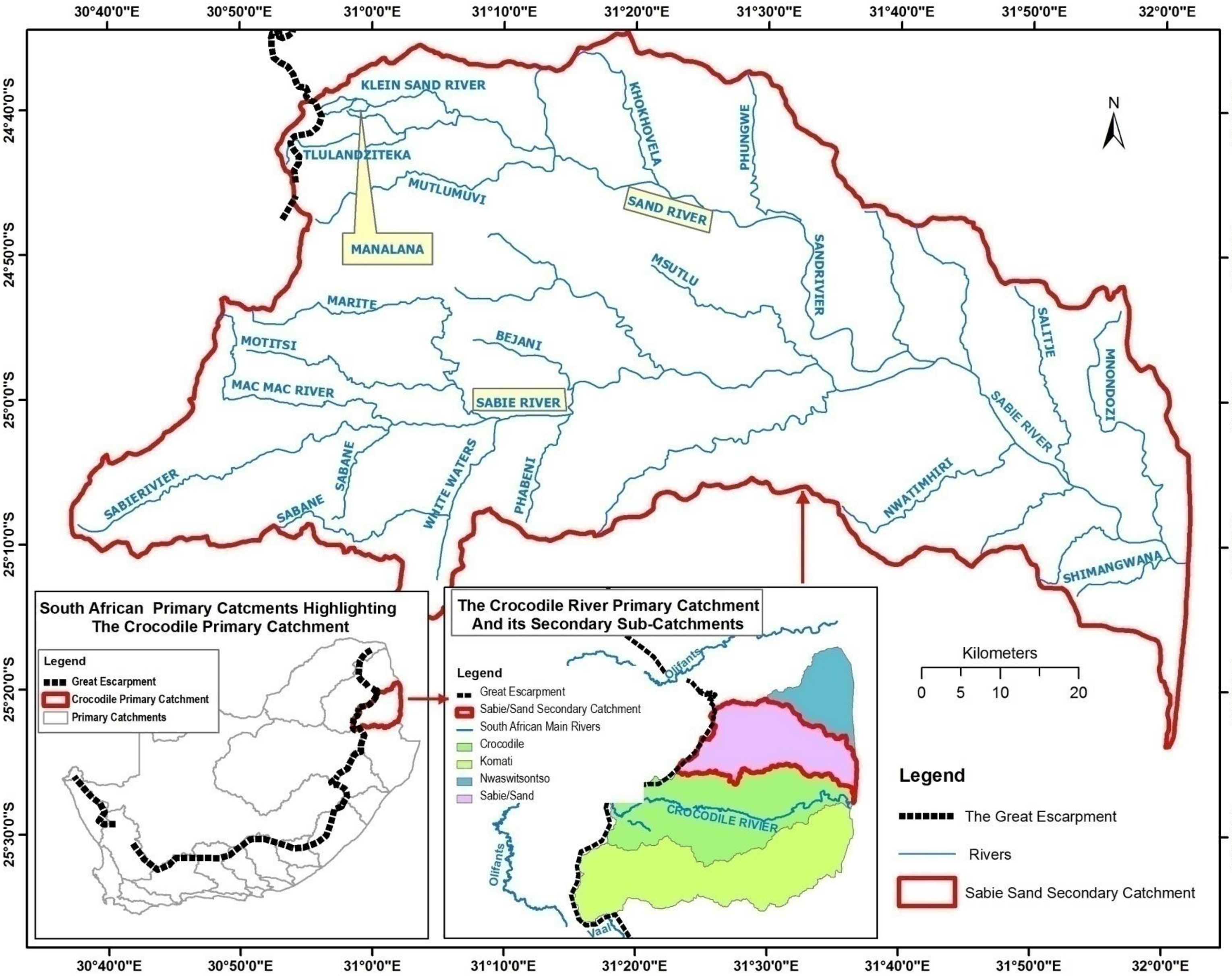


Figure 3.7 The Manalana River at Craigieburn, in the Sabie/Sand Rivers catchment.

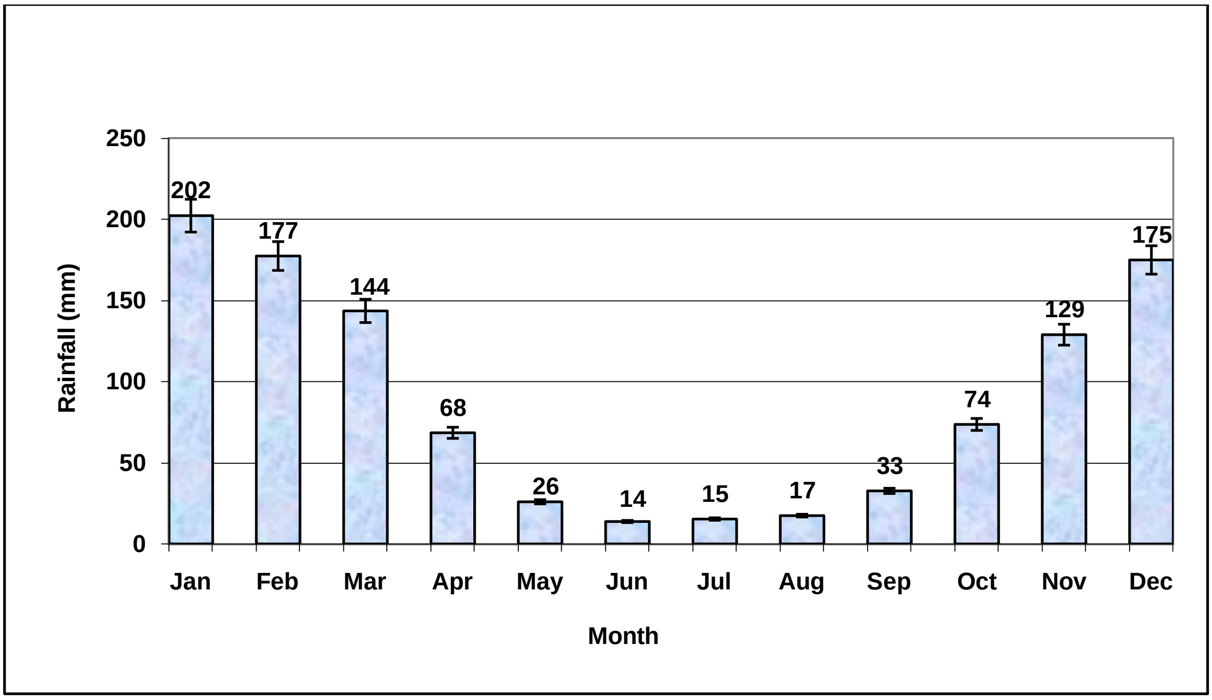


Figure 3.8 Mean monthly rainfall, 1908-1999 (Wales Station, ICFR, 2005).

Note: The mean monthly rainfall distribution above displays a ±5% standard error (I) for each month on top of each bar.

Long term annual rainfall variations analyzed from the 1908-1999 record are quasi-periodic with clear humid periods alternating with less humid periods, similar to models of climatic fluctuations proposed by Deacon and Lancaster (1988), Tyson et al. (2001) and Vines (1980). The underlying tenet is that long term climatic variations in South Africa are controlled by solar cycles (about 11 and 22 years) and thus global quasi periodic rainfall fluctuations are in the order of ~16-24 years, ~9-12 years and ~6-8 years, corresponding to sunspot cycles.

Considering the average 1075 mm rainfall (1908-1999) as a threshold between very humid and less humid periods (Figure 3.9), it is observed that 1912-1935 was a 23 year period of less humid or fluctuating climate followed by a 26 year wetter period (1936-1962), then an 8 year less wet period (1963-1970) followed by another 8 year more humid period (1971-1978). Presently, since 1995, the study area seems to be in a more humid phase. The humid and less humid periods identified in the study area correspond more or less with Tyson’s (1990) and Tyson and Preston-Whyte’s (2000) wet and dry spells though revealing some minor variations. This may be attributed to the fact that their model is countrywide which hides local variations.

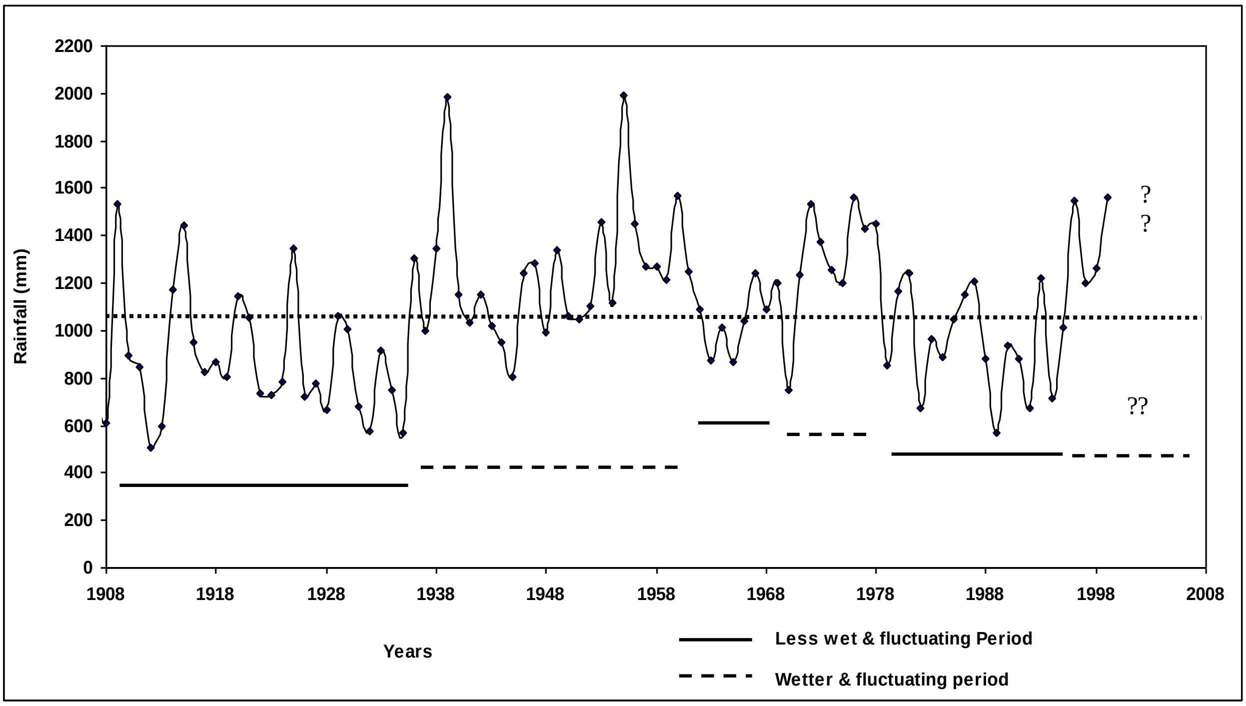


Figure 3.9 Seasonal and yearly rainfall variation 1908-1999 (Wales Station, ICFR, 2005).

The wind circulatory pattern in the study area is influenced by two factors, the Great Escarpment and temperature variation between the lowveld below and the highveld above the Escarpment. This pattern is responsible for the production of two rainfall types namely orographic and frontal rainfall. These rainfall types supplement the hydrological regime and the increased discharge during summer.

CHAPTER FOUR

MATERIALS AND METHODS

4.1. Introduction

The methods employed in this study are summarized into field and laboratory methods. Field methods include field observation, terrain survey (topographical profiles), soil sampling and description, topographical mapping and terrace sampling; while laboratory methods are divided into soil and demographic analysis.

4.2. Field methods

4.2.1. Field observations

Observations were conducted in the catchment of the Craigieburn wetland system for evidence of anthropologic and geomorphic processes that may have contributed to the catchment's morphology and to wetland evolution. This resulted in the identification of different land use types in and around the wetland system, gully morphology and development, the existence of terraces, catchment rock weathering, and the related erosional and depositional processes. These field observations paved the way for a more focused approach to data collection and analysis in relation to the aims and objectives of the study (Section 1.3).

4.2.2. Topographical profiles

Two long profiles and four cross sections (Figure 4.1) were surveyed over the wetland catchment using standard surveying techniques (Hart & Hart, 1973; Herubin, 1991; Hewitt, 1972; Higgins, 1970; Malcolm, 1967). The choice of each surveyed transect was determined by the presence of specific morphological features related to the aim and objectives of the study, that is, gullies, erosion surfaces and valley floor depositional fills. A research assistant was employed to navigate with the metre staff while I did the recording of readings from a dumpy level. The readings were then processed using the rise and fall method of differential levelling (Hart & Hart, 1973; Herubin, 1991; Malcolm, 1967) for the accurate construction of topographical profiles (Chapter Seven).

4.2.3. Soil sampling and field description

Soil samples from the study area were collected for the characterization of soil properties. Transects and sample sites were chosen along or close to surveyed lines (Figure 4.1) to determine soil characteristics around specific morphological features namely, gullies, erosion surfaces and valley floor depositional fills (Figure 4.2). Though not surveyed due to its similar morphology to Transect 2, soil samples were collected along Transect 5 (Figure 4.1).

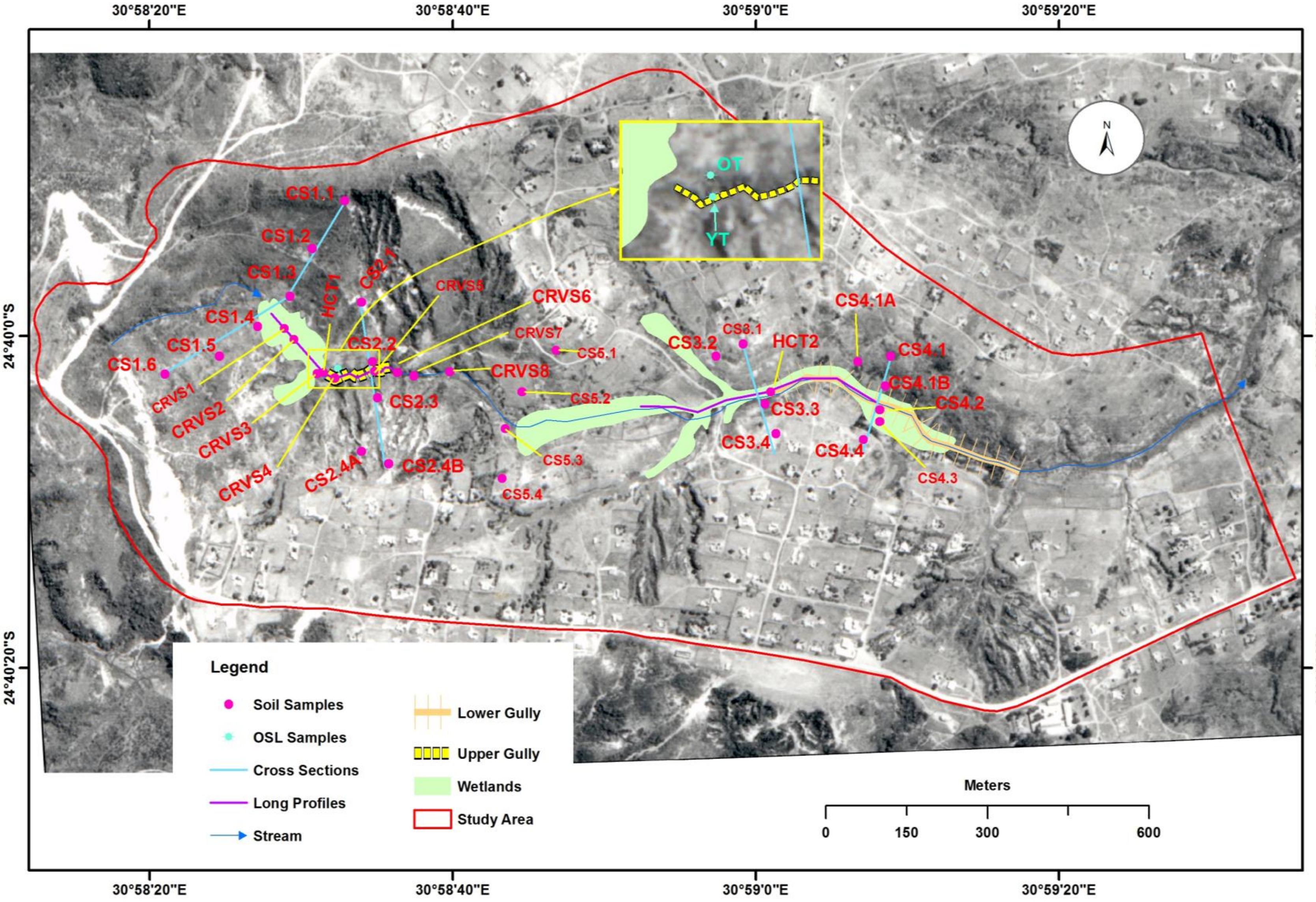


Figure 4.1 Location of cross-sections, long profiles and sample points (CS1.1- Craigieburn section 1 sample 1, CRVS1 - Craigieburn valley sample 1, HCT1- Headcut 1 or upper headcut, HCT2 - Headcut 2 or lower headcut, OSL – Optically stimulated luminescence, OT – Older Terrace and YT – Younger Terrace) at Craigieburn.

The samples were obtained either by augering, from exposed surfaces (Bettis, 1983; Dotterweich et al., 2003; Rowell, 1994; Simpson, 1983; White, 1979), or digging soil pits to facilitate the collection of samples from each horizon (Fenton et al., 2005; Rowell, 1994; Simpson, 1983).

The soil pits were 1.3 m long, 0.5 m wide and 1.5 m deep (Figure 4.3A) and not only aided sample collection but also the photography of their walls for visual presentation and further analysis. To minimize the likelihood of initiating erosion through sample pits and for environmental considerations, the valley bottom and some sensitive parts of the catchment were augered to various depths (down to 435 cm just above the upper gully in search of the water table). When augering, the soil was sequentially laid on the ground to reflect the profile (Figure 4.3B), samples were then collected from homogeneous sections of the augered profile. On the valley floor, samples were augered to greater depths in search of the parent bedrock. Where exposed soil surfaces occurred along parts of some transects these were cleaned (Figure 4.3C) and soil samples collected as described in Rowell (1994) and White (1979). The code for each sample is defined by the study area, the section and the sample number. Thus CS1.1 refers to Craigieburn section 1 (surveyed line 1), sample number 1; while CS4.4 stands for Craigieburn section 4, sample number 4.

In total 157 soil samples were collected along the five cross-sectional transects and two long profiles (Section 4.2.2 and Figure 4.2) within the wetland and in the catchment for detailed analysis including particle size, pH, exchangeable bases and clay mineralogy. The number of samples collected from each pit or auger hole was dependent on soil profile changes, indicative of distinct layers, and ranged from two to eight samples across the catchment.

The soil diagnostic horizons were described according to the South African soil classification (Soil Classification Working Group, 1991), and the software package Corel Draw was used to represent the soil catena of sample pits illustrated in Appendix 4.1. Soil colour was determined using the Munsell colour chart (Munsell Soil Color Charts, 2000), field texture by rubbing moist soil samples between fingers, and plasticity by rolling a moistened soil crumb into threads. These and other soil properties such as structure, mottling and presence of organic matter were analyzed in the field following the procedures described in Ollier (1984), Simpson (1983), Gardiner and Dackombe (1983) and Fitzpatrick (1986). These field analyses and observations aided in the construction of a generalized soil map for the study area. All soil samples were air-dried and ground to pass through a 2 mm mesh prior to laboratory analysis.

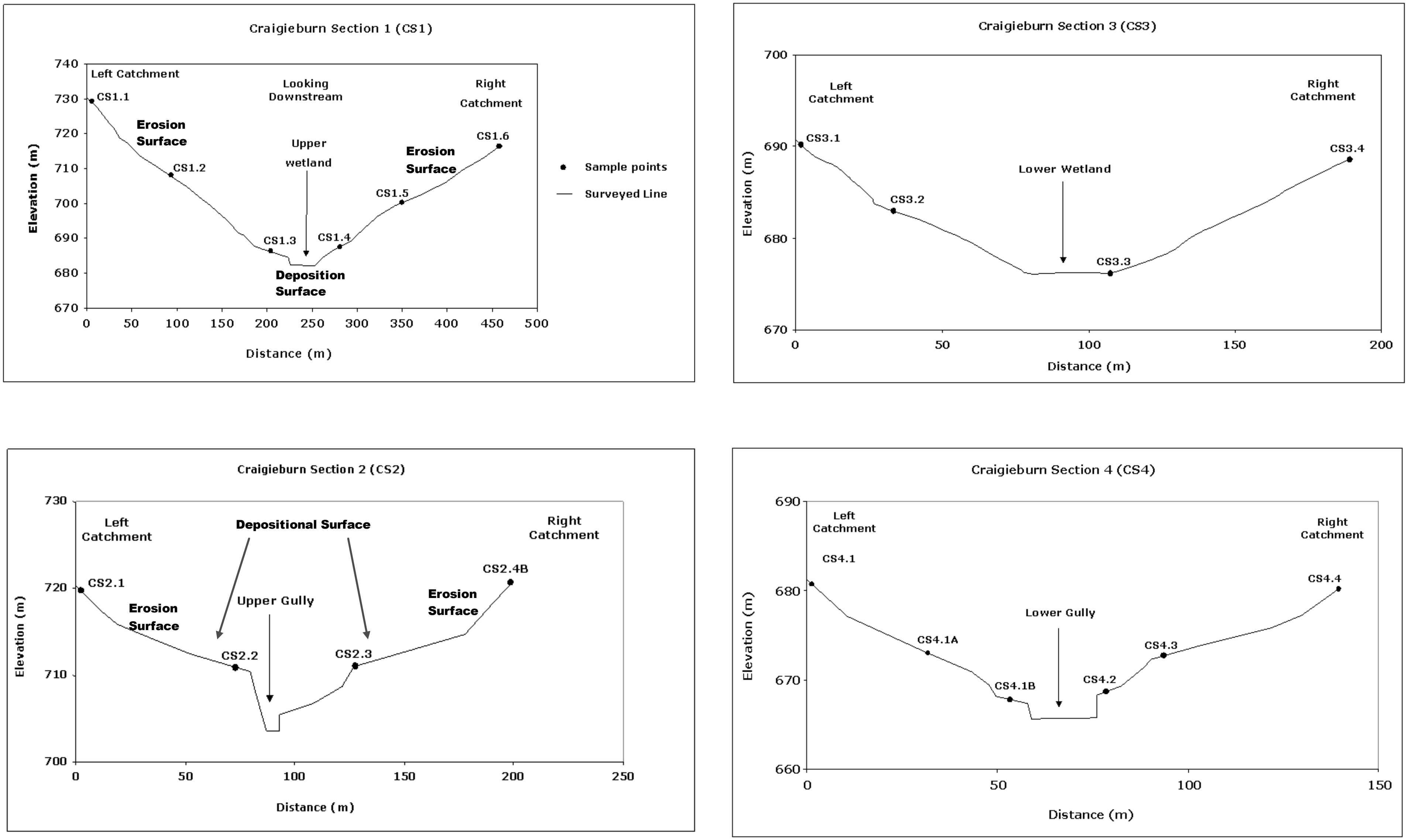


Figure 4.2 Cross-sections of Craigieburn showing soil sampling positions.

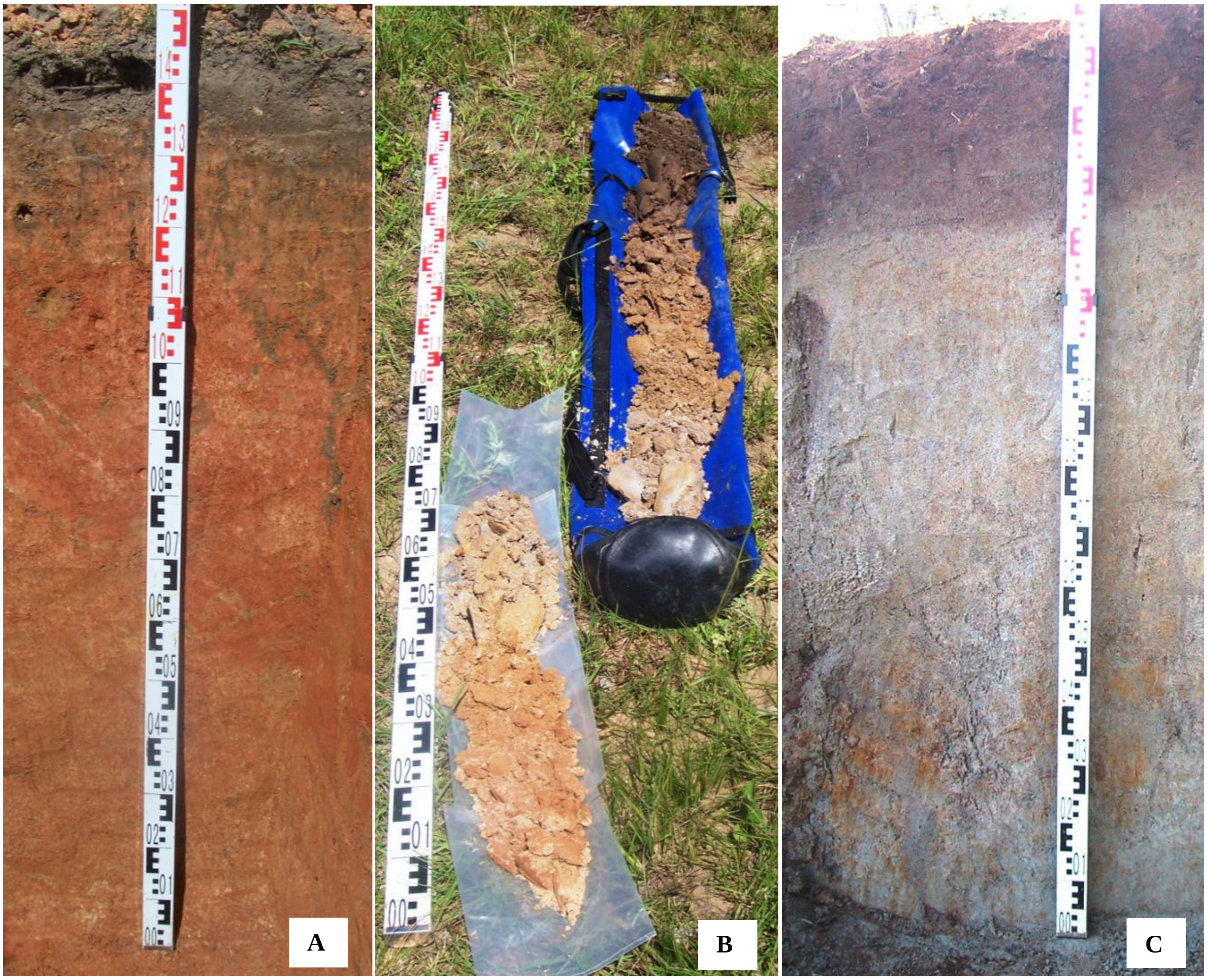


Figure 4.3 Soil sampling procedures used at Craigieburn – A (Soil pit), B (Auger profile), C (Cleaned surface).

4.2.4. Geomorphic mapping and digital elevation model

Geomorphological maps offer a visual presentation of geomorphic units and provide a clue to Earth surface processes and the resulting features. Methods of landscape mapping include the land system approach developed by the Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia, where sections of the landscape with similar landform properties are mapped (Cook & Doornkamp, 1974). Despite its accreditation for simplicity and integration, this method has been criticised by Wright (1972) for its reliance on generalities to the exclusion of detailed local variations, hence the detailed method suggested by Cook and

Doornkamp (1974) and Gardiner and Dackombe (1983). The mapping method adopted in this study is an integration of both the land system approach and the detailed method. To accomplish this undertaking, the 1990 orthophoto was scanned and georeferenced for desktop mapping before field ground-truthing. In the field, tracing paper was overlain on the orthotophoto for detailed mapping, including new features. To enhance locational accuracy, Global Positioning System (GPS) positions of selected features were obtained in the field and later projected to match the desktop map. These, together with the detailed field map were used to complement and update the 1990 desktop map (Figure 3.3). Attributes of adjacent gullies (earthflows) and valley headcuts were input into SPSS (Leech et al., 2008, Voelkl & Gerber, 1999) for correlation analysis and to determine any significant relationship between headcut migration and the adjacent gullies. To determine the study area catchment, two drainage lines with their tails at the beginning of each headcut were overlain on the 1997 aerial photograph and using ArcMap (9.2) spatial analyst and basin tools, the catchment area for each headcut was calculated, so providing the platform for further analysis.

Digital elevation models (DEMs) display height above sea level and are preferred to simple contour maps due to their spatial interpolative effect. They can be used to model relief and to provide a topographic overview of study areas (Ellery et al., 2003; Stocks & Heywood, 1994). Drawing from the experiences of Carlisle and Heywood (1996), Fix and Burt (1995), Lange and Gilbert (1999), Smith et al. (1996) and Wilkie (1990), a Trimble GPS datalogger (TSCI asset surveyor) and a 4600LS surveyor receiver were used to collect elevation data from selected sections of the study area chosen in relation to the main aims and objectives of the study. The advantage of this Trimble GPS system over simple handheld single position receivers lies in improved elevation accuracy after differential correction. While simple handheld single position non-differential receivers are said to be accurate between 100 m and 156 m, differential Trimble GPS of the type used in this study has an accuracy ranging from sub-metre to 5 m (Erickson & Héroux, 1994; Lange & Gilbert, 1999; Raju, 2004; Smith et al., 1996). The calibration of the instrument and its base station (Figure 4.4) along with data capture using the mobile device or rover was carried out as suggested in the software user manual. In brief, the base station was set up from 8:00 am to 5:00 pm on the highest elevation of the area to be surveyed while the mobile receiver (the rover) was carried using a Trimble backpack. Elevation points for the areas of concern were surveyed by navigating at intervals of 2-3 m with a residence time of 5 seconds per point, resulting in the collection of 5,154 elevation points. The data were then downloaded into a computer and differentially corrected in Pathfinder (version 2.51) office software for DEM production in ArcMap (9.2). At 95% level of accuracy, the differentially corrected elevation produced an average horizontal precision of 50 cm and 97 cm for the vertical.

Figure 4.4 Trimble base station set up at the highest elevation within the Craigieburn Catchment.

4.2.5. Dating

Soil profiles in the study area did not reveal the presence of any datable carbon in the horizons, necessitating the use of optically stimulated luminescence (OSL) dating as an alternative. Optically stimulated luminescence dating requires that samples are not exposed to light during sampling because light excites and releases stored electrons (Godfrey-Smith et al., 1988; Huntley et al., 1985; Lian & Roberts, 2006; Wintle, 1985), leading to unreliable results. In line with this principle, and following the procedure provided by the Utah State University exposed faces of two depositional terraces were cleaned to remove any material previously exposed to light (Figure 4.5 and Figure 4.6). The terraces clearly show layered multiple phases of sedimentation. Sample sites in the fills were guided by particle size suitable for dating (fine – medium sand) and precaution to include the oldest layer (earliest fill event). Four samples were collected (3 from the older terrace and 1 from the younger terrace (Figure 4.1 and Figure 4.6)) vertically along the clean surface using metal pipes, 20.32 cm long and 3.8 cm in diameter. The sharpened end of each pipe was fitted with Styrofoam plugs after which it was then pushed into the targeted layer of the fill at different depths, by pounding the pipe from one end (Figure 4.6). Once the pipe was filled and flushed with the cleaned surface outcrop, two other samples were collected from the sampled layer around the pipe. One was stored in a film canister to determine moisture content and the other in a 1-quart ziplock freezer bag to determine the environmental dose rate. The pipe was then retrieved, capped at both ends and taped with duct tape to prevent mixing of sediments during transportation. Thus at each sample point, 3 samples were collected for OSL dating, moisture content and dose rate (Figure 4.7). All 12 samples were labelled and sent to the Utah State University for dating.

Figure 4.5 A cleaned surface of the older terrace at Craigieburn.

Figure 4.6 Sampling for OSL dating at Craigieburn. (A) Collecting an OSL sample from the younger valley terrace; (B) Sample sites on the older terrace.

Figure 4.7 Four OSL samples and ancillary samples prepared for shipment to the laboratory.

4.3. Soil analysis

Particle size distribution was determined using the pipette method (Gee and Bauder, 1986) after organic matter removal with hydrogen peroxide and ultrasonic dispersion with addition of sodium hexametaphosphate and sodium carbonate. Soil pH was measured in a 1:2.5 soil : distilled water suspension on a YSI 556 MPS Multiprobe pH meter. Exchangeable Ca, Mg, K and Na were extracted in 1:10 soil:0.1M ammonium chloride solution (5g:50ml) and exchangeable sodium percentage calculated. Bulk soil and parent rock mineralogy was determined by X-ray diffraction using powder samples packed into aluminium holders to achieve random orientation (Jenkins & Snyder, 1996). Samples were analysed on a Philips PW1050 diffractometer fitted with a graphite monochromator and using CoKα radiation from 3 to 75^0 2 theta at 1^0/minute with a step size of 0.02^0. Data were collected using a Sietronics software 122D automated micro-processor. Minerals were identified using the Joint Committee on Powder Diffraction Standards (JCPDS) databook (Bayliss et al., 1980). In addition one dolerite boulder was cut open (Figure 4.8) and the mineralogy of the various layers determined.

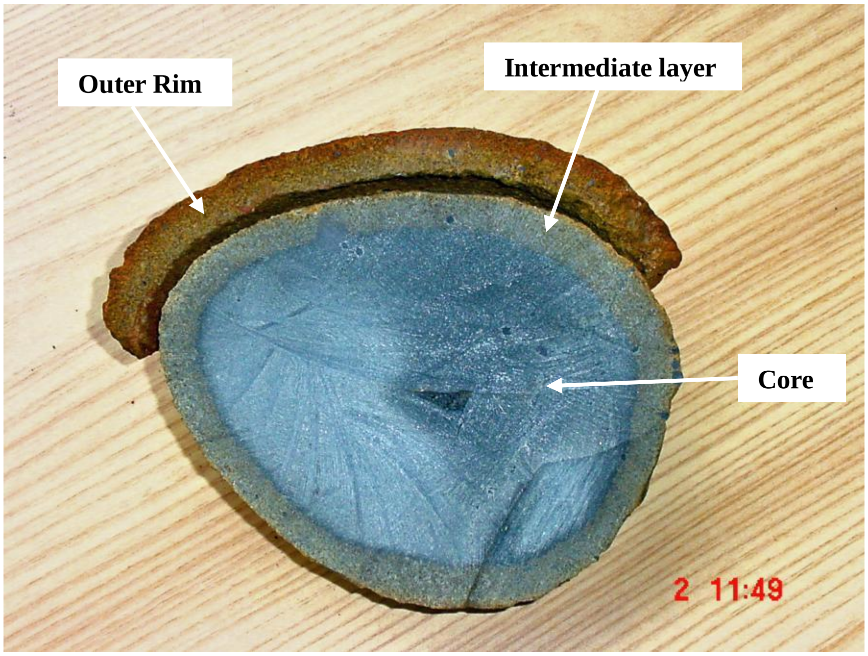


Figure 4.8 Dolerite parent rock indicating sample areas on the split surface.

Total major elements were determined after fusion of the samples with lithium tetraborate by X-ray fluorescence on a Philips 1404 spectrometer.

4.4. Human impacts on gully development

Due to lack of census data, it was not possible to obtain figures for population change over time for the study area. Thus five generations of aerial photographs (1954, 1965, 1974, 1984 and 1997) were scanned, georeferenced and the study area clipped out to assess the demographic evolution and landscape change of the area. To accurately identify each household, homestead and other socio-economic activities, recourse was made to techniques of aerial photograph interpretation and analysis as described in Avery and Berlin (1992), Seymour (1957), Spurr (1960), Stone (1956) and Wolf (1974). Aerial photographs have been successfully used in the study of historical evolution of landscape features due to their ability to reveal change with time (Baptista et al., 1999; Benninghoff, 1953; Faulkner, 1998; Graf 1979; Parry & Beswick, 1973; Spurr, 1960).

To track these changes and their impact on the wetland system, its catchment was subdivided into two, relative to the upper and lower wetland gullies. The upper catchment is a sub-catchment of the lower catchment and includes all areas draining into the upper headcut, while the lower catchment is the area draining into the lower headcut including the upper catchment and the area just below the lower headcut which completes the entire drainage line. The area just below the lower headcut was included because households within it have the propensity to influence gully development in the study area. The rationale for sub-dividing the catchment according to the two gullies lies in the fact that both of them are discontinuous, hence it was necessary to investigate whether any local variation of factors in the sub-catchments affects the two gullies differently. A further reason for this sub-division is provided by Patton and Schumm (1975), who argued that discontinuous gullies develop in areas of oversteepened valley floor, which are products of large quantities of sediments from tributary streams. At Craigieburn, more tributary streams connect to the lower gully than the upper gully. This subdivision was also based on field evidence showing that the number of homesteads and human activity below the upper gully far surpassed their presence in the upper catchment.

Although the study area catchment has been divided into two sub-catchments (upper and lower) corresponding to the two headcuts, it is possible that the two gullies are connected by the same factors, for example households within any part of the catchment may influence the wetland system through grazing, farming and fuel wood harvesting.

To assess population change and evolution of socio-economic factors in the study area, homesteads, dirt roads, footpaths and animal tracks were then digitized from the five generations of aerial photographs using geographic information system (GIS) techniques. In GIS, attribute tables were created containing the actual number of houses, homesteads, lengths of dirt roads, footpaths and animal tracks in the study area. Using SPSS (Version 15.0) statistical software, linear and multiple regressions were performed to determine the significance of population and the other socio-economic dynamics in relation to gully development at Craigieburn.

4.5. Methodology summary

The overall methodology adopted for this thesis is presented in Figure 4.9. It begins with office preliminary planning and analysis, followed by field procedures, laboratory and desktop analysis, leading to results, discussion and conclusion.

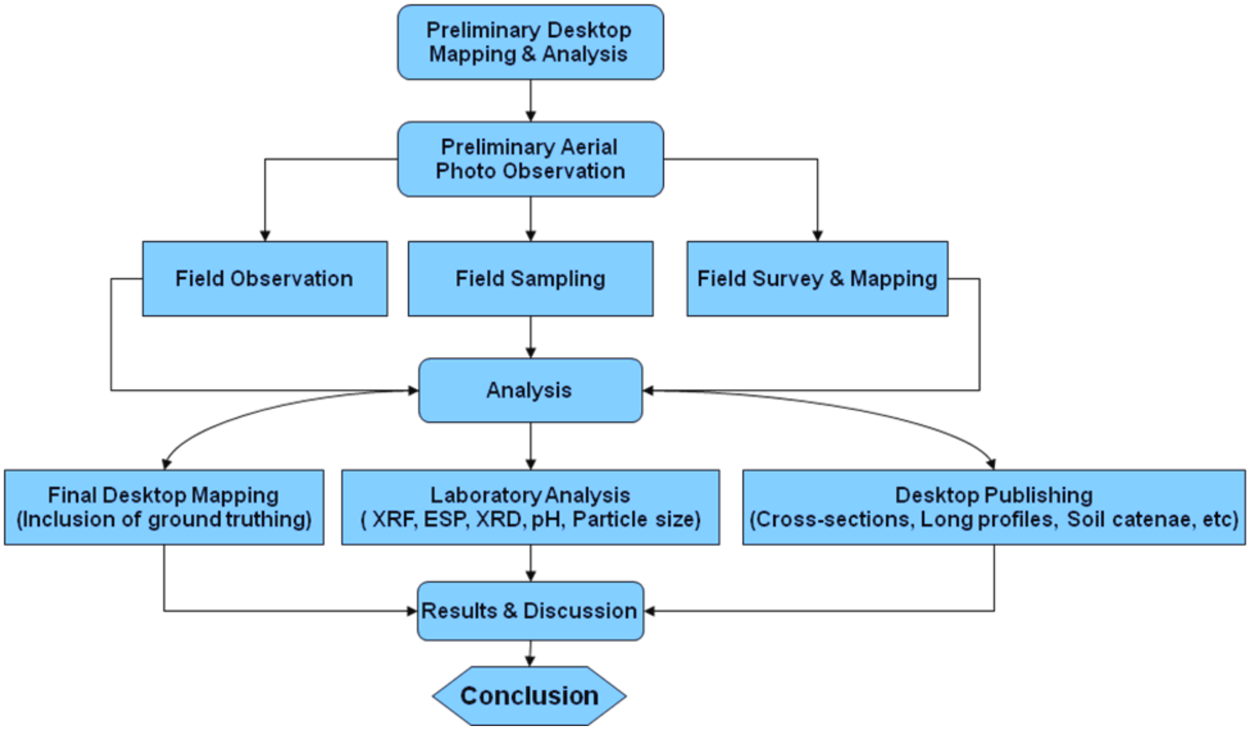


Figure 4.9 A summary of the methodology used for the study at Craigieburn.

CHAPTER FIVE

SOCIO-ECONOMIC FACTORS INFLUENCING GULLYING AT CRAIGIEBURN

5.1. Introduction

The debate relating human impacts to gully development occupies a significant place in agricultural and biogeomorphological literature. As already discussed (Sections 1.1 and 2.2), gully initiation and evolution is most often blamed on human activities including deforestation, poor farming methods, overgrazing and human habitation (Baptista et al., 1999; Faulkner, 1998; Liggit & Fincham, 1989; Lespez, 2003; Lowe & Walker, 1997; Milne & Hartley, 2001; Twidale, 1997). To an extent, when communities reside adjacent to wetlands, these may be vulnerable to human exploitation for various uses. These uses can either be wise or unwise, affecting wetland health and ecoservice provision positively or negatively. In order to understand whether or how human presence at Craigieburn has contributed to the erosion of its wetland system, it is imperative to consider the human evolution of the study area. This chapter evaluates the significance of community impacts on the Craigieburn wetland system and its catchment with particular reference to population change, agricultural activities, road development and the presence of footpaths and animal tracks.

5.2. Demographic evolution of the study area

A brief demographic history of the study area was provided in Section 3.2 explaining how the political history of the region has played a key role in population dynamics and landuse management. Observation, interpretation and extraction of data from aerial photographs (Section 4.4) show that homesteads and individual homes have varied in numbers and spatial distribution from 1954 to 1997 (Figure 5.1).

The settlement history (Figure 5.1) clearly shows that the catchment head has undergone less human occupational change compared to the central and downstream areas. A few homes occupied the catchment head in 1954 but were vacated by 1965 and since then, the catchment head has not witnessed any further human settlement. This population history of the study area’s catchment head poses a serious question to what extent local human settlement on this section of the study area has contributed to evolution of the upper headcut. What complicates any suggestion of human induced causes on erosion of the upper wetland is the existence of the wetland gully long before human presence, its stability between 1954 and 1965 in the presence of few homes, and the steady increase of gully length between 1965 and 1997 in the absence of population increase in the catchment head.

See accompanying Figure in A3 size pdf

Figure 5.1 Spatial distribution of homesteads and individual homes at Craigieburn from 1954 – 1997.

To determine the extent of human contribution to gully erosion in the wetland system at Craigieburn, GIS digitizing techniques and other analytical methods (Chapter Four), were used to extract selected human imprints (dirt roads, footpaths and animal tracks) from the 1954 to 1997 aerial photographs (Tables 5.1a and 5.1b) for the sub-catchments of the two wetlands. The number of individual homes for the upper sub-catchment declined from 7 to 0 between 1954 and 1965 followed by an increase to 36 in 1974, remaining constant in 1984 and then declining to 19 in 1997. This pattern of fluctuating population rise and fall is also reflected in Table 5.1b for the lower sub-catchment.

AWARD (2004) estimated that in 1997, there was a total of 182 homesteads with a population of 1,367 at Craigieburn and suggested that about 40% of these households were making use of the wetlands. In the present study, homesteads digitized for the same year confirmed the same total. However, it is not clear whether the same percentage suggested by AWARD (2004) still make use of the wetland system more than a decade later.

Table 5.1a Some socio-economic variations in the upper sub-catchment and upper wetland gully length between 1954 and 1997 at Craigieburn.

Year	Length of Dirt Roads (m)	Length of Footpaths/Animal Tracks (m)	Total Length of Roads (m)*	No. of Homesteads	No. of Individual Homes	Upper Gully Length (m)
1954	101	808	909	3	7	106
1965	99	1,379	1,478	0	0	106
1974	177	4,746	4,923	11	36	127
1984	421	2,533	2,954	11	36	130
1997	430	2,287	2,717	9	19	136

Table 5.1b Some socio-economic variations in the lower sub-catchment and lower wetland gully length between 1954 and 1997 at Craigieburn.

Year	Length of Dirt Roads (m)	Length of Footpaths/Animal Tracks (m)	Total Length of Roads (m)*	No. of Homesteads	No. of Individual Homes	Lower Gully Length (m)
1954	2,545	4,162	6,707	16	56	0
1965	2,545	5,346	7,891	0	0	100
1974	5,423	17,480	22,903	206	496	214
1984	6,465	12,488	18,953	197	344	408
1997	7,900	12,757	20,657	173	266	522

* Total length of roads refers to the sum of footpaths/animal tracks and dirt roads.

The total length of dirt roads in each of the sub-catchments was almost the same in 1954 and 1965 and increased thereafter to 1997. The total length of roads and footpaths/animal tracks for the upper sub-catchment increased from 1954 to 1974 and then decreased thereafter. This pattern differs slightly from the lower catchment where the total lengths of roads and footpaths/animal tracks increased from 1954 to 1974, decreased in 1984 but then increased in 1997. Despite fluctuations in all road lengths and population from 1954-1997, the two gully lengths increased steadily during the same period.

5.3. Socio-economic factors and wetland gully length at Craigieburn

One of the research questions raised in Chapter One was to what extent have socio-economic factors contributed to gully evolution at Craigieburn? To answer this question, linear correlation and multiple regression was performed on untransformed data and scatter plots produced to determine the relationship between gully length and some socio-economic variables. Figures 5.2 and 5.3 (linear correlation) and Tables 5.2 and 5.3 (multiple regression) provide the basis for assessing not only the nature and strength of the relationships between independent socio-economic variables, but also the degree (R^2 and adjusted R^2 for the small sample size) to which they may have contributed to gully incision and development. At the upper gully (Figure 5.2), all socio-economic variables and gully length exhibit a positive linear correlation with varying strengths. For example, individual homes, footpaths/animal tracks and total roads (Figures 5.2a, 5.2b and 5.2d, respectively) display a weak positive correlation in comparison to dirt roads (Figure 5.2c). However, a combined adjusted R^2 value of 0.92 for individual homes, footpaths/animal tracks and dirt roads (ABC in Table 5.2) shows that these three variables account for a large proportion of the increase in upper gully length. Despite this, their combined level of significance is low ($p = 0.18$) and the sample size extremely small.

Further, the variables themselves are likely to be correlated and so these apparent relationships must be viewed with considerable caution. The best relationship is between gully length and time (Figure 5.2e). However, the only measured variable that mirrors this trend in gully length with time is the length of dirt roads (Figure 5.2c) with a linear relationship of $R^2 = 0.78$. Both are significant at $p = 0.05$ for dirt roads and $p = 0.02$ for time (Table 5.2), suggesting their possible contribution to gully evolution at Craigieburn.

The lower gully is identical to the upper gully in its trend, that is, a small sample size, a weak positive linear relationship between lower gully length and all socio-economic factors (Figures 5.3a, 5.3b and 5.3d) except dirt roads (Figure 5.3c) and evidence that these factors (ABC, Table 5.3) account for a large proportion of the increase in lower gully length ($R^2 = 0.90$) with no significant relationship ($p = 0.21$). The high value for ABC factors can be attributed to the heavy contribution of dirt roads ($R^2 = 0.91$) in comparison to footpaths and animal tracks ($R^2 = 0.20$), total roads ($R^2 = 0.46$) and individual homes ($R^2 = 0.06$). As with the upper gully length, time ($R^2 = 0.98$, $p = 0.02$) and dirt roads ($R^2 = 0.91$, $p = 0.01$), present the strongest and most significant relationships with lower gully length.

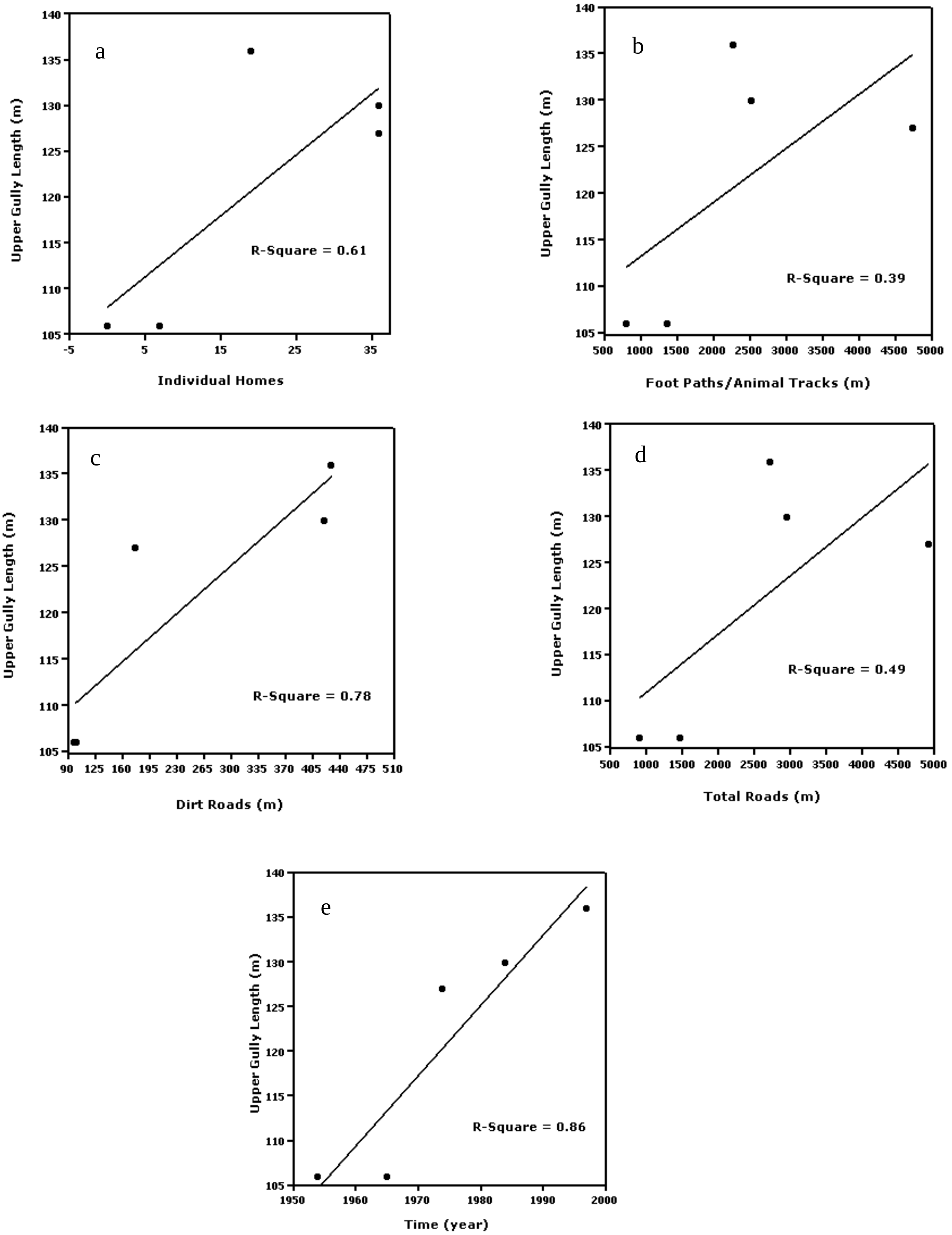


Figure 5.2 The relationship between socio-economic variables and time with upper wetland gully length at Craigieburn.

Table 5.2 The contribution of socio-economic variables and time to upper wetland gully length at Craigieburn.

Independent Variable	**R^2**	**Adjusted R^2**	**Significance (p)**
Footpaths/Animal Tracks (A)	0.39	0.18	0.26
Dirt roads (B)	0.78	0.70	0.05
Total Roads (A&B)	0.49	0.32	0.19
Individual Homes (C)	0.60	0.47	0.12
ABC	0.98	0.92	0.18
Time	0.86	0.82	0.02

5.4. Livestock grazing and farming within the catchment

During three field visits, a daily count of the only existing cattle herd grazing on the catchment was conducted and amounted to an average of 25 in the herd. The physical impact of livestock grazing on the study area catchment is evident in the number of animal tracks that crisscross the catchment (Figure 5.1). However, the absence of historical records made it impossible to assess the annual stocking rate from 1954 to 1997. Though household numbers increased during this period, no attempt has been made in this study to correlate households with cattle numbers because not all households own cattle.

It is customary for families in the study area to have a garden within the perimeter of their homesteads. Subsistence farming, including the cultivation of maize (*Zea mays*), madumbe (*Colocasia esculenta*), beans (*Phaseolus vulgaris*) and sweet potato (*Ipomoea batatas*) as major crops, is also practiced elsewhere on catchment slopes, in the valley bottom and within the wetlands. The farming pattern is a mixture of ridge and furrow across and sometimes parallel to the slope and valley floor. These practices are at the centre of the controversy over their contribution to gullying and wetland degradation at Craigieburn, and may have legitimately contributed to erosion of the wetland system. However, the poor quality of some of the aerial photographs disallowed the proper assessment of these agricultural practices and land use changes with time. Moreover, the general impact of agricultural activities in the study area was not considered because family gardens do not directly encroach on the wetland valley and, in most cases, are buffered by uncultivated strips.

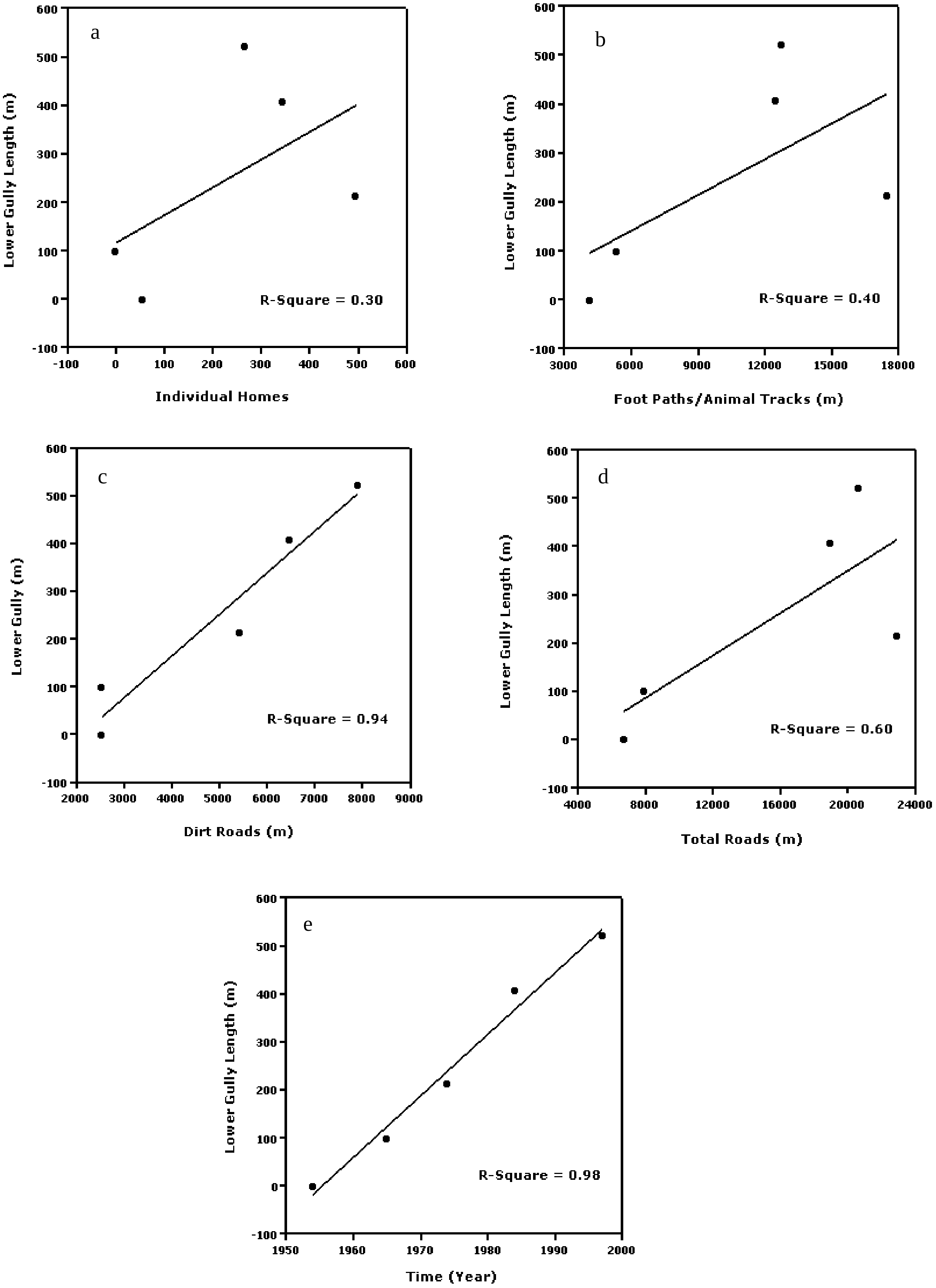


Figure 5.3 The relationship between socio-economic variables and time with lower wetland gully length at Craigieburn.

Table 5.3 The contribution of socio-economic variables and time to lower wetland gully length at Craigieburn.

Independent Variable	R^2	Adjusted R^2	Significance (p)
Footpaths/Animal Tracks (A)	0.40	0.20	0.25
Dirt roads (B)	0.94	0.91	0.01
Total Roads (A&B)	0.60	0.46	0.13
Individual Homes (C)	0.30	0.06	0.34
ABC	0.97	0.90	0.21
Time	0.98	0.98	0.02

5.5. Discussion

The population trend (Section 5.2) is apparently related to the political history of the region when the homes on the 1954 aerial photograph may have been forcibly removed from the area during the first half of the 1960s. This was then followed by a change in government policy permitting human re-colonization of the catchment from the 1970s to the present. Though oral history in the area does not account for the disappearance of homes by 1965, it does explain their reappearance by 1974. Personal communication with two residents (Monareng & Sekatane, pers. comm, 2009) revealed that in the area before 1960 the indigenous people lived behind the Great Escarpment to the west of the study area and only travelled to and from the Craigieburn vicinity to work. Then between 1961 and 1963 there were forced removals of the indigenous people to the north causing immigration to the Craigieburn area. This oral history and AWARD's (2004) theory harmonize with the increased population on the Craigieburn catchment sometime after 1965, and which is evident on the 1974 aerial photograph.

Research has proven that roads, footpaths and animal tracks compact the soil and concentrate water flow, hence increasing erosivity (Grieve, 2001; Knox, 2001; Moeyersons, 2003; Morgan & Mngomezulu, 2003). Human occupation of catchments in some countries has in the past also resulted in gully initiation and propagation (Baptista et al., 1999; Boardman et al., 2003; Faulkner, 1998; Gallego-Fernandez et al., 1999; Lespez, 2003; Tipping, 1994). However, human occupation of the Craigieburn catchment and its related impacts (with the exception of dirt roads) show no significant relationship to gully erosion. Thus, while other socio-economic factors affecting the two gullies assume a fluctuating trend, dirt roads maintain a steady positive relationship with gully length. While some footpaths were converted into dirt roads (Tables 5.1a and5.1b) by local residents whose lifestyles may have improved over the years after 1974 enabling them to own cars, the increase in gully lengths is likely explained by factors other than dirt roads. This argument is supported by the fact that most dirt roads do not connect to the wetland system except one above the lower wetland. That the increase in the length of dirt roads is not a direct contributor to gully initiation is further supported by evidence on aerial photographs which clearly reveals that the upper gully existed before 1954 and the lower gully before 1965, prior to increasing human occupation from the 1970s onwards. The actual date of the initiation of the gullies is not able to be assessed, only the time period in which it occurred. Although results of multiple regression correlating lengths of the two gullies and possible predictive factors suggest a strong relationship (adjusted R^2, 0.90 - 0.92), that is very significant for dirt roads ($p < 0.05$ for the two sub-catchments), this does not imply causality (Clayton, 1984; Larson & Farber, 2003) especially with a small sample size and considering that interrelationships exist between the different factors (Appendix 5.1a and 5.1b). In this Appendix (Appendix 5.1a and 5.1b), an example showing such a strong relationship between factors which does not imply causality is found between dirt roads and adjacent gullies at the upper gully ($R^2 = 0.75$) and at the lower gully ($R^2 = 0.97$). This argument is supported by the fact that the dirt roads do not connect to the adjacent gullies. Moreover, these adjacent gullies (considered as natural factors) appear on the 1954 aerial photograph, long before any significant increment of dirt roads from 1974 – 1997. Definitely time has played a great role in gully evolution at Craigieburn as is evident by the increase in length of the lower gully and statistical results ($p < 0.05$). Nevertheless, a comparison of upper and lower gully lengths shows that from 1965 to 1997, the upper gully increased by a distance of only 30 m compared to 422 m for the lower gully. This faster growth of the lower gully coincides with the influx of human population to the catchment and is in accord with the theory that gully erosion is part of a natural process sometimes accelerated by human activities (Bettis, 1983; Gage, 1970; Graf, 1979).

5.6. Conclusion

Although in some cases human activities may be responsible for the initiation of gully erosion, this does not seem to be the case for the two discontinuous gullies that have reduced the size of two wetlands in Craigieburn. Undoubtedly, human occupation of the study area over the last 40 years has physically impacted on the catchment, raising questions on its relationship with the two headcuts. Nevertheless, no significant relationship with gully propagation was found, except for the apparent effect of dirt roads on the two gully lengths. Although the impact of agricultural activities and stocking rate of livestock was not measured due to the poor quality of aerial photographs and lack of historical records, the upper and lower gully initiation predates major human occupation in the 1970s suggesting that instead, physical factors were largely responsible for gully initiation at Craigieburn. That the greatest growth in gully length, 21 m (upper gully) and 114 m (lower gully), occurred between 1965 and 1974 when human occupation of the entire catchment increased dramatically (0 – 36 and 0 – 496 homes, in the upper and lower catchments, respectively), may suggest its probable contribution to gully extension but not its initiation (especially the upper gully). This conclusion encourages a rethink of previous ideas that human occupation at Craigieburn and their activities in and around the wetlands are solely responsible for gully initiation and development in the area. The next chapter will describe and explain the geomorphological processes within the wetland catchment and their relationship to wetland erosion at Craigieburn.

CHAPTER SIX

WEATHERING, PEDOGENESIS AND GULLY EROSION AT CRAIGIEBURN

6.1. Introduction

Chemical weathering plays a significant role in gully initiation and development being a major catalyst in a process that disintegrates parent rock, releasing clastic sediments which are then eroded and transported by overland flow into the valley. The transport and deposition of these sediments into a valley may eventually increase its gradient, creating the propensity to erode. Hence, cut and fill events are not isolated processes in a valley, but are related to time driven processes in a wider environmental setting, including weathering and pedogenesis. This also applies to wetlands which are not isolated units but are integral parts of their catchments. This explains why wetland processes should not be studied independently but in relation to catchment geomorphological processes. This concept has been endorsed by studies showing that catchment size is inversely related to gully initiation and headcuts (Patton & Schumm, 1975; Schumm & Hadley, 1957). In addition to weathering, other physical factors at the catchment scale which affect valley floor and wetland erosion are seasonal variation of catchment vegetal cover, gradient and geology. Though a significant physical factor, a study of detailed vegetation types, characteristics, taxonomical classification and cover was not carried out at Craigieburn to avoid duplication of previous and on-going studies by other researchers. However, a study of weathering products and soil characteristics in the study area catchment has provided insight into the processes that contributed to wetland erosion at Craigieburn. Analytical results and discussion of the weathered products and soil characteristics for the Craigieburn catchment are the main focus of this chapter. The objective is not only to demonstrate that natural factors have contributed to wetland erosion at Craigieburn but also to show that catchment geomorphological processes are a major part of the debate on whether human or natural factors are responsible for wetland gully initiation and development.

6.2. Weathering at Craigieburn

Weathering disintegrates parent rock to finer material contributing to soil development (pedogenesis) and is a source of sediment supply to valleys and basins (Gerrard, 1981; Simpson, 1983). To authenticate the provenance and supply of clastic sediments into the Craigieburn valley and to determine the degree of catchment weathering, X-ray diffraction (XRD) was conducted on selected whole soil samples along five transects (Section 4.2.3). These results reveal that quartz, which is an indicator mineral of the degree of weathering (Dacey, 1981; Ollier, 1975), predominates in all samples followed by kaolinite and feldspar (Figures 6.1 – 6.5). Other minerals noted are vermiculite, illite and haematite. The abundance of quartz and kaolin in these samples suggests that the area has undergone deep weathering (Allen et al., 2001; Dacey et al., 1980; Palacios et al., 2003; Ruxton & Berry, 1957).

The lateral distribution of minerals varies with kaolinite dominating the catchment summit in the north-west of the study area while quartz dominates elsewhere on the slopes and valley bottom.

In an attempt to test whether the weathered mantle is in-situ or external to the present environment, a parent dolerite rock obtained from the hilltop in the north-west of the study area was cut open (Figure 4.8), revealing spheroidal weathering (Ollier, 1975; Ollier, 1979; Reiche, 1962; Ruxton & Berry, 1957) in progress. The fresh dolerite boulder was collected from the same pit as sample CS1.1 (Figures 6.1 and 6.7), which contain some characteristics of soils developed from dolerites namely feldspar, kaolin, quartz and especially hematite together with the red soil fabric (Bell & Jermy, 2000; Edwards, 1942; Khan et al., 2009; Osok & Doyle, 2004; Tiller, 1962). X-ray diffraction (Figure 6.6) was then conducted on material from each layer of the split dolerite rock (Figure 4.8) and the proportions of quartz and feldspar in the outer, intermediate and inner layer (or the core) indicates some degree of weathering. For example the amount of quartz increases outward from the core suggesting a relative accumulation as other minerals have weathered. This is true of chlorite and hornblende which decrease from the core outward. However, their presence shows that the parent rock is still at an early stage of weathering. The presence of quartz and feldspar in the fresh dolerite (Figure 6.6) and also in the weathered soils on the topslope in the north-west of the catchment (CS1.1, Figures 6.1 and 6.7) in addition to the characteristics of soils developed on dolerites as mentioned above, is an indication that dolerite is apparently the parent material from which these soils have developed. This in-situ weathering hypothesis is supported by a section of the excavated soil profile (Figure 6.7) that contains corestones of dolerite boulders. The bottom corestones are round in shape due to in-situ spheroidal weathering (Ollier, 1979; Ruxton & Berry, 1957), while the overlying rocks are angular (Figure 6.7) in shape suggesting colluvial movement or physical weathering and mass movement of angular scree boulders over a short distance.

Due to advanced weathering of granite in the study area, it was not possible to obtain a fresh sample for XRD analysis, thus a comparison between fresh and weathered granite was not performed. However, further evidence supporting the in-situ weathering hypothesis is provided by the walls of some excavated soil pits, some exposed gully walls and earthflow scars that contain features such as quartz veins (Braucher et al., 1998; Braucher et al., 2004; Ollier, 1979), rock joints and outlines of the original parent granite still in place (Figure 6.8) (Osok & Doyle, 2004; Ruxton & Berry 1961; Small & Clark, 1982). The vertically aligned quartz veins (Figure 6.8d-f) are quartz gravels specifically considered to be in-situ coarse remains of weathering. There are strong indications that the quartz veins at Craigieburn are autochthonous products of an in-situ weathering process (Braucher et al., 1998; Braucher et al., 2004; Cullinet, 1969; Morrás et al., 2005; Muller et al., 1981; Ollier, 1979) because of their association with partially weathered granite parent material.

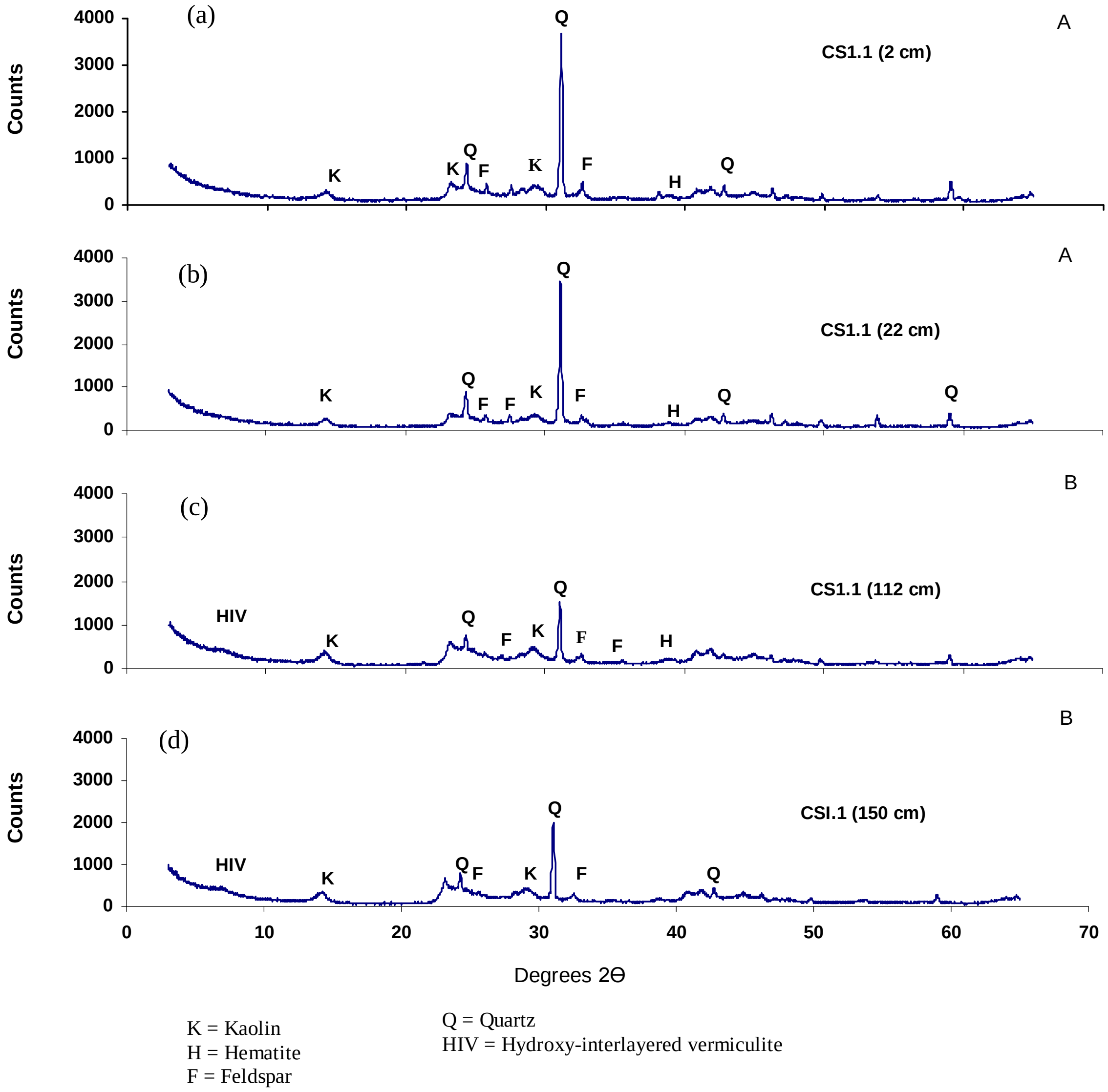


Figure 6.1 X-ray diffractograms of the Hutton soil form (topslope transect 1). A horizon - (a) 2cm depth, (b) 22 cm depth, B horizon – (c) 112 cm depth, and (d) 150 cm depth.

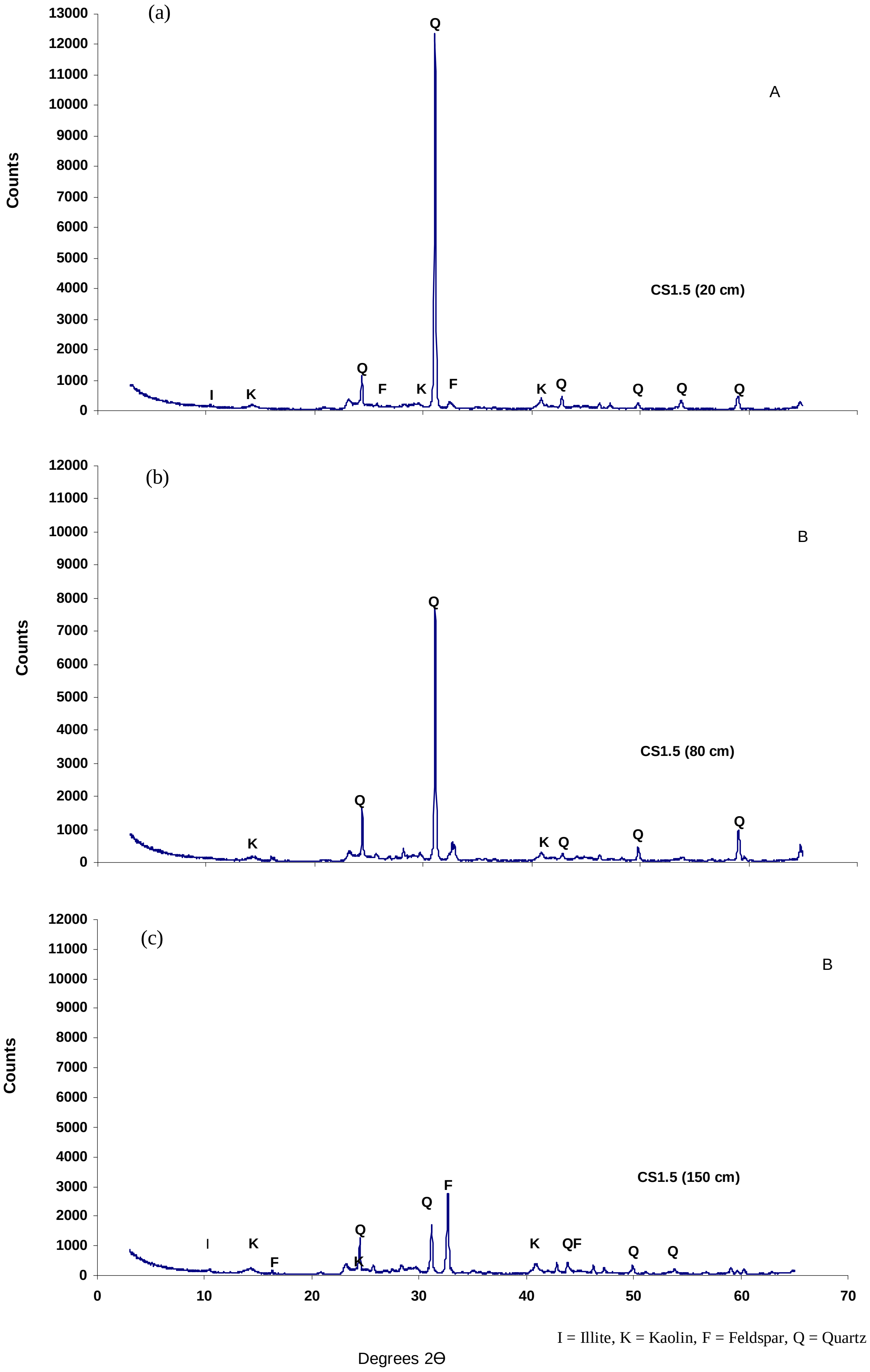


Figure 6.2 X-ray diffractograms of the Glenrosa soil form (midslope transect 1). A horizon – (a) 20 cm depth, B horizon – (b) 80 cm depth, and (c) 150 cm depth.

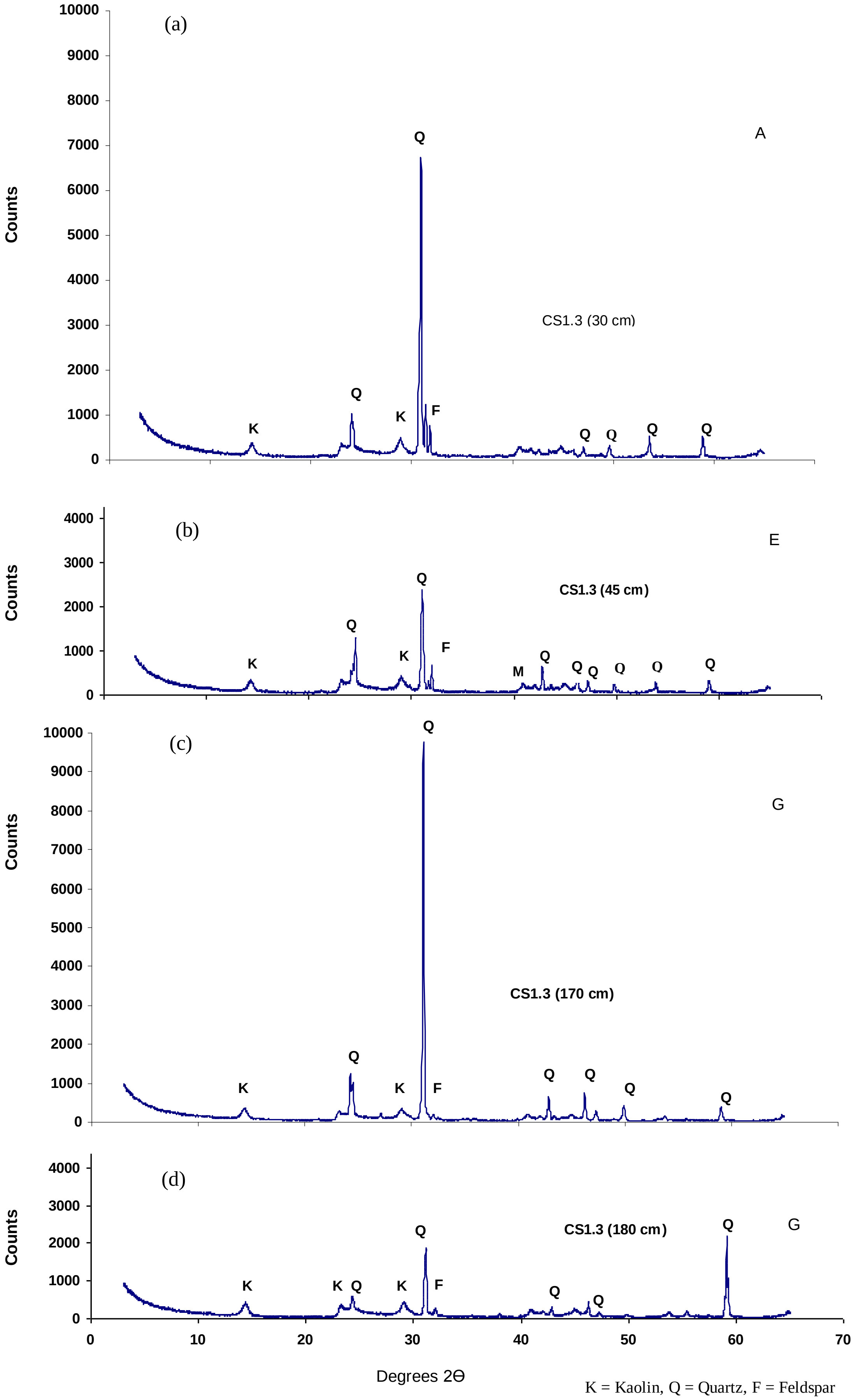


Figure 6.3 X-ray diffractograms of the Kroonstad soil form (footslope transect 1). A horizon - (a) 30 cm depth, E horizon - (b) 45 cm depth, G horizon – (c) 170 cm depth, and (d) 180 cm depth.

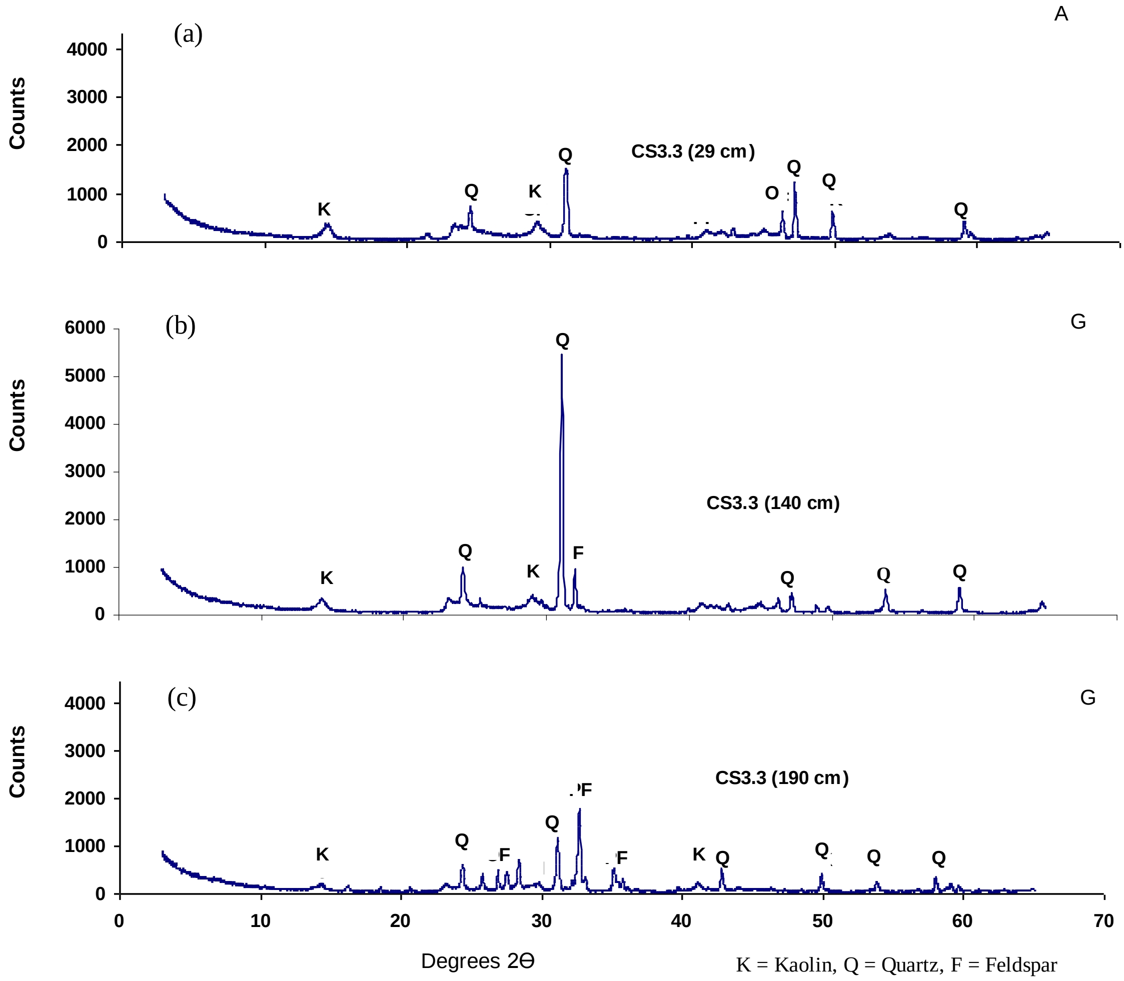


Figure 6.4 X-ray diffractograms of the Katspruit soil form (footslope transect 3). A horizon - (a) 29 cm depth, G horizon - (b) 140 cm depth, and (c) 190 cm depth.

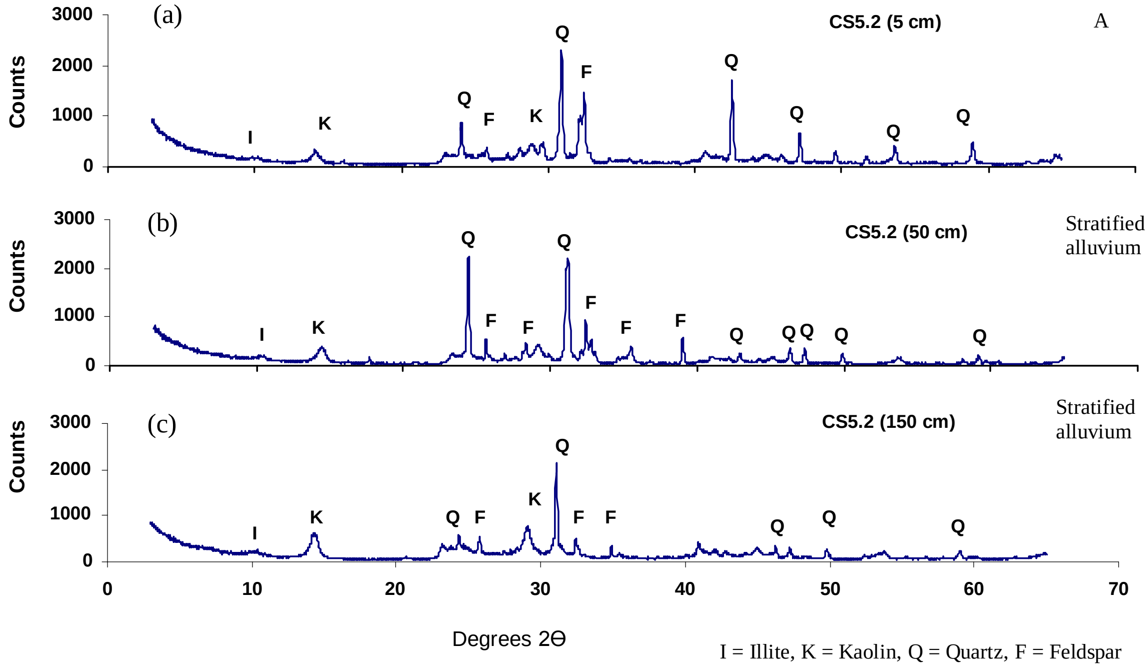
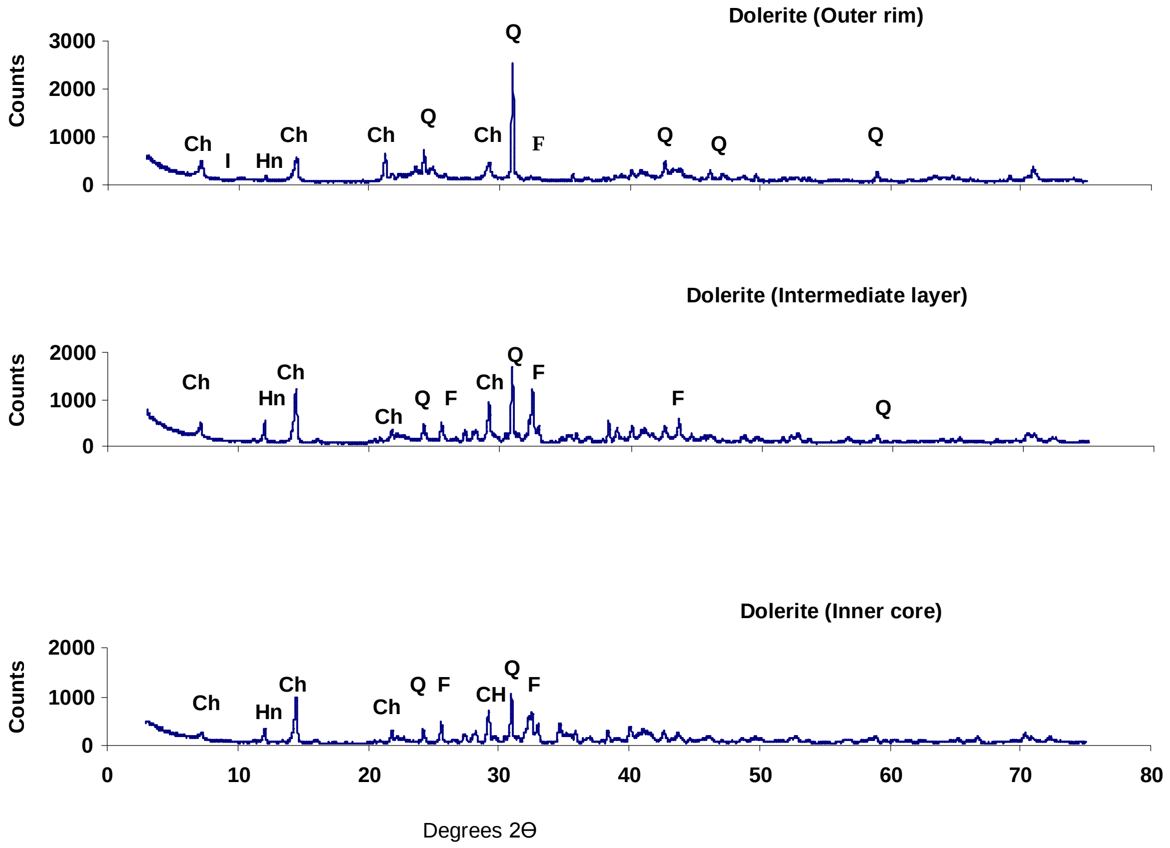
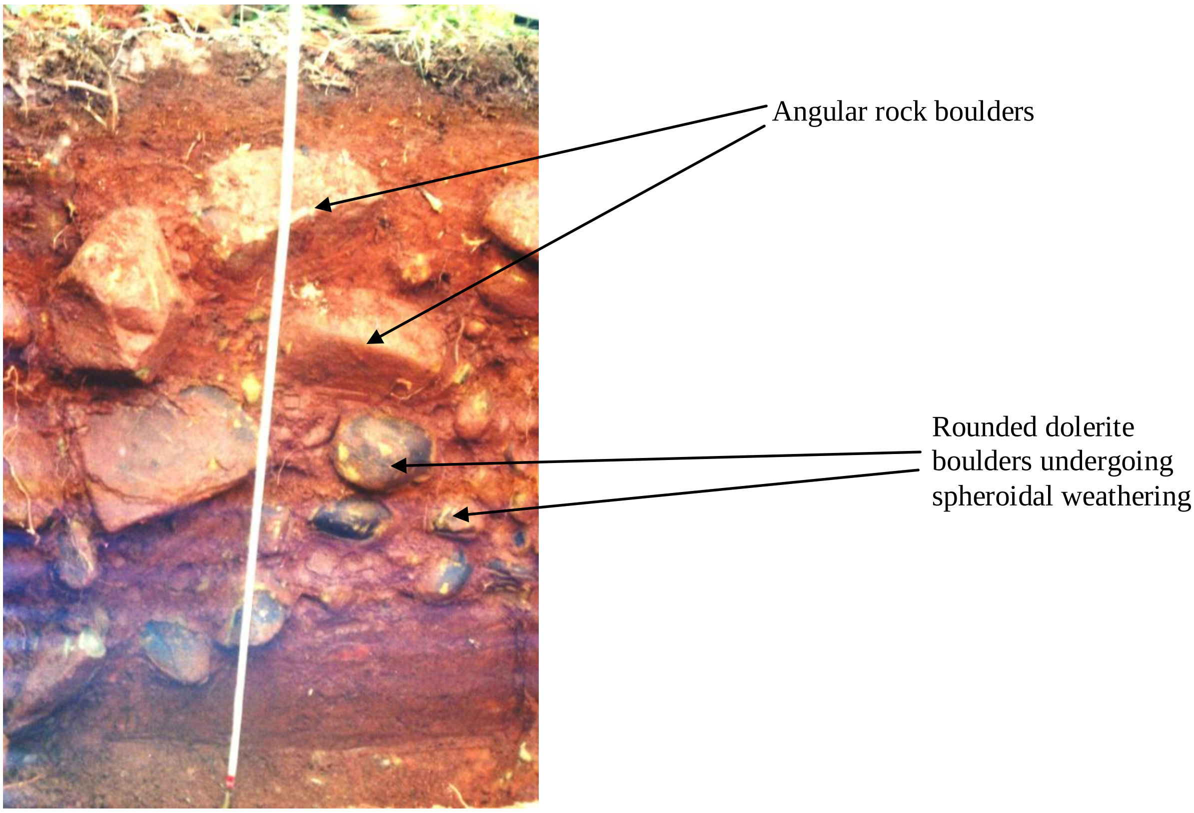


Figure 6.5 X-ray diffractograms of the Dundee soil form (Valley bottom transect 5). A horizon - (a) 5 cm, Stratified alluvium - (b) 50 cm depth, and (c) 150 cm depth.



Ch = Chlorite, F = Feldspar, Hn = Hornblende, Q = Quartz, I = Illite

Figure 6.6 X-ray diffractograms of dolerite parent rock.



Angular rock boulders

Rounded dolerite boulders undergoing spheroidal weathering

Figure 6.7 Corestones of dolerite boulders in sample pit CS1.1. The fresh dolerite sample (Figure 4.8) was obtained from this pit and analysed in Figure 6.6 above.

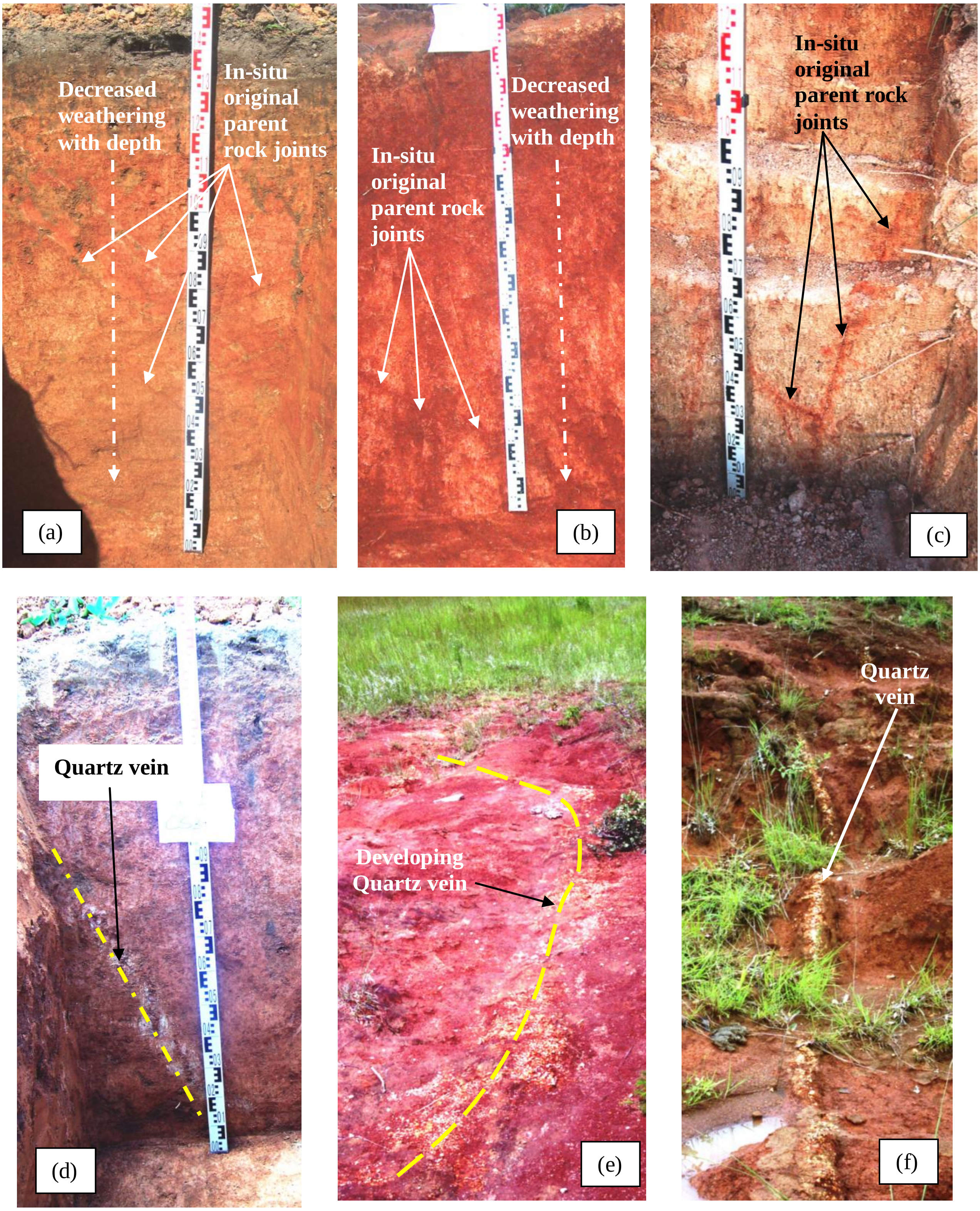


Figure 6.8 Evidence of in-situ weathering, (a) = CS1.6, (b) = CS2.1, (c) CS2.4B, (d) = CS3.1, (e) and (f) = left midslope, downstream adjacent to CS3.1. Except for (e) and (f), the locations of these sites are shown on Figure 4.1.

Note: The presence of original parent rock outlines, joints, incomplete weathering with depth and the absence of distinct layering in the weathered regolith (Figure 6.8a, b and c) suggests in-situ weathering. This is also true with the quartz veins and developing quartz vein (Figure 6.8d, e and f) which are vertical or near vertical, also characterized by the absence of distinct layering on both sides of the quartz veins. The “developing quartz vein” in (e) is probably being influenced by soil creep.

A semi-quantitative estimate of quartz content from the XRD patterns was obtained to better understand the degree of weathering in the catchment. The results show a general decrease of quartz with depth (Figure 6.9) except for some areas in the valley where deposited alluvium shows no clear pattern of quartz distribution. This pattern of quartz distribution in the catchment profiles is characteristic of deep weathering (Allen et al., 2001; Dacey et al., 1980; Palacios et al., 2003; Ruxton & Berry, 1957). Weathering in the study area has produced a thick regolith of varying depth (greater than 20 m in some surface cliffs and exposures) and this provides the parent material for pedogenesis and the characteristic soil profiles, especially those on the top and midslopes.

The presence of quartz in most weathered profiles suggests that they are sources of clastic sediments transported from the slopes into the valley bottom and the wetlands. Once in the valley, these sediments accumulate with time especially during less pluvial periods with low stream flow, hence progressively raising the valley floor gradients at certain locations within the valley to a threshold gradient above which erosion begins.

6.3. Particle size distribution

Particle size analysis does not only assist in soil classification and mapping but it also serves as an indicator of the degree of weathering, susceptibility to erosion and records the magnitude of events responsible for deposition (Ollier, 1984; Simpson, 1983). Particle size distribution of soils and materials at Craigieburn (Appendix 6.1) is described from topslope to footslope on each side of the wetland valley and along the valley floor from the catchment head downstream and vertically at each sample site.

Generally, topslope soils on both sides of the wetland valley (CS1.1, CS2.1, CS3.1, CS3.4, CS4.1, CS4.4, CS5.1 and CS5.4) exhibit a higher clay content in the upper horizons (ranging from 40-77%) than the footslopes, except for a section to the right (south-west) of the catchment head at CS1.6, where the original surface appears to have undergone stripping. The midslopes have a low silt and clay content compared to the topslopes but higher than the footslopes. Sand dominates the footslopes at the catchment head and portions of the wetland valley that are constantly undergoing seasonal channel adjustment to erosion and deposition. The greatest concentration of sand is within the gullies below the two head cuts (1st HCT and 2nd HCT – Figure 4.1).

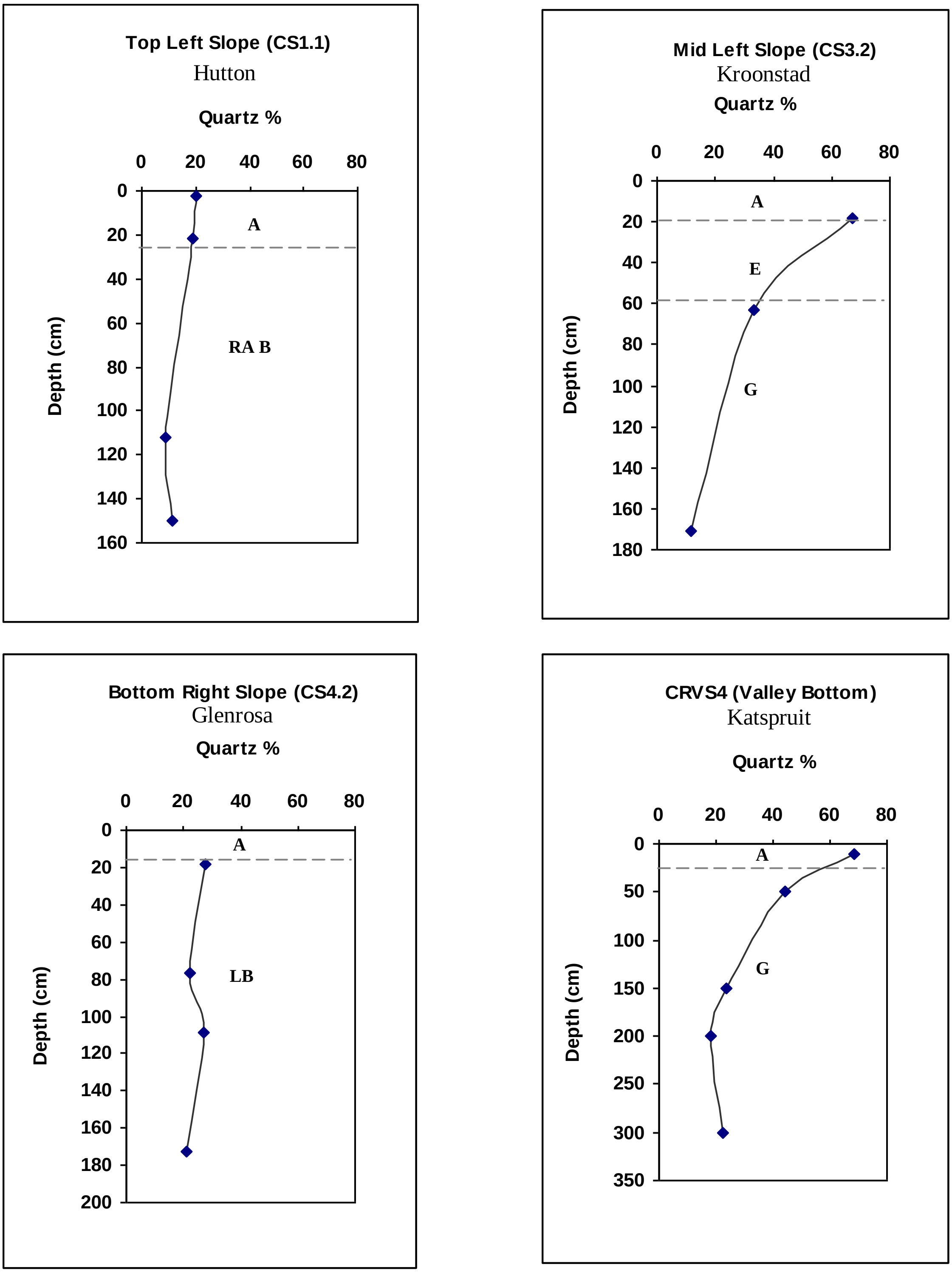


Figure 6.9 Quartz distribution in different soils at selected topographic positions

Note: In relation to Figure 6.9, horizon A: surface mineral horizon mixed with humified organic matter; E: mineral layer with lower organic matter than in A; G: mineral layer showing strong features of reduction, RAB: red apedal B is a red structureless horizon, LB: lithocutanic B is a weathered variegated horizon overlying the weathering bedrock (Soil Classification Working Group, 1991).

A number of cut and fill episodes were identified within the wetland valley and in adjacent minor tributaries. These include the two major head cuts (1st HCT and 2nd HCT) within the main valley fills flanking the wetland valley at CS2.2, CS2.3 and CS5.2 (Figure 4.2). These fills or depositional surfaces manifest a unique distribution of particle size where layers of high sand concentration alternate with thin layers (~ 5-7 cm) of finer particles (silt and clay). This is especially the case at the 1st HCT close to the catchment head and the abandoned fill (CS2.3) on the right side of the wetland valley just below the 1st HCT. In addition to these valley floor fills, other sections of the valley including (CRVS1 to CRVS8) are dominated by sand.

Vertically at each sample location, sand portrays a clear distribution pattern in the topslope soils on both sides of the wetland valley (CS1.6, CS3.1, CS3.4, CS4.1, CS4.4, CS5.1 and CS5.4), increasing in percentage with depth. The midslopes soils on both sides of the wetland valley exhibit different vertical particle size distribution patterns. Some show an increasing percentage of sand while others decrease in sand percentage towards the lower horizons. This may be attributed to the geological pattern (Section 3.4), which shows a superposition of dolerite (with less quartz content) on granite (high quartz content) at certain locations or due to localized deposition of colluvial material from upslope over the parent rock. The left midslope (CS1.2) at the catchment head is an exception with a strong depositional tendency where layers of high sand content alternate with layers of finer particles.

6.4. X-ray diffraction and particle size

In search of homogeneous patterns that explain landscape morphology, results of XRD and particle size analysis have been combined graphically (Figure 6.10). Generally, quartz and sand display a parallel pattern in both in-situ and dynamic (depositional) settings. For example on the upper slopes (in-situ settings), quartz and sand decrease with depth within most Hutton and Glenrosa soil forms (Figures 6.10a & 6.10b). This may be attributed to the fact that as weathering decreases with depth, quartz released from the parent rock accumulates in the upper profile. However, its lower content in the Hutton soil form (CS1.1) situated on the left topslope of the catchment may be accounted for by its low initial content in dolerite. At the footslopes some Katspruit soil forms (Figure 6.10c) display a pattern of increasing quartz and sand. Located at the footslope, this pattern may occur as a result of a previously leached profile being superimposed by subsequent colluvial and /or alluvial deposits. This probably explains the sudden change in quartz and sand distribution at a depth of about 160 cm (Figure 6.10c). The Dundee soil form within the valley does not display a consistent pattern (Figure 6.10d) due to its depositional setting characterized by alternating layers of sediments with different textures.

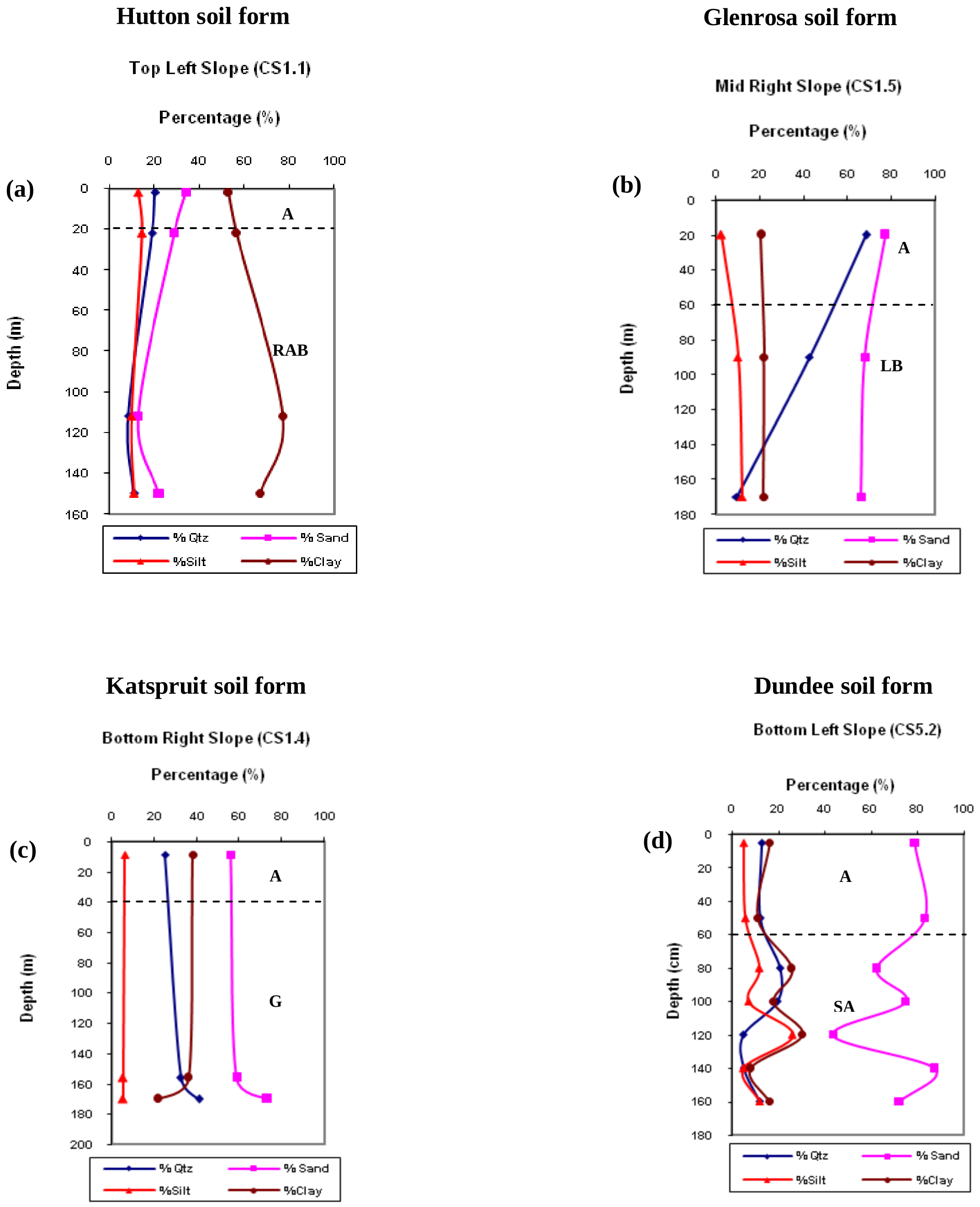


Figure 6.10 Comaparison of particle size distribution and estimated quartz percentage obtained from X-ray diffraction in selected soil profiles (a) Hutton; (b) Glenrosa; (c) Katspruit and (d) Dundee. A, G, LB and RAB refer to soil horizons. See footnote to Figure 6.9. SA: Stratified alluvium).

6.5. Soil chemistry at Craigieburn

6.5.1. X-ray fluorescence

Results of XRF for the granite and the dolerite parent samples; and for the catchment and valley-bottom soils (1st and 2nd headcut – HCT) are presented in Tables 6.1 – 6.3. These reveal that in all three sample groupings, SiO_2 predominates followed by Al_2O_3 and Fe_2O_3. A more detailed comparison of the three material types shows a higher content of SiO_2 in the granite parent material and catchment soils than in the fresh dolerite but higher Fe_2O_3, CaO and TiO_2 in the dolerite than in catchment soils. There is less concentration of plagioclase (CaO and Na_2O) and more K-feldspar (K_2O) in the weathered catchment soil indicating deep weathering has occurred removing much of the plagioclase which is less resistant to weathering. The relatively higher concentration of K-feldspar and the accumulation of quartz (SiO_2) suggest granite as the parent material.

Within the valley bottom, XRF results of total elements show that the soils are layered at the 1st and 2nd headcuts (1ST HCT and 2ND HCT). This is evident in Table 6.3 where three layers can be observed immediately upstream of the 1st headcut at depths 0 - 120 cm, 120 - 160 and 220 - 435 cm; and all through the 2nd headcut profile.

Table 6.1 XRF results of the dolerite boulder from topslope, north-west of the study area.

Sample	**SiO_2%**	**Al_2O_3%**	**Fe_2O_3%**	**TiO_2%**	**MnO%**	**MgO%**	**CaO%**	**Na_2O%**	**K_2O%**	**P_2O_5%**	**L.O.I%**
Outer Rim	32.30	19.51	22.21	2.66	0.25	3.22	0.98	0	0.35	0.27	17.88
Inner Rim	43.08	16.19	20.03	2.21	0.22	4.75	4.05	1.76	0.97	0.26	6.02
Core	48.51	13.15	15.80	1.76	0.23	5.39	8.43	2.28	0.97	0.34	2.51

Table 6.2 XRF results of parent materials from selected sites at Craigieburn.

SAMPLE	**SiO_2%**	**Al_2O_3%**	**Fe_2O_3%**	**TiO_2%**	**MnO%**	**MgO%**	**CaO%**	**Na_2O%**	**K_2O%**	**P_2O_5%**	**L.O.I%**
Right Topslope (granite)	73.47	15.00	2.64	0.40	0.01	0.62	0.04	0.03	4.54	0.03	3.52
Valley Bottom (dolerite)	65.60	17.57	3.92	0.53	0.05	0.95	1.79	3.77	1.30	0.03	4.53
Hill Top Rock (granite)	71.37	15.98	2.63	0.29	0.07	0.90	0.04	0.20	5.63	0.03	3.09
Hill Top Saprolite (granite)	68.87	17.75	2.84	0.34	0.01	0.69	0.03	0.00	3.33	0.03	6.36

Table 6.3 Total element analysis by XRF of weathered catchment and valley-bottom materials at selected sites, Craigieburn.

SAMPLE	**SiO_2%**	**Al_2O_3%**	**Fe_2O_3%**	**TiO_2%**	**MnO%**	**MgO%**	**CaO%**	**Na_2O%**	**K_2O%**	**P_2O_5%**	**L.O.I%**
1ST HCT 0 -10	74.33	12.33	2.36	0.44	0.01	0.29	0.10	0.33	1.67	0.04	7.64
1ST HCT 10 - 40	84.09	8.10	1.60	0.47	0.00	0.21	0.06	0.27	1.26	0.03	4.19
1ST HCT 50 - 90	81.59	9.32	2.10	0.39	0.01	0.18	0.09	0.50	1.51	0.03	4.57
1ST HCT 90 -120	84.09	8.04	1.68	0.34	0.01	0.18	0.27	1.14	1.41	0.02	2.78
1ST HCT 120 - 145	72.43	14.07	3.70	0.49	0.01	0.32	0.40	1.25	1.63	0.03	5.73
1ST HCT 145 - 160	62.24	19.19	5.31	0.77	0.01	0.53	0.18	1.13	1.95	0.04	8.82
1ST HCT 220-230	48.25	30.79	3.47	0.63	0.02	0.65	0.07	0.29	1.68	0.03	13.93
1ST HCT 230 - 320	47.49	30.77	3.99	0.61	0.02	0.82	0.09	0.47	1.68	0.03	13.62
1ST HCT 320-435	46.64	30.58	4.67	0.61	0.04	0.67	0.05	0.21	1.58	0.03	14.80
2ND HCT 0 - 70	70.17	13.04	4.84	0.57	0.03	0.21	0.12	0.37	0.82	0.06	9.73
2ND HCT 70 - 80	53.61	21.52	5.85	0.96	0.04	0.35	0.30	0.47	1.39	0.09	15.54
2ND HCT 80 - 110	89.40	5.28	1.03	0.22	0.00	0.06	0.23	0.89	1.34	0.01	1.64
2ND HCT 140 - 160	60.88	18.98	3.80	0.89	0.03	0.62	0.42	1.24	1.84	0.06	11.62
2ND HCT 160 - 170	84.79	7.65	1.36	0.31	0.01	0.35	0.22	0.92	1.29	0.02	3.29
CS1.6 0 - 25	71.31	13.65	2.85	0.50	0.01	0.45	0.04	0.40	2.00	0.04	8.86
CS1.6 25 -37	69.93	15.34	3.03	0.38	0.00	0.46	0.02	0.46	2.12	0.03	8.31
CS1.6 37 - 150	63.39	20.14	3.43	0.42	0.01	0.56	0.03	1.10	3.00	0.03	8.05
CS2.2 0 - 20	69.66	14.87	2.47	0.42	0.04	0.58	0.43	1.69	3.04	0.04	7.17
CS2.2 20 - 34	68.68	16.29	2.92	0.53	0.03	0.71	0.61	2.02	2.71	0.02	5.78
CS2.2 34 - 59	84.70	7.18	2.51	0.34	0.01	0.32	0.18	0.85	1.93	0.01	2.17
CS2.2 59 - 150	76.95	11.18	3.06	0.32	0.02	0.42	0.26	0.90	2.43	0.02	4.41
CS3.1 0 - 13	72.07	14.01	2.71	0.65	0.01	0.24	0.15	0.41	1.16	0.03	8.80
CS3.1 13 - 60	55.68	22.86	4.93	0.56	0.02	0.40	0.09	0.24	1.01	0.04	14.44
CS3.1 60 - 150	56.06	24.24	5.01	0.55	0.02	0.58	0.04	0.18	0.94	0.03	12.53
CS3.2 0 - 18	87.13	9.52	0.62	0.62	0.00	0.05	0.11	0.23	1.00	0.01	3.23
CS3.2 18 - 63	86.32	7.56	0.91	0.61	0.00	0.07	0.14	0.31	1.07	0.01	3.37
CS3.2 63 - 150	75.37	14.25	1.31	0.60	0.01	0.14	0.18	0.53	1.26	0.00	6.46
CS4.3 0 - 27	79.37	10.50	1.35	0.46	0.01	0.09	0.86	2.07	1.17	0.01	4.52
CS4.3 27 - 53	82.09	9.54	0.75	0.57	0.00	0.15	0.71	1.78	1.73	0.01	2.73
CS4.3 53 - 109	72.49	14.46	1.79	0.66	0.00	0.21	0.84	1.84	1.20	0.01	6.61
CS4.3 109 - 159	77.89	12.03	0.92	0.52	0.01	0.03	1.08	3.10	2.43	0.01	2.19

Note

1. In Table 6.3, 1ST HCT: 1st headcut, 2ND HCT: 2nd headcut, CS1.6 0-25: Craigieburn section 1, sample 6 at the depth of 0-25 cm, ... *etc*.
2. Sites were selected based on their position on the landscape (land unit), soil type and their vulnerability to erosion. For example, CS1.6 (Glenrosa) and CS3.1(Hutton) are found on topslopes, CS4.3 (Katspruit, midslope-valley bottom), CS3.2 (Kroonstad, duplex soil, midslope-valley bottom), CS2.2 (Dundee, valley bottom depositional soil), 1st HCT (eroding gully at 1st headcut upstream) and 2nd HCT (eroding gully at 2nd headcut, downstream).

An exception is in the valley bottom downstream of the lower headcut (Figures 3.4 and 3.5), where weathering of the dolerite parent rock appears to be in the intermediate stage. This is shown by its higher content of Ca and Na in comparison to K (Table 6.2).

6.5.2. Exchangeable bases and exchangeable sodium percentage (ESP)

A previous study by Raw (2003) hypothesized that the study area contains dispersive soils that are responsible for gully development. To test this assertion, soil samples were collected at the two headcuts (1st and 2nd HCT), on their banks (CS4.2 and CS4.3), upstream and downstream of the two gullies; and tested for exchangeable bases. Those up and downstream of the eroding gullies and the adjacent areas (gully banks) were tested for exchangeable bases because these are the most sensitive parts around the gullies under investigation. The results (Table 6.5) reveal that in most samples the exchangeable sodium percentage (ESP) is below the generally suggested threshold (15%) above which a soil is said to be dispersive (Bell and Walker, 2000; Rengasamy, 1998). Though the ESP of some samples measured above the 15% threshold, their pH was below 6 indicating a rather acidic soil that would not be prone to disperse (Bell & Maud, 1994a). However, as discussed earlier (Section 2.3.1) there is no agreement on a standard pH or ESP threshold so that some soils with ESP above 15% do not disperse while others below this threshold disperse, and also that some soils with pH of 5 have been known to disperse.

To resolve this controversy, attention was given to the sodium (Na) content of the total base complex, which is low in comparison to Ca and Mg. A discrepancy exists where the ESP is much higher than the suggested 15% threshold as is the case with the samples highlighted (Table 6.4). The high ESP values which suggest dispersivity do not harmonise with the lower Na content in all selected samples compared to the total of Ca and Mg or Ca, Mg and K (Figure 6.11). In all selected samples Na is lower than the total of the other bases (Ca, Mg and K). The high ESP problem lies in the fact that total exchangeable bases are very low and when this occurs, very low amounts of Na become a large percentage, but does not necessarily imply soil dispersivity. This interpretation is further supported by the low pH of almost all soil samples even at downstream sites (CS3.2; Figure 4.1) that display duplex physical characteristics (Figure 6.12).

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Table 6.4 Exchangeable bases at selected sites in the study area.

	cmolc/kg soil						
Sample	**Calcium**	**Magnesium**	**Sodium**	**Potassium**	**Total bases**	**ESP**	**pH.H$_2$0**
1ST HCT 0-10	1.27	0.80	0.11	0.21	2.39	4.7	4.67
1ST HCT 40-50	0.32	0.21	0.12	0.04	0.69	**18.1**	4.60
1ST HCT 80-90	0.46	0.54	0.11	0.01	1.13	9.9	5.04
1ST HCT 115-120	0.38	0.57	0.13	0.02	1.11	12.0	5.43
1ST HCT 135-145	0.88	1.27	0.20	0.31	2.66	7.43	5.26
1ST HCT 150-160	0.89	1.25	0.21	0.29	2.63	7.83	5.17
1ST HCT 220-230	0.83	1.32	0.22	0.04	2.41	9.28	4.96
1ST HCT 235-245	0.50	0.84	0.19	0.02	1.54	12.3	4.61
1ST HCT 320-435	0.44	0.80	0.16	0.02	1.41	11.3	4.68
CRVS2 0-10	0.84	1.27	0.18	0.16	2.45	7.37	4.91
CRVS2 40-50	0.26	0.50	0.13	0.02	0.91	14.2	5.26
CRVS2 90-100	0.52	1.03	0.15	0.00	1.69	8.67	5.35
CRVS2 140-150	0.19	0.48	0.09	0.03	0.79	11.5	5.38
CRVS2 170-180	0.05	0.17	0.09	0.00	0.32	**28.7**	5.12
CRVS3 0-10	0.39	0.60	0.18	0.06	1.23	14.7	5.26
CRVS3 40-50	0.84	1.22	0.18	0.04	2.28	8.12	5.30
CRVS3 90-100	0.21	0.44	0.15	0.03	0.84	18.0	5.65
CRVS3 160-170	0.12	0.30	0.13	0.00	0.55	24.4	5.15
CRVS3 240-250	1.15	0.24	0.15	0.03	1.57	9.57	5.05
CRVS3 260-270	1.75	0.25	0.21	0.02	2.23	9.46	5.05
CS4.2 0-5	1.45	0.77	0.11	0.09	2.41	4.63	5.18
CS4.2 70-80	4.10	1.87	0.27	0.04	6.28	4.31	6.89
CS4.2 120-130	4.15	1.27	0.23	0.01	5.65	4.03	7.00
CS4.3 0-5	1.21	0.80	0.14	0.15	2.31	6.15	5.47
CS4.3 30-50	1.34	0.52	0.25	0.00	2.11	12.0	5.86
CS4.3 70-90	2.98	1.29	0.26	0.02	4.54	5.68	7.58
CS4.3 130-150	1.88	0.57	0.28	0.00	2.73	10.1	7.89
CRVS4 0-10	0.65	0.67	0.15	0.03	1.51	10.3	5.20
CRVS4 40-50	0.21	0.32	0.15	0.01	0.69	**22.5**	4.88
CRVS4 100-150	0.34	0.37	0.25	0.00	0.96	**26.0**	5.11
CRVS4 190-200	3.00	1.75	0.26	0.03	5.04	5.21	5.33
CRVS4 290-300	2.01	1.22	0.29	0.01	3.53	8.27	5.85
CRVS5 0-10	0.52	0.62	0.17	0.04	1.35	12.5	4.91
CRVS5 40-50	0.36	0.46	0.19	0.06	1.07	**17.8**	4.64
CRVS5 60-70	0.32	0.45	0.16	0.02	0.95	**17.2**	4.82
CRVS5 90-100	1.04	1.13	0.17	0.00	2.33	7.18	5.45
CRVS7 0-10	0.71	0.87	0.14	0.16	1.88	7.55	5.36
CRVS7 40-50	0.21	0.30	0.15	0.01	0.67	**22.3**	4.41
CRVS7 90-100	0.34	0.52	0.23	0.00	1.09	**21.5**	4.53
CRVS7 180-190	0.33	0.52	0.24	0.02	1.11	**21.4**	4.77
CRVS7 240-250	0.13	0.30	0.20	0.03	0.64	**30.7**	4.76
BL HCT2 0-10	0.62	0.35	0.18	0.02	1.17	**15.8**	5.03
BL HCT2 20-40	0.83	0.37	0.24	0.08	1.52	**15.9**	5.01
BL HCT2 40-60	0.59	0.48	0.18	0.09	1.33	13.9	6.39
BL HCT2 130-150	0.93	0.66	0.28	0.01	1.86	14.8	5.50
BL HCT2 200-210	1.33	0.81	0.18	0.03	2.36	7.85	5.92
2nd HCT DP 40-50	1.37	0.62	0.24	0.08	2.31	10.3	4.60
2nd HCT DP 70-110	3.75	1.42	0.31	0.02	5.50	5.55	6.00
2nd HCT DP 120-136	0.27	0.24	0.19	0.04	0.74	**26.2**	5.30
2nd HCT DP 150-160	1.51	0.77	0.22	0.01	2.51	8.74	5.30
2nd HCT DP 160-170	0.36	0.27	0.23	0.00	0.87	**26.8**	4.90
2nd HCT DP 170-180	1.14	0.86	0.18	0.05	2.22	7.94	5.20

Note: In Table 6.3, 1ST HCT 0 – 10: 1st headcut at depth 0 – 10 cm , CRVS2 0-10: Craigieburn valley cross-section 2 at depth 0 – 10 cm, BLHCT2 0 -10: Below 2nd headcut at depth 0 – 10 cm; 2ND HCT: 2nd headcut, CS4.2 0 - 5: Craigieburn cross-section 4, sample 2 at the depth of 0 - 5 cm.

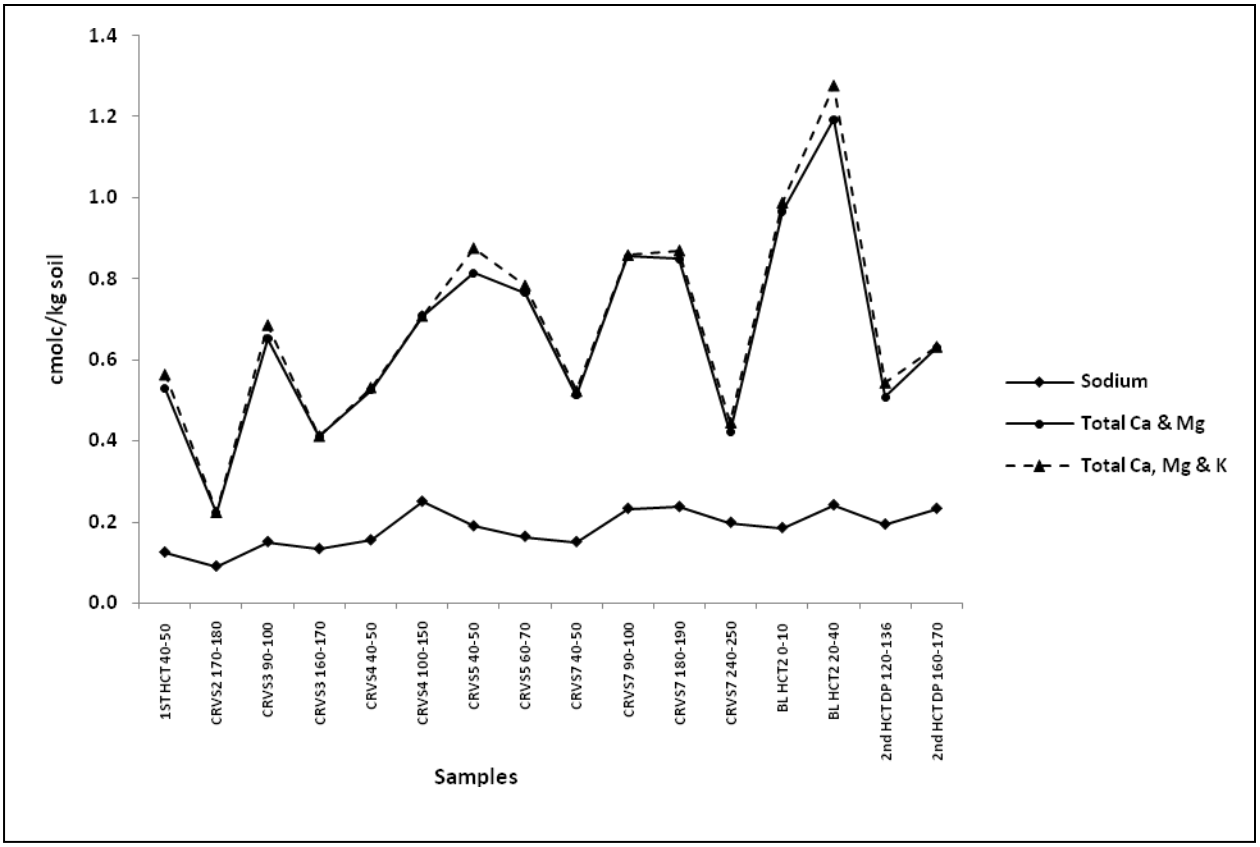


Figure 6.11 Comparison of sodium and other bases in selected soil samples at Craigieburn.

Some duplex soils have been cited as having higher exchangeable sodium, and are thus more erodible than non duplex soils (Seitlheko, 2003). Raw (2003) suggested that soils downstream in the study area with duplex characteristics may be dispersive and thus erodible. The analysis of exchangeable bases (low Na content) and low pH values (< 6) in suspected sites including areas with duplex soil morphology does not support the soil dispersivity hypothesis at Craigieburn. Rather, the duplex characteristic at observed sites relates to a sandy upper horizon superimposed on clayey and less permeable subsoil. Evidence is provided by particle size analysis with particular attention to the site depicted (Figure 6.12), where the percentage sand and clay of the surface horizon is 84% and 11%, respectively (Appendix 6.1) compared to the clayey sub-horizon with lower percentage sand (61%) and increased clay content (36%).

Figure 6.12 The duplex characteristics of a downstream soil form (Kroonstad – CS3.2) at Craigieburn. CS3.2: Craigieburn section 3.2.

This contrasting pattern of particle size distribution between the A and B horizon which is indicative of a duplex soil form is also found at site CS1.3 upstream close to the catchment head and downstream at site CS4.1a close to the catchment mouth. Further evidence of their duplex nature is the hardened subsoil horizons or hardsetting characteristic (Cochrane et al., 1994) when exposed to sun by surface erosion and abrupt textural boundary. All three sites are located within the valley, close to the main and adjacent gullies and are of the Kroonstad soil form. The origin of duplex soils at site CS3.2 appears to be the deposition of coarser grained colluvium that has moved downslope over the finer material (Phillips, 2001). A similar morphology has been identified in the Sydney Basin, Australia (Bishop et al., 1980) and in Western Australia, where sandy materials stripped upslope from deeply weathered mantles were deposited on a footslope clayey saprolite, resulting in a strong textural contrast between the A and the B horizon (Chittleborough, 1992; Oertel & Blackburn, 1969). At sites CS1.3 and CS4.1a, their occurrence is due both to deposition as mentioned before and also probably to inheritance from weathered parent material (Paton et al., 1995; Phillips, 2007) as the geology of these sites (Section 3.4) are believed to be granite (which weathers into more sandy material) overlying dolerite (which weathers into more clayey material). It is probable that at some locations within the study area where duplex soils previously occurred, especially those areas bordering the gully, the coarser surface layer has been stripped leaving behind the relatively finer textured subsoil, which in some cases is currently undergoing fresh surface deposition. This appears to be the case at sites CS3.3 (Katspruit), CS4.3 (Katspruit) and CS5.3 (Katspruit).

Despite the presence of duplex soils at Craigieburn, they are not directly related to gully erosion and development in the wetland system in recent years. The downcutting and gullying has occurred in valley fill while erosion along some duplex soils has been occurring not within the wetland system but towards the upslope area adjacent to the main valley. While no duplex soil was identified along the eroding section of the wetland system, two arguments can be advanced in favour of their contribution to wetland gully erosion. Firstly, erosion, transportation and deposition of soil material from the adjacent duplex soils have contributed to a raised valley floor gradient resulting in gully erosion at Craigieburn. Secondly, it is probable that the existence of duplex soils within some parts of the valley may have been a major initiating factor of the gully in the distant past, a claim that is supported by the occurrence of these soils in the valley bottom adjacent to the present gully. In addition to this hypothesis, it appears that the valley in general was initially cut through weathering bedrock by fluvial erosion in the geological past during periods of regional uplift and base-level fall (Fair & King, 1954; King, 1955; Matmon et al., 2002; Moon & Dardis, 1988; Ollier et al., 1985) and then later filled progressively during long periods of tectonic stability. However, in the past decades, these fills have been eroding at weak points, mostly the sandy layers at depth. Thus, the underlying fragile sandy layers are undercut by knickpoint erosion resulting in the collapse of the overlying, more coherent material.

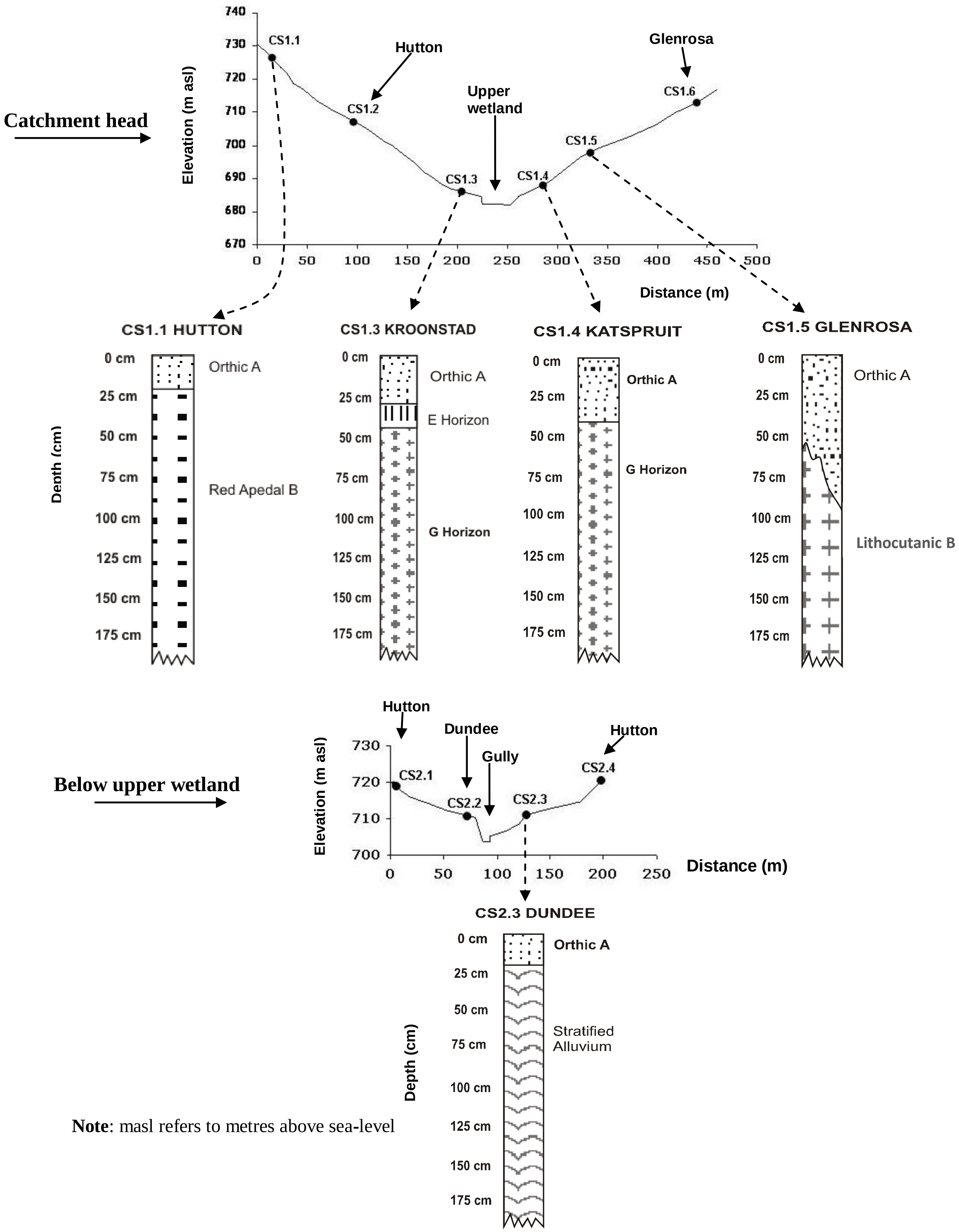
6.6. Pedogenesis at Craigieburn

Soils at Craigieburn were classified using the South African taxonomic system (Soil Classification Working Group, 1991). Figure 6.13 shows the location of each soil type in relation to catchment slope profile. The slope summits are generally characterized by Hutton, a strongly weathered soil characterized by a deep red apedal B horizon indicative of oxidation. Exceptions occur on some steeper valley slopes where the thick, red apedal B horizon is replaced by a highly variegated soil material interspersed with saprolite or weathering rock in various stages of breakdown (a lithocutanic B horizon; Glenrosa form). While the mid-slope bears no distinctive pattern of soil type, the bottom slopes are mostly Kroonstad and Katspruit. These soil forms contain signs of prolonged or seasonal saturation in the past, though they are drained at present and extremely hard when dry. Their gleyed and bleached appearance together with mottling are imprints of once flooded conditions which resulted in net removal of iron oxides, and organic matter by reduction and/or lateral water flow and some subsequent oxidation as the water level retreated. As such, these bottom slope soils are the best indicators of the previous extent of the Craigieburn wetland. The valley floor comprises of the Dundee soil form characterized by distinctive fine – medium sand stratifications (no evidence of buried soil). It is a depositional soil that has been cut into a series of terraces that occur on the valley sides as evidence of past cyclical erosion processes. The generalized spatial pattern of soil distribution at Craigieburn is presented in Figure 6.14 and representative profile descriptions for all sample sites are given in Appendix 4.1.

6.7. Discussion

The geological map (Geological Survey, 1986) identifies two geological formations in the study area, granitoid (Barbarin, 1999; Rizaoglu et al., 2009), and dolerite, both intrusive igneous rocks. This was verified by field observation of rock outcrops, soil pits and by augering the weathering bedrock. That XRD results portray the abundance of quartz, feldspar (mostly orthoclase) and kaolin further testify to the granitic and dolerite origin (Ollier, 1984). Feldspar is not only a primary rock mineral for some granites but also of dolerite together with quartz, minerals which were found both in weathered material and parent rock in the study area. With the exception of quartz, strong weathering reduces these primary minerals to clays, mostly kaolin. The dominant weathering process in buried granite and dolerite is hydrolysis, a process during which hydrogen ions from water replaces cations in minerals thus weakening the rock fabric (Duchaufour, 1982; Marsh & Dozier 1981; Ollier, 1975; Small & Clark, 1982; Strahler & Strahler, 2006). This is likely to be the bedrock weathering process in the study area favoured by the hot, humid summers, an average annual precipitation of about 1000 mm and daily maximum temperatures ranging from 26^{o}C in winter to 33^{o}C in summer (Raw, 2003).

X-ray diffraction analysis of the dolerite parent rock, catchment soils, and the partially weathered hilltop and valley materials display similarities in mineralogy and chemistry, lending support to the argument that the overlying saprolite and soils are largely products of in-situ weathering even though the original parent material may have been of exotic origin (Section 6.2 and Figure 6.7). An example that underpins this hypothesis is a comparison of weathered (Figure 6.1) and fresh dolerite XRD (Figure 6.6) results showing a similarity in mineralogy and an increase of some minerals (notably kaolin) in the weathered profile as other minerals decompose. Additional evidences suggesting in-situ weathering within the catchment in general are the existence of quartz veins, partially weathered parent granite, rock joints and the in-situ outlines of the original rock fabric still evident in the weathered regolith (Section 6.2).



Note: masl refers to metres above sea-level

Figure 6.13 Location of representative soil profiles along selected cross-sections of the Craigieburn catchment.

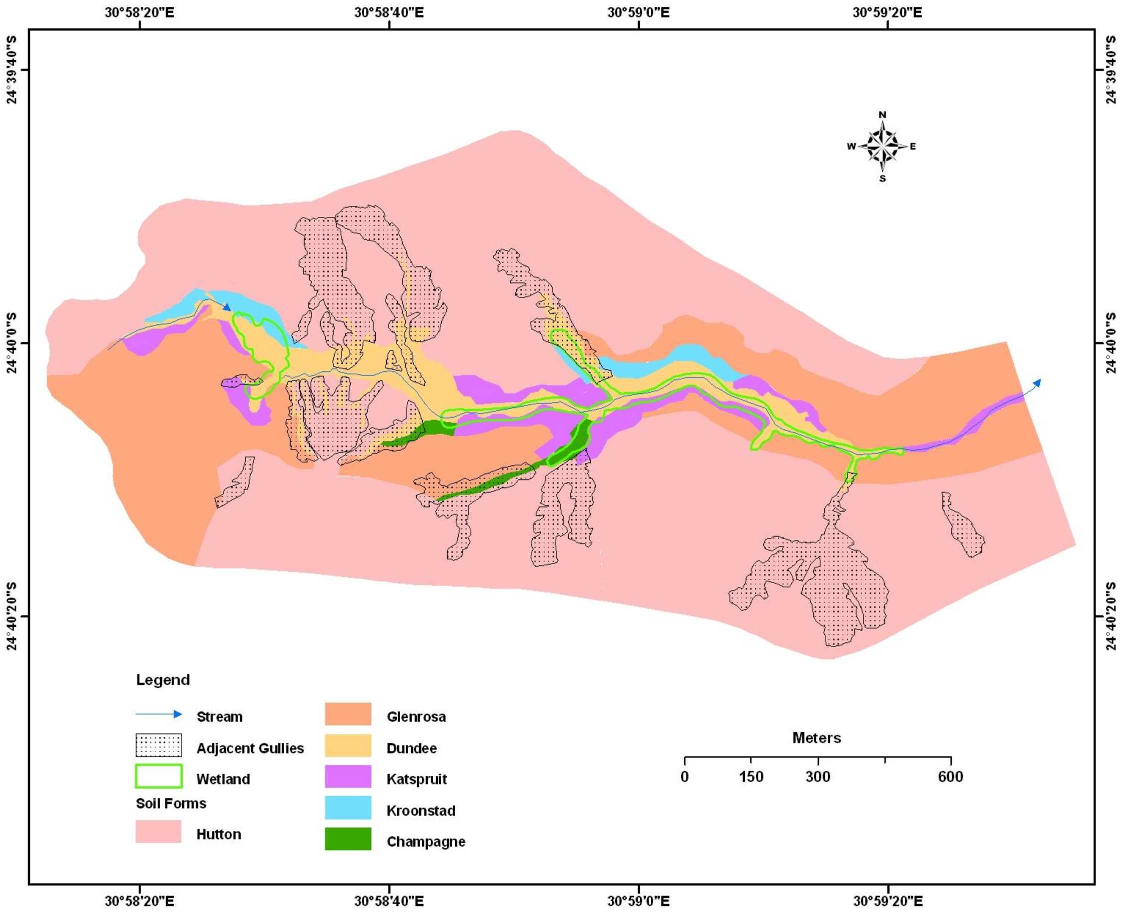


Figure 6.14 Generalized spatial distribution of soils at Craigieburn based on the Soil Classification Working Group (1991).

Supporting this conclusion are XRF results and the particle size distribution. The XRF of weathered catchment soils also display similarities in soil chemistry to either the fresh dolerite rock or partially weathered granitic material selected at different locations in the study area. This can be verified by comparing the XRF results of the fresh dolerite rock (Table 6.1) and partially weathered valley bottom dolerite material (row 2 in Table 6.2), both containing more plagioclase and less K-feldspar. In contrast, a comparison of the weathered catchment soils (Table 6.3) and the granite parent material (rows 1, 3 and 4 in Table 6.2) reveal that K-feldspar and quartz dominate over plagioclase. That weathered catchment soils and parent material display such similarities engenders the belief that catchment soils at Craigieburn are probably not of external origin but have developed in-situ from weathering parent rock (although the original parent material may be of external deposition as explained earlier). This contrasts with the layered pattern of soil profiles immediately upstream of the 1st and 2nd headcuts (Table 6.3), which reveal episodes of colluvial and alluvial deposition by the Manalana stream and overland flow.

High clay content (40-77%) in some topslope profiles notably CS1.1, CS2.1, CS3.4 CS4.4 and CS5.1 and the dominance of kaolin suggests deep weathering and an advanced stage of soil development. Stripping in the midslopes and deposition in the valley explains the predominance of sand in these sections of the slope profile. Clastic sediments eroded from the catchment are deposited in the low lying areas explaining why the valley bottom at Craigieburn is dominated by sand. This inherent geomorphological process is substantiated by results of particle size distribution within the Craigieburn wetland valley (Section 6.4), field observation of colluvial deposits and the soil distribution pattern. For example, the Hutton soil forms, occupying the topmost part of the catchment in the north-west of the study area, seem to have been subjected to less erosion probably due to the low gradient, vegetative cover and surface roughness provided by the protruding rock boulders. This is in contrast to the midslope, which has undergone stripping (Ollier, 1974; Ollier, 1975; Osok & Dolye, 2004) facilitated by a steeper gradient; hence the development of the shallow Glenrosa soil forms. The valley bears the imprint of a once large wetland which has shrunk to its present size. Evidence for this resides in the gleyed and bleached appearance of the soils about 2 -3 m above the present river flooding level and about 8 - 10 m away from the present channel, reflecting once flooded conditions. The presence of dried mottles in these valley soil profiles is the result of oxidation as the wetland receded; hence the development of the Katspruit and Kroonstad soil forms.

A key question in this study is what has caused soil failure and wetland erosion at Craigieburn? Results of soil analysis to answer this question are still open to different interpretations considering the existing debate on the true threshold value that defines a sodic and dispersive soil (Bell & Maud, 1994a; Bell & Maud, 1994b; Bell & Walker, 2000; Chartres, 1993, Cochrane et al., 1994; Doyle & Habraken, 1993; Elges, 1985; Gerber and Harmse, 1987; Rengasamy, 1998; Richards, 1954; Seitlheko, 2003; So & Alymore, 1993). However, soil pH values which are generally much less than 7 and the very low concentrations of exchangeable Na in comparison to Ca and Mg, strongly suggest that soil dispersivity is not the main cause of gully erosion at Craigieburn.

Weathering has been identified as a major factor in slope instability as it reduces effective cohesion (Cooke & Doornkamp, 1974). Studies by Palacios et al. (2003) in Spain have also shown that slopes overlain by thick weathering mantles developed from granites are very susceptible to debris flow and channeling. That no clearly dispersive soils were identified in the study area prompts the conclusion that the scars adjacent to the main valley relate to deep weathering, slope instability and subsequent incision of the valley fill debris in the manner of Cooke and Doornkamp (1974) and Palacios et al. (2003).

6.8. Conclusion

A previous suggestion that soils at Craigieburn are dispersive has not been confirmed in this study. This conclusion is supported by the low soil pH (< 6 at most sites), the lower Na : Ca and Mg ratio at all sites. Therefore soil and wetland erosion at Craigieburn is not driven by soil dispersivity but by deep weathering of the catchment dolerite and granite parent rocks and the subsequent soil failure by gravity especially during wet periods. This conclusion is supported by X-ray diffraction and X-ray fluorescence analyses which clearly show that the study area catchment is deeply weathered. Evidence is provided by the presence of kaolin, the absence of biotite, low plagioclase, the higher SiO_2, TiO_2, Fe_2O_3, and Al_2O_3 in the selected samples. Further proof of deep weathering is supplied by results of particle size analysis which shows clay-dominated soils on the topslopes (See CS1.1, north-west of the study area) and sandy midslope soils, reflecting dolerite and granite, respectively. Sediments, mostly the clastic fractions washed down from the weathered slopes, have accumulated in the valley and are responsible for the oversteepened valley floor gradient (Chapter 7).

CHAPTER SEVEN

NATURAL PROCESSES, WETLAND ORIGIN AND GULLYING AT CRAIGIEBURN

7.1. Introduction

Contemporary wetland gullying has and continues to be often blamed on poor management and insensitive human activities adjacent or within wetlands leading to their degradation, erosion and loss (Bryan, 2000; Knox, 2001; Miles et al., 2001; Poesen et al., 2003; Whitlow, 1992; Whitlow, 1994). This has been the prevailing conception about wetland erosion at Craigieburn to the neglect of natural factors including climate change and geomorphic processes. While the causes of wetland erosion remain debatable, studies have proven that long term geomorphic changes can initiate gullying independent of human activities.

7.2. Geomorphic origin of the Craigieburn wetland system

Past geomorphic processes and the study area morphology provide insight into the origin and evolution of the wetlands. Major factors responsible for the origin of a wetland include surplus water, low gradient and the presence of a geomorphological or geologic barrier (Goudie & Thomas, 1985; Grenfell, 2007; Marshall & Harmse, 1992; Mitsch & Gosselink, 1993; Nahm et al., 2006; Shin, 1983; Tooth et al., 2004). The study area has high average summer monthly rainfall (±170 mm) which together with subsurface storage supplies the water that sustains the wetland system. Sediment, washed into the valley and transported downstream caused localized raised valley floor gradient within the wetland system, creating an upstream damming effect due to the lower gradient which provide a "platform" for reduced flow and wetland creation. The wetland basin is saucer-like suggesting that after deep weathering, the catchment head denuded differentially along lines of weakness fanning the material into the valley. This geomorphic process has been aided by the flow of weathered material from catchment slopes into the valley, creating a "bottle-neck" morphology; damming flow upstream resulting in wetland formation (Figure 7.1). This hypothesis is supported by site evidence and successive aerial photo observation and interpretation that show catchment scars of earthflows and valley damming.

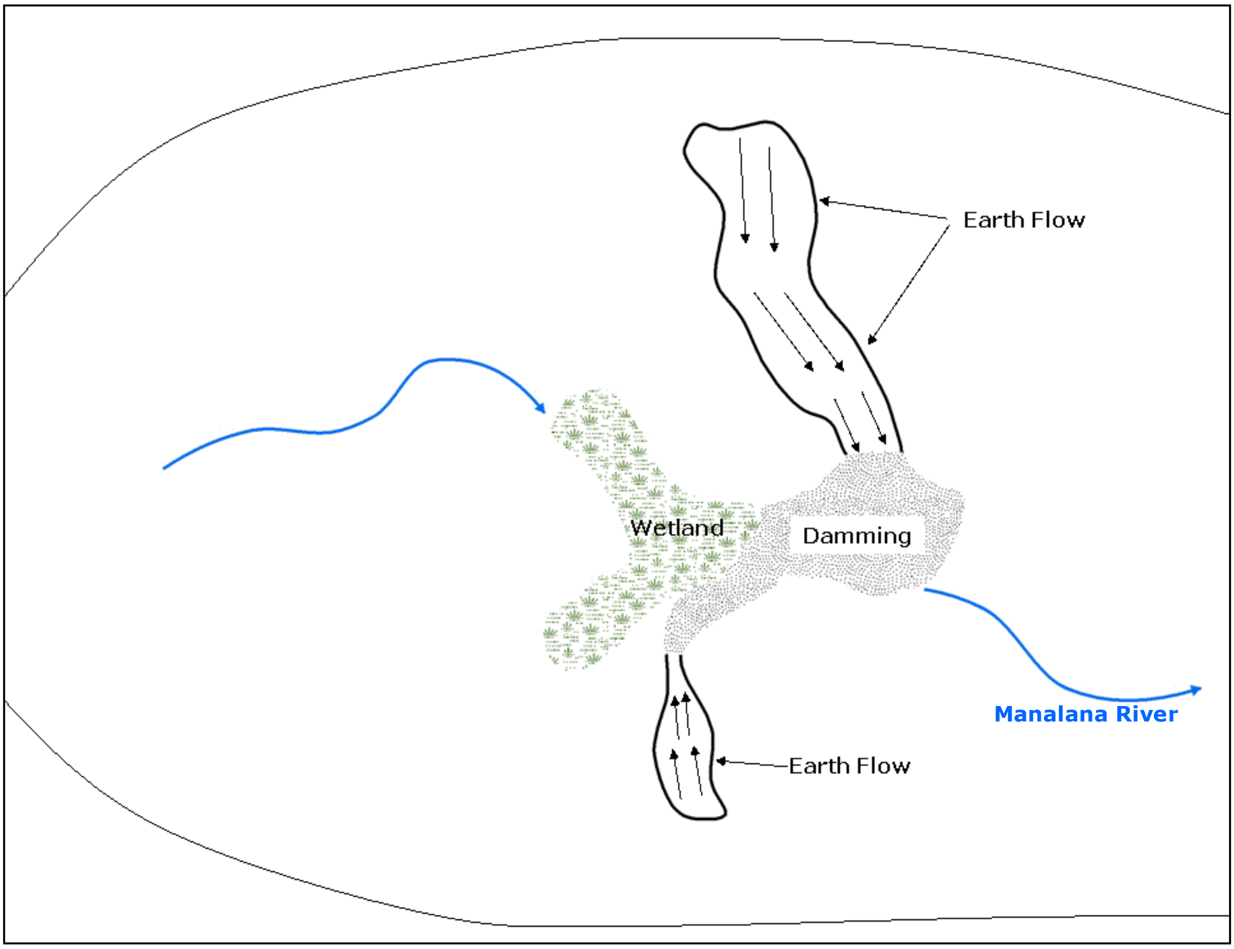


Figure 7.1 Earthflow and wetland creation at Craigieburn.

A conceptual model for wetland creation at Craigieburn (Figure 7.2) shows the interplay of its formative processes. It combines atmospheric processes including precipitation, sub-surface and groundwater inflow close to or intercepting the surface during summer, the geomorphological processes of weathering and the resultant earthflow damming the valley and leading to low valley head gradient. There is also a possibility of a clay plug at the upper wetland, precipitated from materials washed into the valley (Ellery pers. comm, 2007; Riddel 2009). Result of particle size analysis in the wetland valley immediately upstream of the upper headcut show 25- 58% clay content. If this is part of the suggested clay plug, then it may have contributed to wetland formation and retarded headward migration of the upper gully.

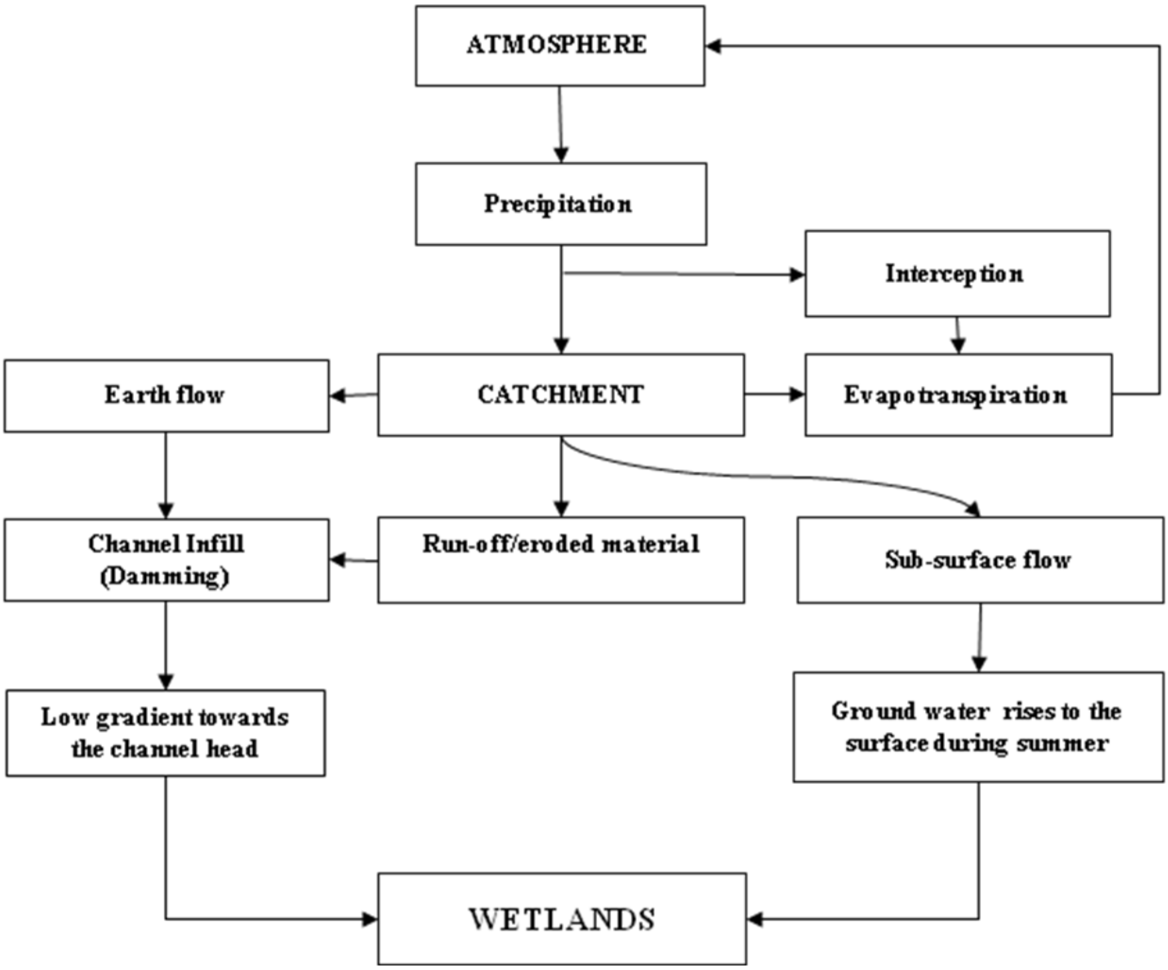


Figure 7.2 A model of wetland origin at Craigieburn.

7.3. Geomorphic processes and wetland erosion at Craigieburn

Wetland erosion at Craigieburn is a result of intrinsic and extrinsic factors within the catchment. The extrinsic factors refer to those that are external to the wetlands but having the propensity to cause erosion namely human impacts, climate change and local base-level change. Intrinsic factors are those operating within the wetlands (raised valley floor) which can cause erosion independent of external factors. The interactions of those factors which may be responsible for wetland erosion at Craigieburn are included in the erosion model (Figure 7.3). The process begins with in-situ deep weathering which prepares the materials for other processes (natural and anthropogenic). The natural processes are earthflow and long term climate change (cool dry period), which results in low vegetal cover and reduced flow; while the anthropogenic factors are footpaths and animal tracks, dirt roads, overgrazing and poor land uses practices. These processes and factors encourage mobilization of sediments into the valley which raises valley floor gradient to a threshold condition after which erosion begins.

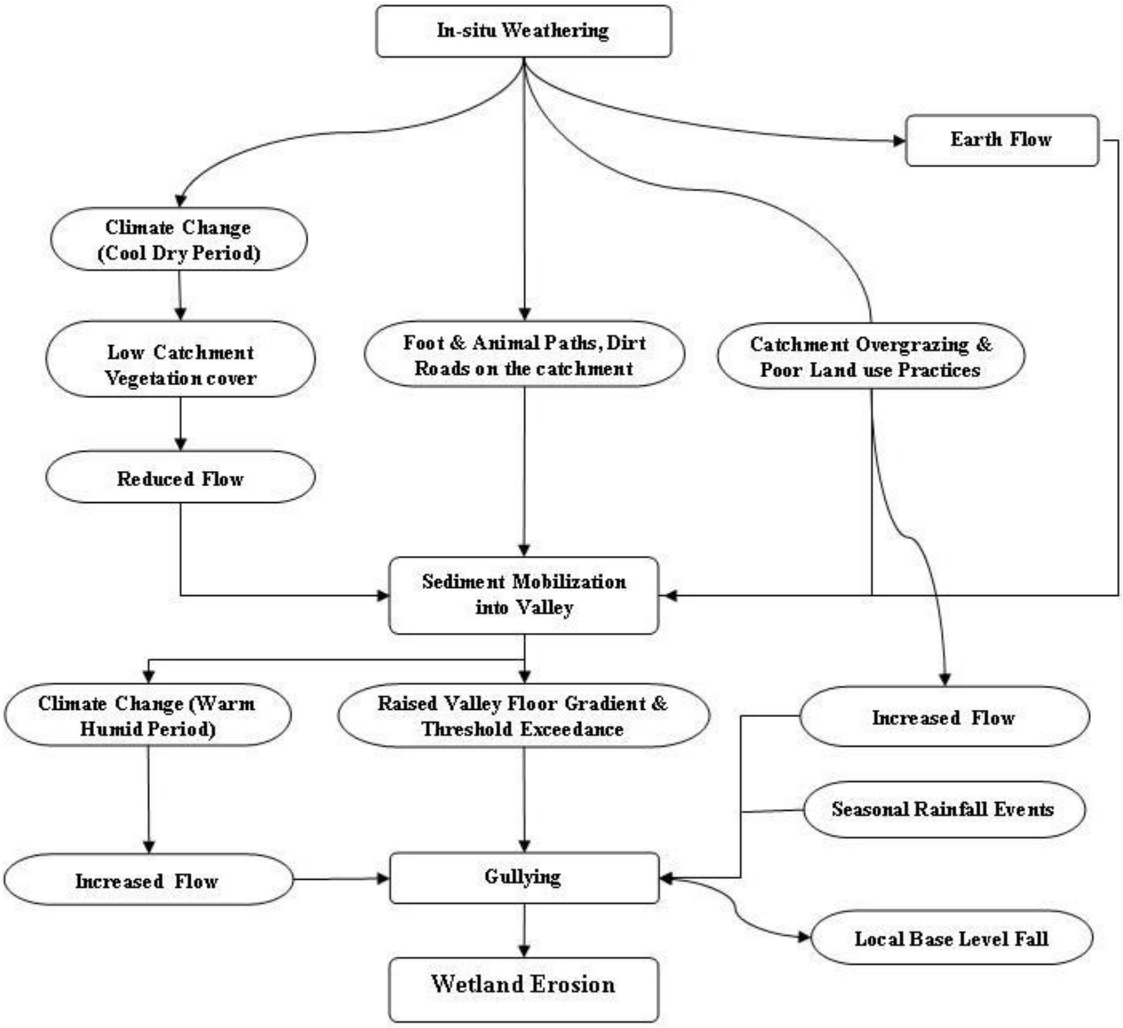


Figure 7.3 An erosion model for wetlands at Craigieburn.

Valley floor erosion may also result from an increase of streamflow during episodic rainfall events or during a long-term wet climate phase (pluvial period), when catchment soils are stabilized by vegetation. Flows during such periods carry less sediment; therefore those deposited in the valley during previous less pluvial periods become vulnerable to erosion. In addition to the processes described, it is likely that at Craigieburn erosion of the lower wetland lowered upstream base-level, leading to further incision of the upper wetland.

One objective of this study was to identify the valley floor threshold gradient above which erosion occurs for the Craigieburn wetlands. The rationale for performing this task stems from the hypothesis that sediment storage within a valley progressively increases the valley floor gradient to a critical threshold above which erosion begins (Schumm, 1979; Schumm & Hadley, 1957). In search for this geomorphic threshold, long profiles of the wetlands (Figures 7.4 and 7.5) were surveyed and the gradient for various reaches determined. In order to investigate the water supply to the wetland system and how this might contribute to wetland erosion, the upper wetland was augered to the water table which is lower in winter (Figure 7.4). This winter water table rises in summer, intersects the toe of the upper headcut and together with in-channel surface flow contributes to knickpoint erosion of the gully.

The valley floor gradient of the eroding section at the upper wetland (Figure 7.4) was surveyed from upstream of the headcut down to the abandoned bank terrace (right and left fill) and it measured 0.0336 which is higher than the sections further upstream and downstream that had gradients of 0.0208 and 0.0167, respectively. At the lower wetland (Figure 7.5), the valley floor gradient just upstream of the lower headcut was 0.0337; higher than the upstream and downstream gradient, which measured 0.0229 and 0.0226, respectively. That the valley floor gradient of the eroding sections of both wetlands is higher than their up and downstream sections is evidence of localized raised valley floor gradient. This supports the hypothesis that downstream deposition and localized raised valley floor gradient within the wetland valley creates incipient instability enabling erosion to be triggered by environmental factors, in this case probably episodic high rainfall events. The valley floor gradients of the two eroding reaches of the wetland system at Craigieburn are almost identical suggesting that the threshold valley gradient for gully erosion to initiate within the system is situated around 0.0336. This threshold gradient for the currently eroding sections could therefore be used as a benchmark for determining reaches within the Craigieburn valley likely to erode (for example 0.0321, further downstream of the upper wetland; Figure 7.4).

The extent of gully erosion at Craigieburn and its effect on the wetland valley is shown by a number of the surveyed cross-sections and profiles (Figure 4.2). Cross-section CS1 reveals a quasi U-shaped morphology at the upper reach of the wetland valley occupied by the first (upper) wetland. Downstream, the gully fill has been incised deeply creating a V-outline (CS2) with the eroded material deposited further downstream on a wider U-shaped basin (CS3). The constricted nature of the valley downstream below this point may well explain why the upstream material has not been flushed from the system and is probably responsible for the formation of the second (lower) wetland. The increased downstream gradient resulting from this damming effect created the propensity for the second gully (CS4) and the headcut found below the lower wetland.

More recently during a site visit in the summer of 2005/2006 (~9 years after the period analyzed in Tables 5.1a and 5.1b) , knickpoint erosion was identified as the main erosion type, where streamflow attacks and cuts into lower layers of valley fills slumping or crumbling the upper layers by gravity, resulting in gully migration laterally and headward (Figure 7.6). Headward migration of the two headcuts was determined by measurements obtained during successive field visits. During three summer months (December 2005-February 2006), the lower headcut migrated a distance of 19 m (an average of 6 m per month) resulting in 554 m^3 of soil scoured. From February 2006 to October 2006 (~ nine months), the upper headcut advanced 30 m headward, an average of 3.3 m per month and 102 m^3 of soil was eroded showing that much of the erosion occurs in summer. Rainfall data from the nearby Wales Station (ICFR, 2005) (decommissioned in 2000) registered 671.8 mm in February 1939 (Appendix 7.1), one of the highest rainfalls around the study area over a century (1908-1999). This is only surpassed by another extraordinary rainfall event 762.4 mm 30 years earlier in January 1909. Other exceptional high rainfall events but of lesser magnitude to the previous two occurred in February 1956 (557.3 mm), January 1976 (591.5 mm), February 1985 (444.8 mm) and February 1996 (448.5 mm). It is thus apparent that the area is characterized by high intensity rainfall events. Additionally, since annual rainfall had been increasing since 1994 at the Wales Station (ICFR, 2005) before its closure in 2000 (Figure 3.5), the upper and lower gully migrations (30 m and 19 m, respectively) from December 2005 to October 2006 in comparison to their relatively slower migrations in the past decades (1954 – 1997, Chapter Five) may be related to increasing rainfall but more likely to short-term exceptional rainfall events. However, further observations with the passing of years would be necessary to be conclusive.

Provenance of the valley fill material that has been repeatedly cut, either by short term high seasonal rainfall events or long term humid periods (characterized by periods of high rainfall), is no doubt the deeply weathered catchment with subsequent erosion of the loose material or mass flow of material into the valley by gravity. Physical evidence of this latter process is the presence of earthflow scars which can be observed on an orthophoto and digital elevation model (DEM) of the study area (Figure 7.7). The DEM was produced using the method outlined in Section 4.2.4 and is an alternative to aerial or orthophotos in representing earthflow scars. This is so because attempts to zoom into the earthflow on an orthophoto results in the loss of its morphology as the image breaks down into pixels, inhibiting proper visualization, whereas the DEM is produced from sampled elevation points above sea-level and at close intervals. The resulting model thus preserves the shape and structure of the earthflow scars. These deep scars provide visual proof not only of material flow into the valley but also provide a basis for judging the extent of deep weathering in the region.

That earthflow as a physical factor may have greatly contributed to wetland erosion at Craigieburn, especially at the lower gully, is supported by results of linear regression and correlation of gully length with earthflow (adjacent gullies) (Table 7.1 and Figure 7.8). There is a significant relationship between earthflows and the lower gully length over time ($p = 0.002$) but not for the upper gully ($p = 0.08$). The adjacent gullies at Craigieburn appear on the 1954 aerial photograph suggesting that their formation took place long before human occupation of the catchment sometime after 1965. This is also supported by Monareng (pers. comm, 2009) a resident of the study area, who said that the adjacent gullies were in existence long before any human settlement on the Craigieburn catchment.

Thus the adjacent gullies appear to have been created by the natural process of weathering and mass transportation of the weathered material into the valley.

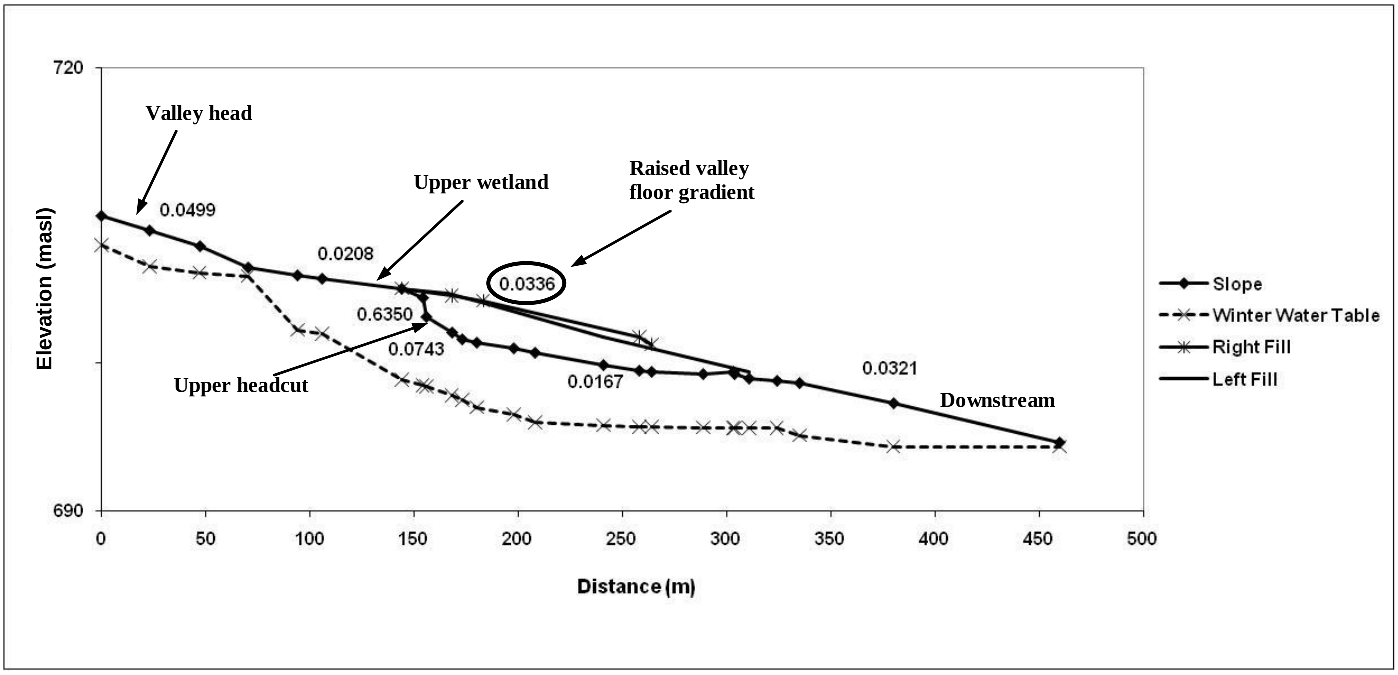


Figure 7.4 Valley floor gradients and winter water table at the upper headcut at Craigieburn.

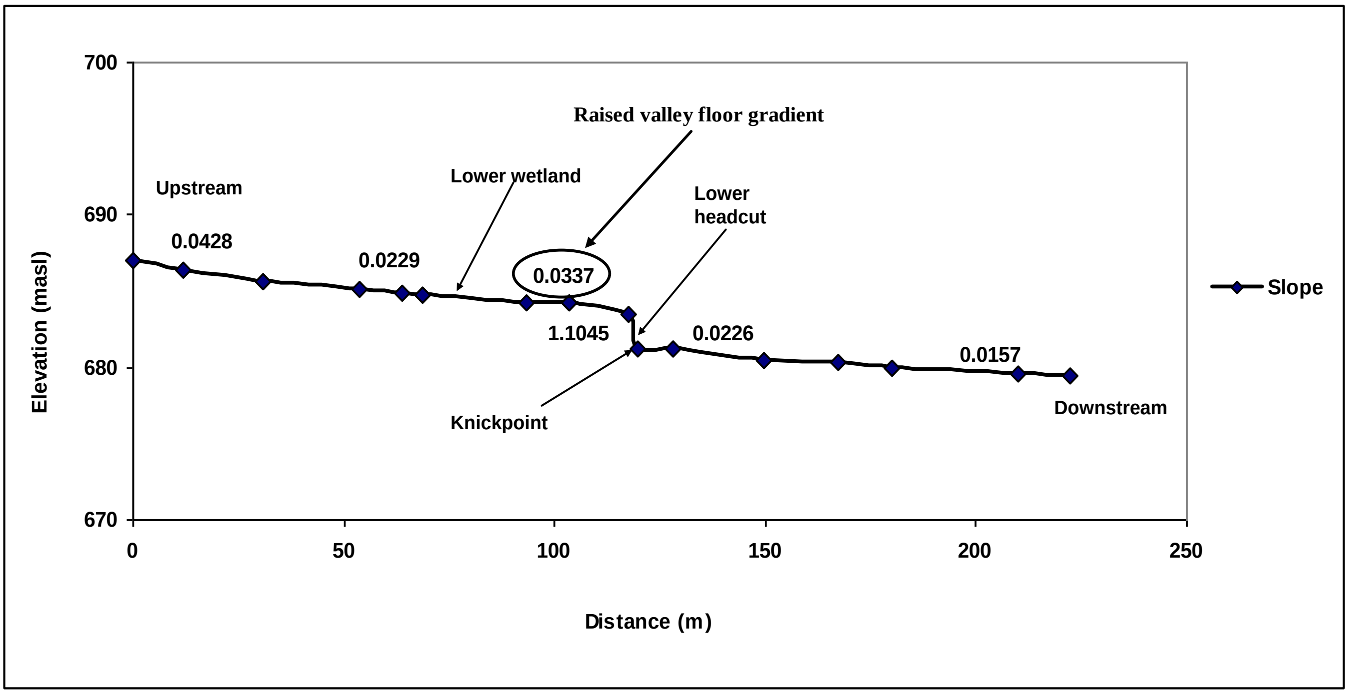


Figure 7.5 Valley floor gradients at the lower headcut at Craigieburn.

Note: masl refers to metres above sea-level

Figure 7.6 Gully migration at Craigieburn – (A) Upper gully, October 2006; (B) Lower gully, February 2006.

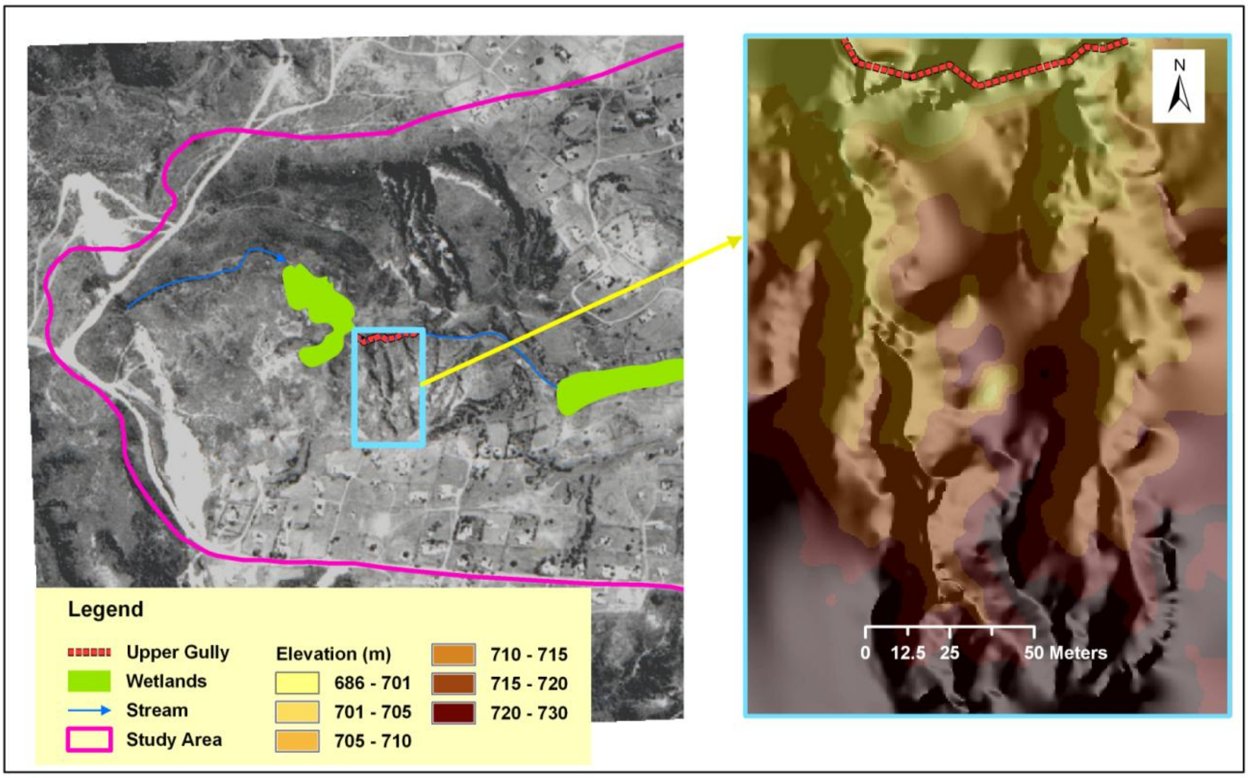


Figure 7.7 Digital elevation model of the upper Craigieburn catchment showing scars of earthflow.

Table 7.1 Relationship between the adjacent gullies# (earthflows) and the upper and lower wetland gully lengths at Craigieburn between 1954 and 1997.

Independent Variable	Main Gully	R^2	Adjusted R^2	Significance (p)
Adjacent Gullies	Upper	0.68	0.58	0.08
	Lower	0.97	0.96	0.002

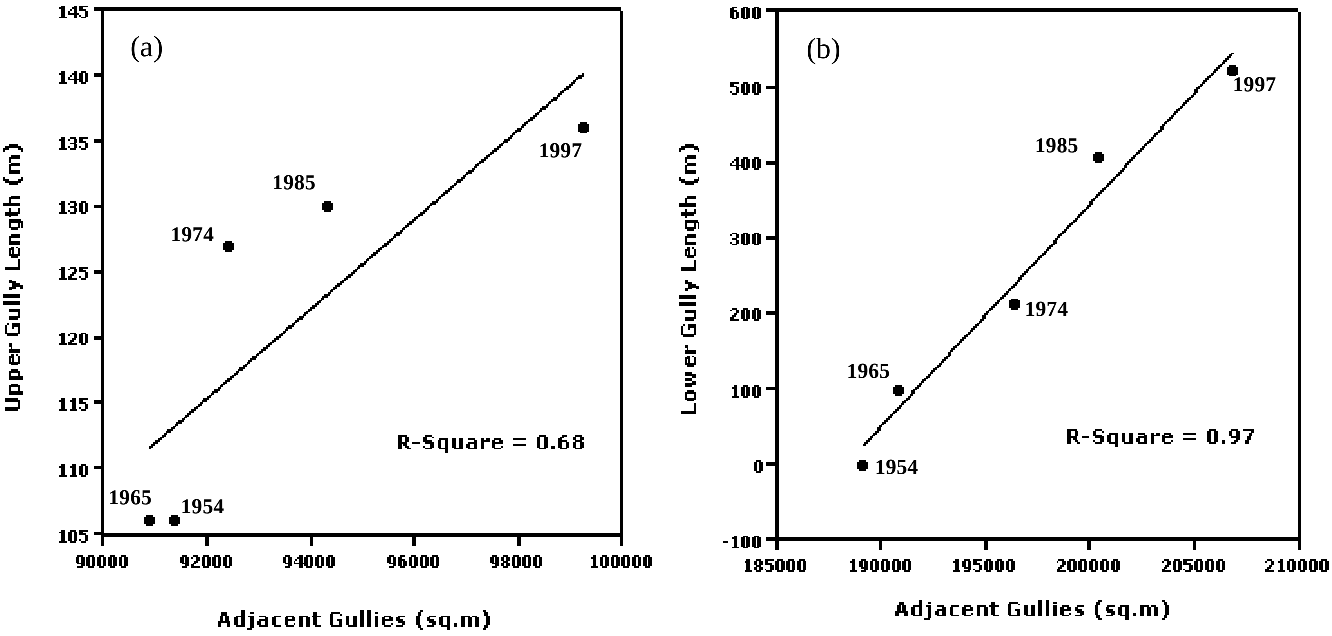


Figure 7.8 Correlation of the area of adjacent gullies (earthflows) to the (a) upper and (b) lower wetland gully length at Craigieburn in 1954, 1965, 1974, 1984 and 1997.

Adjacent gullies in this context are scars left behind by earthflows

7.4. Impact of climate change and geomorphic history on gully erosion at Craigieburn

One research question guiding this study was to what extent has long term climate change contributed to wetland erosion at Craigieburn? The response lies in the current geomorphic features characterizing the two wetlands, namely the current wetland extent, relict soil mottles and the existence of deposition terraces adjacent to the gullies.

7.4.1. Current wetland extent

Erosion of the wetland system at Craigieburn has greatly impacted on their size and spatial extent. The best evidence of previous wetland extent is provided by soil characteristics as it was not possible to obtain aerial photos prior to the 1950s that would have shown the original wetland extent. Augered samples away from the present channel contain dried and preserved mottles together with grayish soil colour, showing that the wetlands once covered a larger area. For example, average measurements at the upper wetland showed that it has shrunk laterally in size 15 m from its current extent.

7.4.2. Contribution of past geomorphic processes

The present landscape of the study area is related to the geological history of southern Africa, part of Gondwanaland (Figure 7.9 A) which broke up in the Cretaceous period (135-65 million years ago). This resulted in the isolation and drifting of the Southern Continents, accompanied by uplift on the African continent (Ollier et al., 1985; Partridge & Maud, 2000; Smith & Briden, 1977). In southern Africa, this uplift mostly affected the eastern part of the continent (Figure 7.9 B) followed by erosion of the marginal areas, leaving behind the resistant Great Escarpment that overlooks the study area (Figure 7.9 C).

After the initial uplift associated with the Gondwanaland break-up, a series of others followed initiating inland headward erosion (Fair & King, 1954; Matmon et al., 2002; Moon & Dardis, 1988; Ollier, 1985) due to the over-steepened, coast-bound gradient produced by the uplifts (King, 1955). Over the millennia, erosional surfaces left behind by the uplifts and the Great Escarpment itself have been pediplained and the latter has retreated from its original position by erosion (King, 1962; King, 1963; Moon & Dardis, 1988).

The low lying area seaward of the Escarpment has imprints of two surfaces ascribed to the Post-Africa I and II erosion surfaces (McCarthy & Rubidge, 2005; Moon & Dardis, 1998; Partridge & Maud, 2000). King (1962; 1963) refers to these as the Post-Gondwana and African surfaces, respectively. These surfaces correspond to episodes of uplift followed by erosion (Moon and Dardis, 1998). That the study area lies seaward of and below the Great Escarpment suggests it may be part of the African surface that is currently undergoing dissection. Evidence for this are the kaolinized weathered profiles that characterize the study area. This corresponds to Moon and Dardis’ (1988) and Partridge and Maud’s (2000) assertion that the African erosion surface is weathered and kaolinized both inland of the Plateau and seaward of the Escarpment.

Despite existing debate surrounding the origin and evolution of the Great Escarpment (Brown et al., 2002; Fleming et al., 1999; King 1955; King, 1963; King, 1972; Matmon et al., 2002; Moon & Selby, 1983; Moore & Blenkinsop, 2006; Ollier 1985; Ollier et al., 1985; Ollier & Marker, 1985; Partridge & Maud, 1987; Van der Beek et al., 2002), its existence to the west of the study area provides a visible background (Figure 7.9 C) against which climatic forces operate and influence the evolution of the Craigieburn wetland system. Moreover, incisions cut through the erosional surfaces abandoned by successive uplifts have produced some of the valley systems occupied by wetlands, one of which is the Craigieburn wetland.

7.4.3. Erosion surfaces and depositional terraces

The importance of erosion and depositional surfaces lies in their role as archives of geomorphic history (Rittenour, 2008). One way of unravelling this history is through environmental dating which plays a key role in environmental reconstruction and the timing of past geomorphic processes (Benito-Calvo & Perez-Gonzalez, 2007; Dewey, 1988; Helgren, 1979; Meadows, 1988; Meadows & Sugden, 1988). Amongst all dating methods (Bierman & Nichols, 2004; Cerling & Craig, 1994; Horiuchi et al., 2004; Migoń & Lidmar-Bergstrom, 2002; Nishiizumi et al., 1993; Schellman & Radtke, 2004), radiocarbon dating remains the leading method to determine the age of terraces (Stokes, 1999). Despite its popularity, the scarcity and age limitation (40 000 years) of organic carbon complicates its applicability to dating depositional terraces (Huntley et al., 1985). An alternative is luminescence dating which targets quartz and feldspar (Chawla et al., 1992; Godfrey-Smith et al., 1988; Stokes, 1992; Stokes, 1999; Wintle, 1985) within the deposit.

The luminescence measured is the energy given off by the sand grains when subjected to heat or light. It is based on the principle that buried sediments absorb and accumulate ionising radiation (energy) from uranium, thorium and potassium, which when heated or exposed to light (luminescence) gives a measure of residence time of the materials and thus the age of the deposit (Chawla et al., 1992; Godfrey-Smith et al, 1988; Huntley et al., 1985; Lian & Roberts, 2006; Lowe & Walker, 1997; Quickert et al., 2003; Richter, 2004; Rittenour, 2008). Stokes (1992; 1999) and Wintle (1985) list some advantages of optically stimulated luminescence dating (OSL) over thermoluminescence (TL) maintaining that OSL dating is more logical in its application to sedimentary deposits because of its ability to more efficiently mimic the actual resetting of events during the past. Both authors (Stokes, 1992; Stokes, 1999; Wintle, 1985) further argue that while buried quartz loses its trapped electrons slowly in TL, sometimes leading to overheating, and hence over-estimation of age, OSL resolves this problem as its laser beam targets quartz with the most light-sensitive electron traps releasing them immediately upon exposure. In addition to these TL setbacks, its dates are often disputed because of the assumption that the deposit was never exhumed once buried (Stokes, 1999) which may not always be the case. Though still considered reliable in dating sedimentary deposits and so providing insight into landscape reconstruction and the timing of geomorphological processes (Stokes, 1999), many authors advocate OSL as a preferred method of dating sedimentary deposits for reasons mentioned above and its strength in dating young (a few thousand years old) fluvial sediments (Choi et al., 2007).

Field observation and cross-sectional survey of the wetland valley at the study site reveal an erosion surface (E) and two distinct depositional terraces (D1 & D2) flanking each side of the wetland valley at different points (Figures 7.10a, b and c). A reconstruction of the wetland valley reveals that these terraces are relics of climate change, providing clear evidence that it has undergone at least two episodes of erosion and deposition (cut and fill).

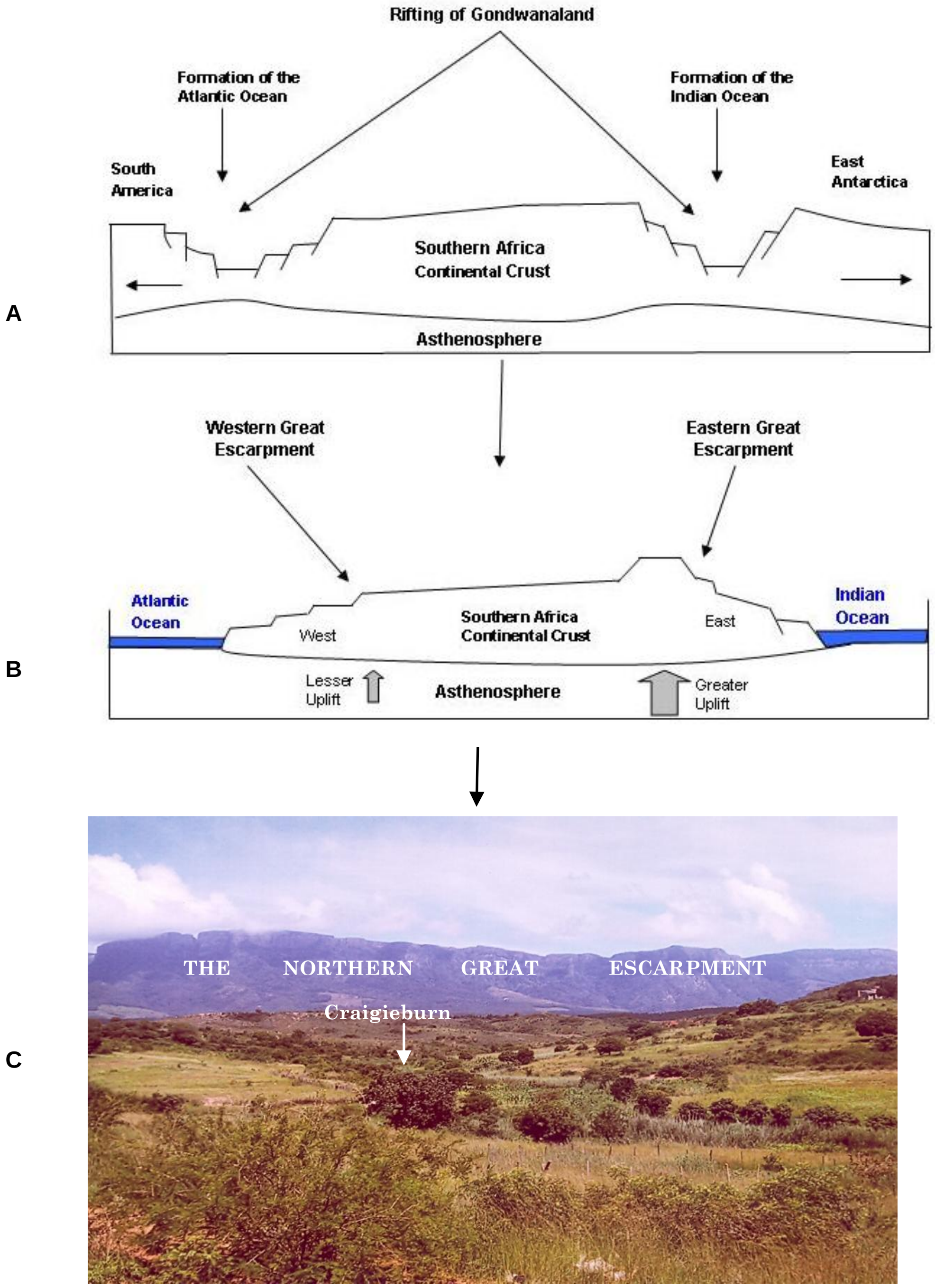


Figure 7.9 Reconstruction and evolution of the Great Escarpment in relation to the Craigieburn wetland system. A (120 million years ago) & B (20 million years ago) are modified from McCarthy and Rubidge (2000) and C is a field photograph (2006).

To further investigate whether human or natural factors are responsible for gully initiation and development at Craigieburn, sediment samples from each terrace were analysed (Section 4.2.5). Optically stimulated luminescence dates are calculated by dividing the amount of stored radiation during burial, also called the equivalent dose by the rate of absorption per year (dose rate), thus:

$$\text{OSL Age (ka)} = \frac{\text{Equivalent Dose (Gy)}}{\text{Dose Rate (Gy/yr)}}$$

Where Gy: Gray, the SI unit for radiation (Duller, 2007)
ka: kilo-annum or 1000 years.

The younger terrace (D2) is 1.5 m high and so only one sample was collected from this terrace due to the sampling procedure requiring that samples be collected at least 1m below the surface. The sample from the younger terrace was completely bleached or emptied of any previous radiation before burial and thus produced excellent laboratory results. The results of samples from the older terrace varied. These samples showed significant partial bleaching and this is likely responsible for the age reversal with depth and overdispersion (Table 7.2). Thus the older terrace (D1), which measures about 6 m high, is 1.67 ± 0.89 ka (780 to 2560 yrs) old; while the younger (D2) terrace is 0.32 ± 0.08 ka (240 to 400 yrs) old (Figure 7.11).

Table 7.2 Optically stimulated luminescence ages for the two terraces at Craigieburn.

Terrace	Sample Number	Laboratory Number	Dose Rate (Gy/ka)	Equivalent Dose (Gy)	Overdispersion (%)	OSL Age (ka)
Younger Terrace (D2)	CS2, 1 m	USU 761	1.65 ± 0.07	0.53 ± 0.37	82.20 ± 22.40	**0.32 ± 0.08**
Older Terrace (D1)	CS1, 3.3 m	USU 758	2.26 ± 0.14	5.18 ± 3.24	79.20 ± 14.4	**2.29 ± 1.44**
	CS1, 4 m	USU 759	2.22 ± 0.14	5.87 ± 2.74	54.80 ± 8.20	**2.65 ± 1.26**
	CS1, 4.7 m	USU 760	2.25 ± 0.12	3.76 ± 1.99	66.00 ± 10.30	**1.67 ± 0.89**

Notes: CS1 and CS2: Craigieburn Sample 1 and 2, the figures that follow for example 3.3, 1.4 and 4.7: depth at which samples were collected; USU 758-USU 761: Utah State University laboratory numbers, Equivalent Dose (Gy): total dose of ionised radiation absorbed during burial; Dose Rate (Gy/ka): amount of ionised radiation absorbed per 1000 years; Overdispersion: error of equivalent dose beyond instrument error, where >20% represent large scatter in values.

7.5. Discussion

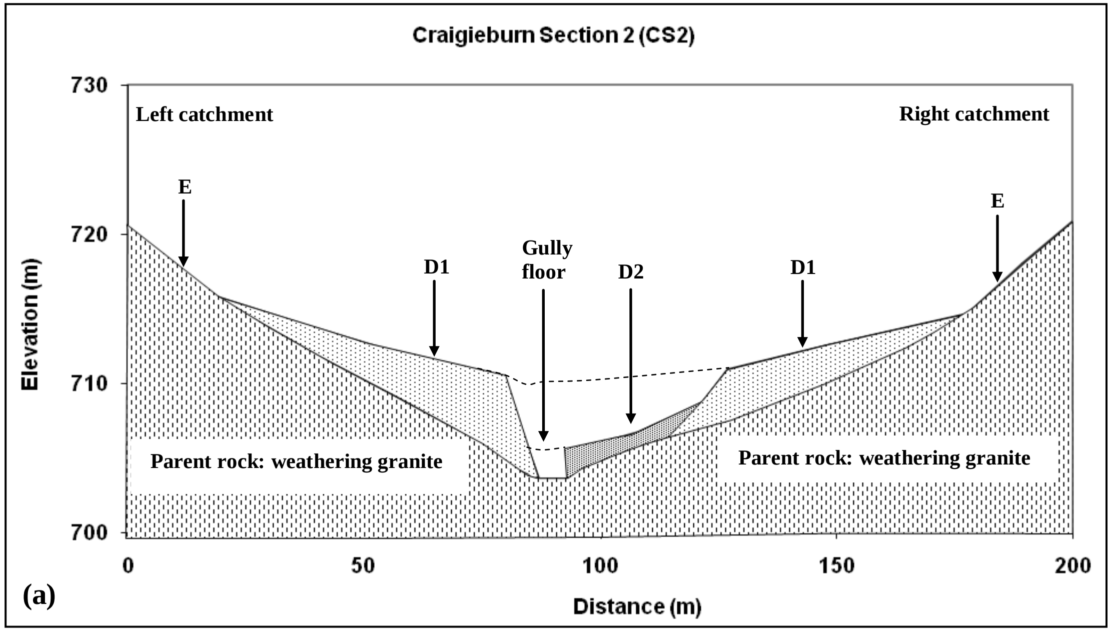
There are compelling reasons to believe that wetland erosion at Craigieburn is more a product of natural factors, though socio-economic factors may be a possible contributor. Results of linear regression between the two gully lengths and various predictor variables show that the most significant relationship exists between gully length and natural factors, which in this study is earthflow or adjacent gullies. These earthflows occur in the study area long before human settlement as evident on the 1954 aerial photograph (Figure 5.1) and originate from deep weathering of catchment rocks, their saturation by rain and downslope flow by gravity when triggered at its "toe" by erosion. However, earthflow could also occur during drier periods with a single catastrophic rainfall event. Thus wetter conditions at Craigieburn have not only caused mass wasting on the slopes but incision in the valleys. While it may be argued that earthflow and the downward displacement of material is a once off phenomenon, the mobilization of material from the scars through bank collapse could be an ongoing process.

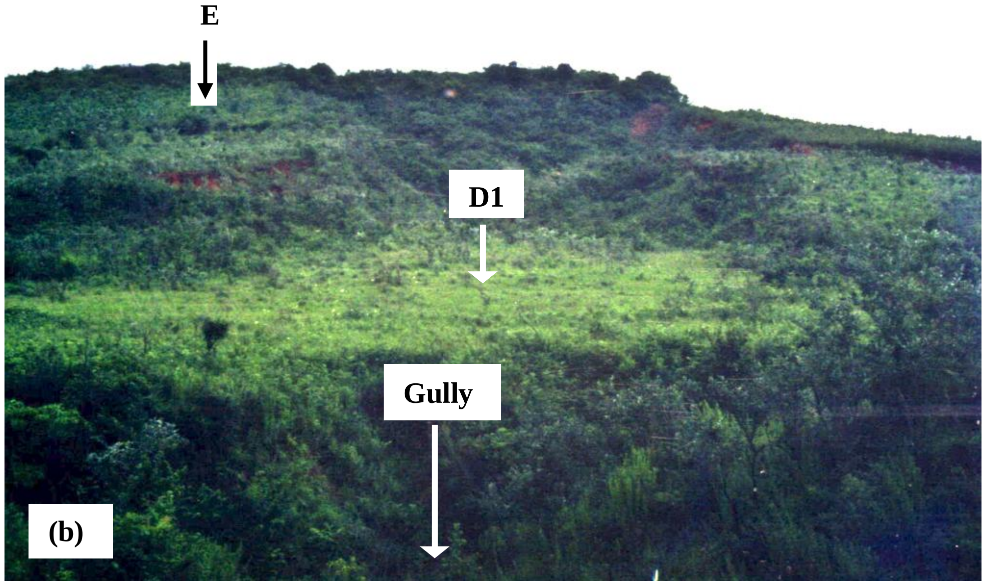
These materials ultimately reach the main valley bottom and contribute to raising the valley floor gradient to a threshold condition for erosion to be triggered either internally when the threshold is exceeded or by an external factor which could be human activities, change in base-level or climate change. Localized raised valley floor gradients around the eroding reaches of the wetland system at Craigieburn align with Schumm's (1973) intrinsic threshold concept which maintains that landforms evolve to conditions of incipient instability following which change occurs irrespective of external factors.

Though the impact of base-level fall on gully erosion has not been investigated in this study, it is likely that the lower wetland lowered upstream base-level, leading to further incision of the upper wetland. Evidence that climate change has contributed to wetland erosion at Craigieburn is provided by the existence of two depositional terraces which were cut and filled as the climate changed. Dates from the two terraces do not only provide a clue to the actual cause of gully initiation at Craigieburn, but also assist in reconstructing the geomorphic history of the valley floor in relation to Quaternary landscape evolution in South Africa. The 6 m high older terrace is estimated to be 1.67 ± 0.89 ka old and may have been incised in the period leading up to the medieval warming which is said to have reached its maximum between 1200 and 1250 AD (Partridge & Maud, 2000; Tyson et al., 2001). The younger terrace dates to 0.32 ± 0.08 ka, which is situated between 1610 and 1810 AD and coincides with the end of the Little Ice Age. This suggests that downcutting of the younger terrace parallels the period of renewed warming after the Little Ice Age. Further evidence supporting this interpretation is provided by high-resolution climate proxy and speleothem records from a stalagmite Cold Air Cave in the Makapansgat Valley of north-eastern South Africa (Holmgrem et al., 2003; Lee-Thorp et al., 2001), which is in the same region as the study area. Oxygen and carbon stable isotope dates from this cave show evidence of climate change in the region indicating a cool and dry period between 2.5 and 6 ka, a warm and wet phase (1-2 ka) and another cold phase between 1500 and 1800. These different phases of past climate in the region largely synchronize with the geomorphic evolution of the valley fill. For example, the older OSL terrace date, especially the upper limit (2560 yrs) closely overlaps with the lower limit of the cold and dry phase in the Makapansgat record (2.5 ka), while the period of its downcutting and formation of the younger terrace (1500-1800 AD) aligns more closely (1-2 ka at Makapansgat). Hence, there is little doubt that both terraces formed during cool and dry periods and were cut during warmer and wetter periods. The formation of these terraces and their subsequent downcutting long before human occupation of the Craigieburn catchment suggests that climate change and other natural factors rather than human activities initiated the gullies within the wetland system.

Further to this debate, the globally recognised long-term climatic changes which may have contributed to terrace formation and their subsequent downcutting often mask local variability and short-term seasonal catastrophic rainfall events that could considerably cut and erode a valley fill in a very short period of time. Residents in the study area testify to such occasional catastrophic rainfall events which have either scoured valleys or caused earthflows in the area (Monareng, pers. comm, 2009). He describes a catastrophic rainfall event in 1939 which significantly eroded valleys and provoked most of the earthflows that left behind the scars evident on most slopes in the area. This narration is confirmed by rainfall data from the nearby Wales Station (ICFR, 2005) (decommissioned in 2000) which registered occasional excessive rainfall events between 1908 and 1999, suggesting that the faster migration of the upper and lower headcuts between December 2005 and October 2006 in comparison to its relatively slower migration in the past decades since the 1950s is more likely related to short-term exceptional rainfall events (Section 7.3) than to human presence, though increased human activity by fewer people since the 1970s may be a contributory cause.

A related issue to terrace deposition and gully initiation or downcutting is the actual timing of these events (Section 2.3.3). Meadows (1988) and Meadows and Sugden (1988) maintain that during the last Glacial Maximum (~ 18000 years BP), when environmental conditions in southern Africa were cooler and drier, the reduction of vegetation cover and low water table induced net sediment removal (downcutting) and that during the Holocene (~ 10 000 years BP), moister and warmer conditions resulted in vegetation growth, less runoff and net sediment accumulation. Terrace dates from Craigieburn, suggest the contrary, that downcutting of the two terraces occurred during a warm wet period thus agreeing with the views of Boll et al. (1988), Hanson et al. (2006), Pan et al. (2007), Sugai (1993) and Zeuner (1945), who argue that valley floor aggradation occurs during a cool dry period due to reduced flow while incision occurs during the wetter phase when vegetation stabilizes the slope and discharge increases. The resulting streams with high discharge are devoid of sediments and tend to erode valley deposits.





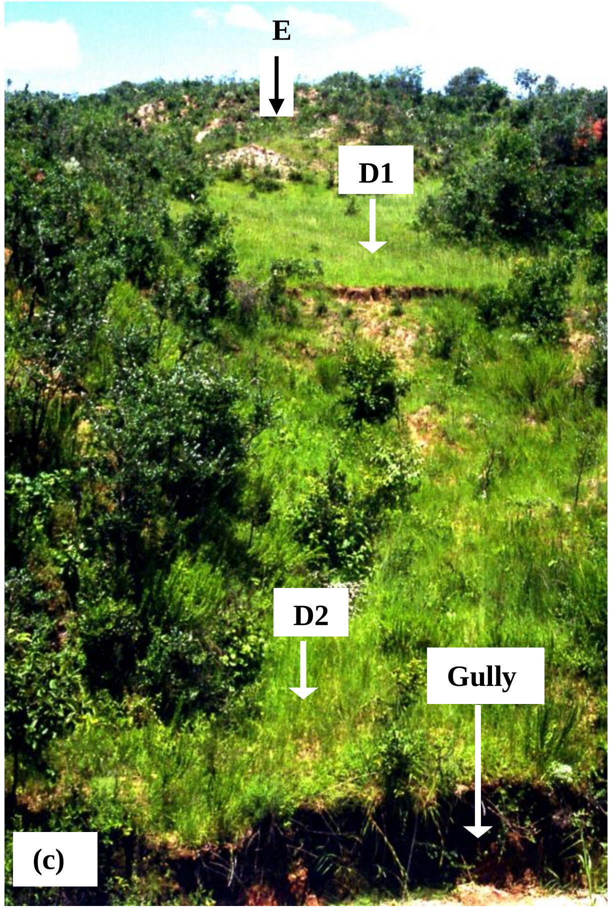


Figure 7.10 Evidence of climate change at Craigieburn. E refers to erosion surface; D1 & D2 refer to depositional terraces 1 and 2. Figure 7.10 (a) is a cross-sectional view looking downstream, (b) is the left bank looking downslope and (c) is the right bank looking downslope

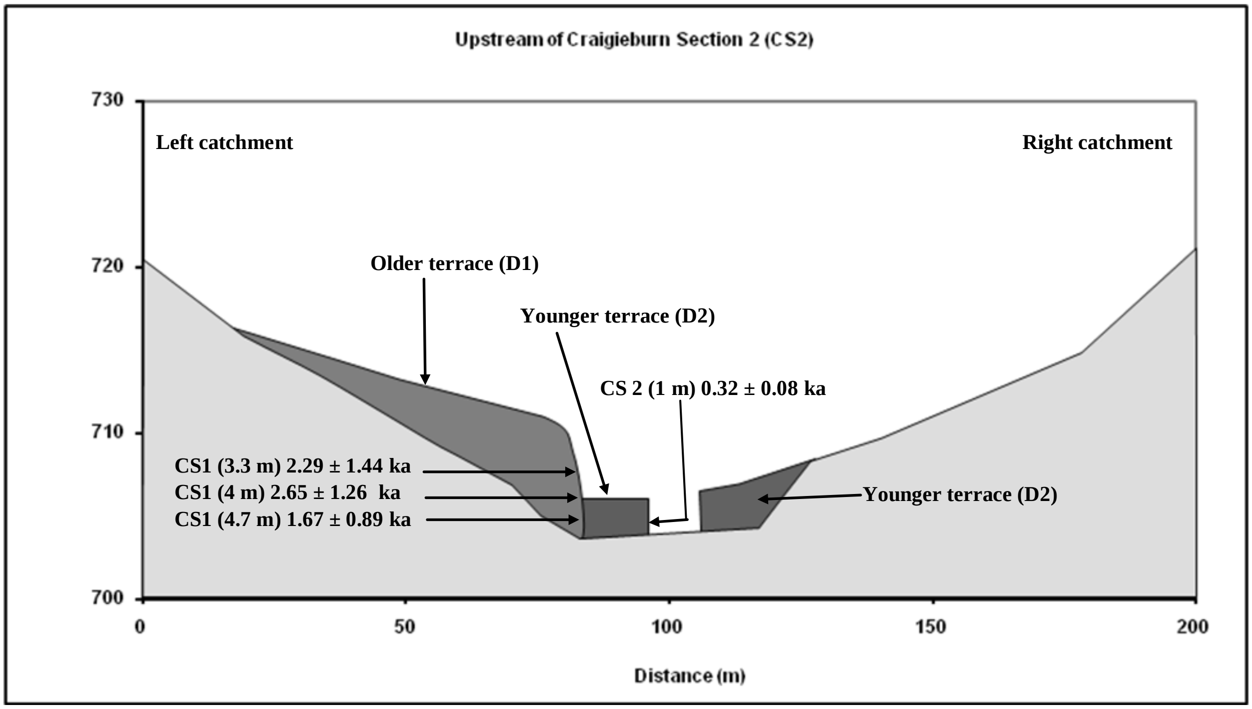


Figure 7.11 Age of the depositional terraces at Craigieburn. Laboratory numbers are on Table 7.2

Note: This cross-section is located very close but upstream of cross-section CS2 (Figure 4.1)

Moreover, the general interpretation of the Holocene by Meadows (1988) and Meadows and Sugden (1988) as a period with uniform climate (warm period), masks details of climatic variability during the Holocene, notably the Little Ice Age (1300 – 1810 AD), which may be responsible for some valley floor aggradation in southern Africa. Lending support to these fluctuating warm and cool periods during the Holocene are the works of Issar (2004) and Tyson and Lindesay (1992) who have sub-divided the Holocene into several warm and cool phases which affected sedimentation and erosion differently. These sub-divisions are further compounded by the several wet and dry spells (Tyson, 1990; Tyson & Preston-Whyte, 2000) which some authors have related to the 11 and 22 years solar cycle (Tyson et al., 2001; Vines, 1980).

7.6. Conclusion

In the quest for causes of wetland gully initiation and development at Craigieburn, the study of natural processes has not only contributed to resolving the debate but also shed light on the geomorphic origin of the wetland system which was formed by the downstream “bottle-necked” valley morphology and the upstream damming of flow by earth material from slope failure. Response to the debate on whether human or natural factors are responsible for wetland gully initiation and development at Craigieburn is provided by results of regression analysis which show a significant relationship between earthflow and gully erosion (gully length). Localized raised valley floor gradient around the eroding sections suggest that the geomorphic threshold has strongly contributed to gully initiation within the wetland system, which is further supported by the discontinuous nature of the gullies. Further evidence for the origin of the wetland gullying at Craigieburn is provided by OSL dates indicating terrace formation prior to and during the Little Ice Age; and periods of gully erosion during warmer and wetter periods.

CHAPTER EIGHT

HUMAN OR NATURAL CAUSES OF WETLAND EROSION AT CRAIGIEBURN WHICH IS RESPONSIBLE?

8.1. Introduction

In view of the value and numerous functions of wetlands (Mitsch & Gosslink, 1993; Ramsar Convention Bureau, 2001), their wise use is imperative. That the Craigieburn wetland system is an important source of water to downstream ecosystems and to one of the largest biosphere reserves in South Africa provide additional reasons for the conservation and wise use of this wetland system. However, its erosion has raised the question as to whether humans or natural processes are responsible. Hence, the main aim of this study was to investigate the causes of wetland erosion at Craigieburn.

8.2. Human or natural causes?

The argument before this study was that poor management of the Craigieburn wetland system is responsible for its erosion (AWARD, 2004). However, statistical analysis of human and natural factors (Section 5.3 and Section 7.4, respectively) showed no significant relationship between socio-economic factors and the evolution of gully lengths ($p > 0.05$) except for the apparent effect of dirt roads ($p < 0.05$); but a significant relationship between natural factors and gully length ($p < 0.05$).

Furthermore, luminescence dates of terraces flanking the gully suggest that their downcutting occurred long before human habitation on the catchment of the wetland system, firstly during the medieval warming probably around 1250 AD; and then secondly during the period of renewed warming after the Little Ice Age which ended around 1810 AD. In comparison to these events, significant human presence on the catchment became evident only recently in the 1970s.

However, in relation to the debate on what is responsible for gully erosion on a landscape, some authors have argued that warm and humid periods in the climatic history is often associated with human population growth and colonization due to the favourable climatic conditions and the availability of resources (Deacon & Lancaster, 1988; Issar, 2004). They further maintain that contrastingly, cool and dry periods have presented harsh conditions accompanied by the shrinkage of resources and a resulting decrease in biodiversity and human population. Therefore a synthesis of the impacts of climate change on human population and geomorphic processes shows that cool dry periods engender a decrease in population growth, valley floor sedimentation and wetland creation, while warm and wet periods favour population growth coinciding with gully initiation and development. Whether such past population dynamics in response to climate change exist at Craigieburn is unknown due to lack of past long term records on population change. Even if such records existed, it would be necessary to determine to what extent population dynamics impacted on geomorphic processes and gully erosion in particular. This is considered to be a separate subject for research.

Nevertheless, the OSL dates on terrace formation and downcutting have not only helped in resolving the dilemma of the causes of wetland erosion at Craigieburn but have also contributed to the record of geomorphic dating in South Africa. While Meadows (1985), Meadows (1988) and Meadows and Sugden (1988) maintain that valley fill occurs during warmer and wetter environmental conditions, followed by downcutting when the climate is cool and dry, terrace dates at Craigieburn reveal the contrary, sustaining the controversy over environmental dating and reconstruction in southern and South Africa (Deacon & Lancaster, 1988; Dewey, 1988). This on-going controversy motivates for further research in different climatic zones within south Africa to shed more light on this subject.

Despite evidence from statistical analysis and OSL dating supporting natural causes of wetland erosion at Craigieburn, it cannot be completely denied that human occupation of the catchment may have been a contributory or causal factor. This can be justified by the greatest extension of gully lengths, 21 m (upper gully) and 194 m (lower gully) during periods of increased human occupation (Tables 5.1a and 5.1b). This does not necessarily support gully initiation but may rather explain the partial contribution of human factors to gully development in accord with the theory that natural factors may set the potential for erosion which might then be aggravated by human activities (Bettis, 1983; Gage, 1970; Graf, 1979). Whatever the contribution of human factors, this would be post-gully initiation as the strongest argument for the natural causes of wetland gully initiation and development at Craigieburn rests on two facts, the existence of gullies prior to human occupation of the catchment and terraces that date to before human colonization of the catchment.

8.3. Soil morphology

Field observation and laboratory results of particle size analysis confirmed the existence of duplex soils in certain parts of the study area (CS1.3, CS3.2 and CS4.1a – Section 6.5.2). However, their existence outside the eroding system does not directly link them to wetland erosion. Rather, sediments eroded from these duplex soils adjacent to the wetlands contributed to raised valley floor gradient within the wetlands creating the propensity for erosion to occur.

8.4. The geomorphic threshold concept

The concept of a threshold valley floor gradient presents a challenge as to whether there is a universally applicable threshold valley floor gradient for a country, region or even a catchment, above which gully erosion is initiated. Surveyed wetland valley floor profiles at Craigieburn and comparisons with results from elsewhere caution against a particular threshold gradient being widely applicable. For example, at Craigieburn, the threshold valley floor gradients above which erosion began are 0.0336 and 0.0337, giving the impression that the system has a single threshold valley floor gradient. However, in Colorado, New Mexico and Wyoming, USA threshold gradients of 0.054, 0.040, 0.036, 0.23 and 0.016 have been established at or above which valley floor erosion began (Schumm & Hadley, 1957; Patton & Schumm, 1975). It is therefore apparent that they are site specific and vary with each system and environment (Brunsden & Thornes, 1979; Poesen et al., 2003) because of the variability of controlling factors in the system. Therefore despite the closeness of Craigieburn valley floor threshold values to 0.036 in the USA, extrapolation of these values to other eroding wetland systems should not be considered as an option. Focus should not be on applying a single threshold but on site specific thresholds for each eroding wetland in a specified climatic region within a country.

8.5. Conclusion

Gully initiation and development have been distinguished as two processes, the first related to the actual trigger of the erosion process while the second relates to the growth and elongation of the gully. Wetland gully initiation at Craigieburn dates prior to human settlement. However, despite the absence of any significant relationship between human factors and gully length in recent decades, the possibility exists that increased human presence in the catchment from the 1970s has contributed to gully development within the Craigieburn wetland system. This interpretation is supported by the increase in gully length within the same period of human settlement, but does not prove causality.

Evidence from this study clearly relates gully initiation to past climate change andgully development in recent years to incipient instability caused by increased valley floor threshold gradients. This process is facilitated by the current warm and moister climate resulting in higher rainfall, occasional catastrophic rainfall events and increased stream erosivity.

The major findings of this study have not only suggested answers to the question of what causes wetland erosion at Craigieburn but have also challenged previous work in the area. They also contribute to the existing debate in other areas of geomorphological research such as the dating of geomorphic events in the southern African sub-continent. However, logistical and other constraints and the inability to access some information identify areas for further research. These include investigating the possible effects of tectonic activity and local base-level change on wetland erosion at Craigieburn. This possibility exists as the eroding wetland system lies just below a past tectonically active margin. A second possible subject for research is the impact of catchment grazing and farming on wetland erosion. This research need emanates from the inability to retrieve information from poor quality aerial photographs and the absence of historical grazing records in the study area. Exploration of the environment bordering the study area and beyond showed imprints of regional climate change. These include 3 to 6 m sandy deposits 25 km away from the study area and the existence of terraces in numerous drainage lines further away. These evidences of wider effect of climate change merit investigation to shed more light on the causes of environmental change at Craigieburn and its surrounding areas. Finally, the technological field offers new tools for scientific research such as the quantitative study of sediment supply from earthflow and gully erosion at Craigieburn using remote sensing.

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PERSONAL COMMUNICATIONS

Ellery, W.N., 2007. Department of Environmental Sciences, Rhodes University. Personal Communication.

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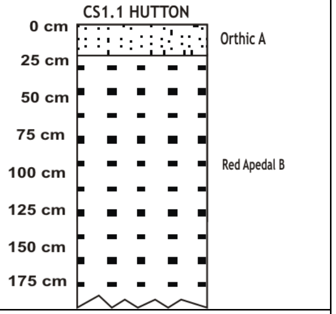
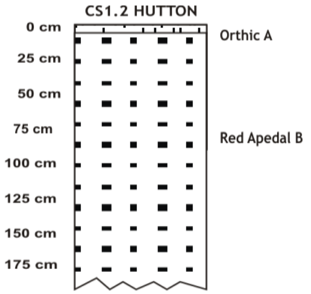
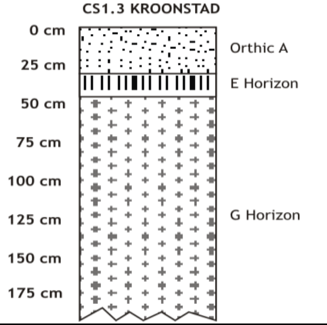
APPENDICES

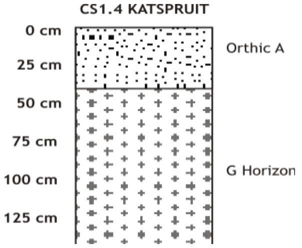
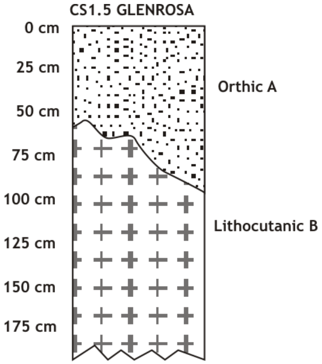
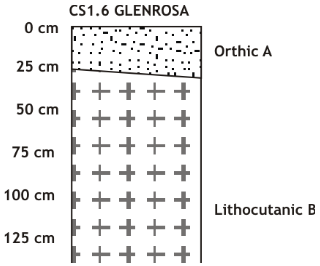
Appendix 4.1 Diagnostic characteristics of Craigieburn soil profiles

Sample	Location	Depth (cm)	Munsell Colour (moist soil)	Dry soil Feel	Plasticity*	Mottling	Organisms	Sample Profile
CS1.1	24^{0} 39.863'S 30^{0} 58.548'E	0 - 2	7.5YR 2.5/1	Clayey	40/4#	None	Ants	
		2 - 22	7.5YR 4/4	Silty/Clay	40/2	None	Ants/Worms	
		22 - 90	2.5YR 4/6	Silty/Clay	40/2	None	Ants/Worms	
		90 - 150	2.5YR 4/8	Silty/Clay	40/2	None	Dead roots	
CS1.2	24^{0} 39.910'S 30^{0} 58.510'E	0 - 13	7.5YR 4/6	Gritty	40/4	None	Live roots & termites	
		13 - 53	7.5YR 4/6	Gritty	40/2	None	Few live roots	
		53 - 78	2.5YR 4/8	Very Gritty	No	None	Dead roots	
		78 -153	2.5YR 4/8	Very Gritty	No	None	Dead roots	
CS1.3	24^{0} 39.957'S 30^{0} 58.487'E	0 - 40	7.5YR 3/3	Slightly gritty	No	Few strong brown	Few	
		40 - 80	7.5YR 5/4	Gritty	40/4	Abundant Reddish yellow	None	
		80 - 180	7.5YR 7/2	Gritty	40/2	Abundant Reddish yellow	None	

* Plasticity refers to the ability of a moist or wet soil to be molded and rolled into a thread of different diameters without breaking (Fitzpatrick, 1986).

\# 40/4 refers to a thread of moist soil molded and rolled to a length of 40 mm with a diameter of 4 mm without breaking (Dackombe & Gardiner, 1983).

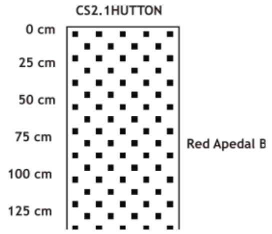
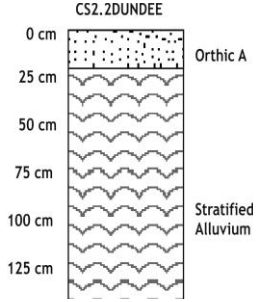
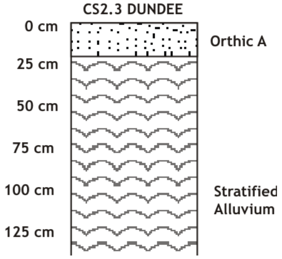
Appendix 4.1 (Continued) Diagnostic characteristics of Craigieburn soil profiles

Sample	Location	Depth (cm)	Munsell Colour (moist soil)	Dry soil Feel	Plasticity[*]	Mottling	Organisms	Sample Profile
CS1.4	24^{0} 39.992‘S 30^{0} 58.451‘E	0 - 39	7.5YR 4/2	Very gritty	40/6[#]	Few strong brown	Live roots	
		39 - 50	7.5YR 6/1	Slightly gritty	40/2	Abundant reddish yellow	None	
		50 - 150	7.5YR 7/4	Gritty	40/2	None	None	
CS1.5	24^{0} 40.019‘S 30^{0} 58.407‘E	0 - 50	7.5YR 4/1	Very gritty	40/4	None	Live roots & termites	
		50 - 90	2.5YR 5/8	Gritty	No	None	Abandoned earthworm pores	
		90 - 150	5YR 7/8	Gritty	No	None	None	
CS1.6	24^{0} 40.040‘S 30^{0} 58.346‘E	0 - 25	7.5YR 2.5/1	Very gritty	No	None	None	
		25 - 37	7.5YR 6/3	Very gritty	40/4	None	Tiny pores & live roots	
		37 - 150	7.5YR 6/6	Very gritty	40/6	None	Abundant pores & live roots	

* Plasticity refers to the ability of a moist or wet soil to be molded and rolled into a thread of different diameters without breaking (Fitzpatrick, 1986).

[#] 40/6 refers to a thread of moist soil molded and rolled to a length of 40 mm with a diameter of 6 mm without breaking (Dackombe & Gardiner, 1983).

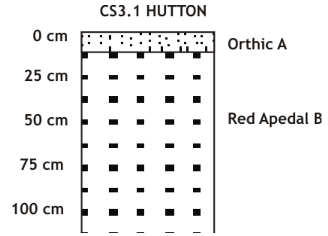
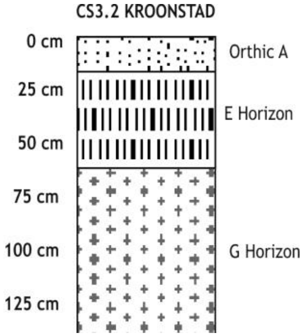
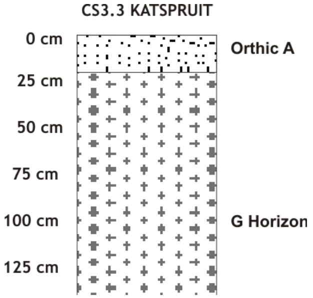
Appendix 4.1 (Continued) Diagnostic characteristics of Craigieburn soil profiles

Sample	Location	Depth (cm)	Munsell Colour (moist soil)	Dry soil Feel	Plasticity[*]	Mottling	Organisms	Sample Profile
CS2.1	24 ^{0}39.867 ˊS 30 ^{0}58.566 ˊE	0 - 80	2.5YR 4/6	Slightly gritty	40/4[#]	None	Live roots	
		80 - 150	2.5YR 5/8	Gritty	40/2	None	None	
CS2.2	24^{0} 40.026ˊS 30^{0} 58.576ˊE	0 - 20	7.5YR 4/1	Gritty	40/6	None	Worms & live roots	
		20 - 34	7.5YR 5/4	Gritty	40/6	None	Dead roots	
		34 - 59	7.5YR 6/6	Very gritty	No	None	Dead roots	
		59 - 150	2.5YR 6/6	Very gritty	No	None	Dead roots	
CS2.3	24^{0} 40.061ˊS 30^{0} 58.582ˊE	0 - 21	7.5YR 5/2	Gritty	No	None	Live roots	
		21 - 65	7.5YR 5/3	Moderately Gritty	40/6	None	Live roots	
		65 - 150	2.5YR 6/4	Gritty	No & 40/6	None	Live roots	

* Plasticity refers to the ability of a moist or wet soil to be molded and rolled into a thread of different diameters without breaking (Fitzpatrick, 1986).

[#] 40/4 refers to a thread of moist soil molded and rolled to a length of 40 mm with a diameter of 4 mm without breaking (Dackombe & Gardiner, 1983).

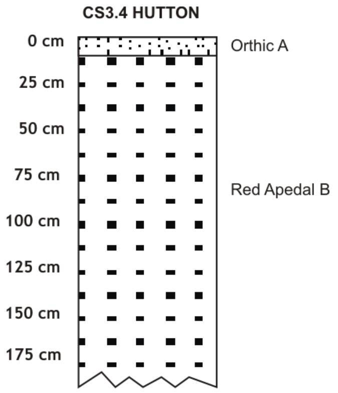
Appendix 4.1 (Continued) Diagnostic characteristics of Craigieburn soil profiles

Sample	Location	Depth (cm)	Munsell Colour (moist soil)	Dry soil Feel	Plasticity[*]	Mottling	Organisms	Sample Profile
CS3.1	24^0 40.005ˋS 30^0 58.988ˋE	0 - 13	7.5YR 4/6	Gritty	40/2[#]	None	Many tiny roots	
		13 - 60	7.5YR 6/6	Gritty	40/2	None	Very few roots	
		60 - 150	2.5YR 6/6	Gritty	40/4	None	None	
CS3.2	24^0 40.018ˋS 30^0 58.954ˋE	0 - 18	7.5YR 4/3	Gritty	40/6	None	Ants, termites & live roots	
		18 - 63	7.5YR 6/2	Very gritty	40/2	Many reddish yellow	Many pores	
		63 - 150	7.5YR 8/2	Very gritty	No	Many reddish yellow	None	
CS3.3	24^0 40.066‘S 30^0 59.010ˋE	0 - 20	7.5YR 3/3	Gritty	40/6	Many strong brown	Ants, termites & live roots	
		20 - 140	7.5YR 5/1	Very gritty	40/6	Many reddish yellow	Live roots	
		140 - 190	7.5YR 7/4	Very gritty	No	Many reddish yellow	None	
		190 - 215	7.5YR 6/6	Very , very gritty	No	Many reddish yellow	None	

* Plasticity refers to the ability of a moist or wet soil to be molded and rolled into a thread of different diameters without breaking (Fitzpatrick, 1986).

[#] 40/2 refers to a thread of moist soil molded and rolled to a length of 40 mm with a diameter of 2 mm without breaking (Dackombe & Gardiner, 1983).

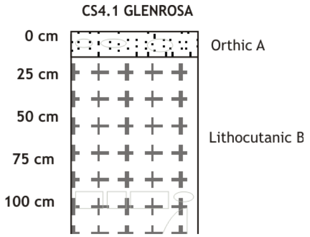
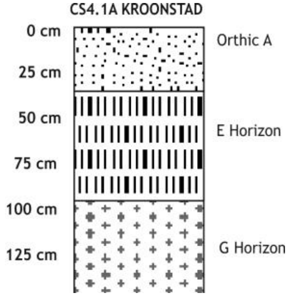
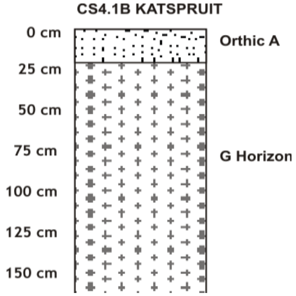
Appendix 4.1 (Continued) Diagnostic characteristics of Craigieburn soil profiles

Sample	Location	Depth (cm)	Munsell Colour (moist soil)	Dry soil Feel	Plasticity[*]	Mottling	Organisms	Sample Profile
CS3.4	24^{0} 40.098‘S 30^{0} 59.021‘E	0 - 7	5YR 3/3	Slightly gritty	40/2[#]	None	Ants, termites & live roots	
		7 – 45	7.5YR 4/6	Moderate-ly gritty	40/2	None	None	
		45 – 143	2.5YR 5/6	Gritty	40/2	None	None	
		143 - 150	2.5YR 5/8	Very gritty	No	None	None	

* Plasticity refers to the ability of a moist or wet soil to be molded and rolled into a thread of different diameters without breaking (Fitzpatrick, 1986).

[#] 40/2 refers to a thread of moist soil molded and rolled to a length of 40 mm with a diameter of 2 mm without breaking (Dackombe & Gardiner, 1983).

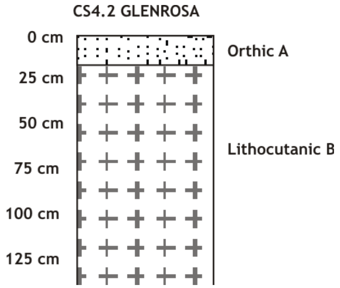
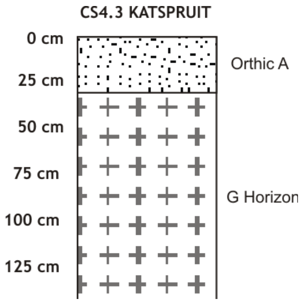
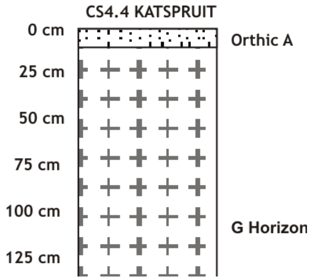
Appendix 4.1 (Continued) Diagnostic characteristics of Craigieburn soil profiles

Sample	Location	Depth (cm)	Munsell Colour (moist soil)	Dry soil Feel	Plasticity[*]	Mottling	Organisms	Sample Profile
CS4.1	24^0 40.022ˋS 30^0 59.145ˋE	0 - 15	2.5YR 4/6	Very gritty	40/2[#]	None	Few dead roots & termites	
		15 - 72	2.5YR 6/6	Slightly gritty	40/2	None	Few dead roots & live termites	
		72 - 150	2.5YR 6/6	Gritty	No	None	Few dead roots & termites	
CS4.1a	24^0 40.018ˋS 30^0 58.954ˋE	0 - 35	7.5YR 4/3	Gritty	40/6	None	Ants, termites & live roots	
		35 - 72	7.5YR 6/2	Very gritty	40/2	Many reddish yellow	Many soil pores	
		72 - 150	7.5YR 8/2	Very gritty	No	Many reddish yellow	None	
CS4.1b	24^0 40.051^{0}S 30^0 59.139^{0}E	0 - 23	7.5YR 2.5/1	Gritty	40/2	Few strong brown	Many tiny roots	
		23 - 84	7.5YR 5/1	Very gritty	40/2	Many reddish yellow	None	
		84 - 150	7.5YR 7/1	Very gritty	No	None	None	

* Plasticity refers to the ability of a moist or wet soil to be molded and rolled into a thread of different diameters without breaking (Fitzpatrick, 1986).

[#] 40/2 refers to a thread of moist soil molded and rolled to a length of 40 mm with a diameter of 2 mm without breaking (Dackombe & Gardiner, 1983).

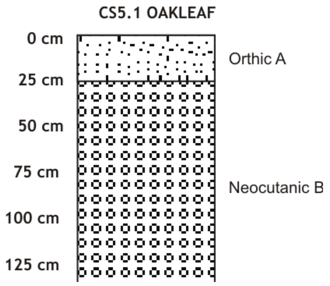
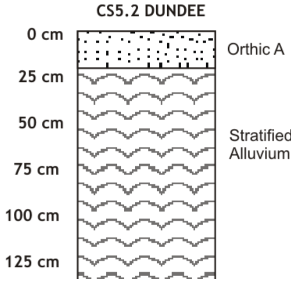
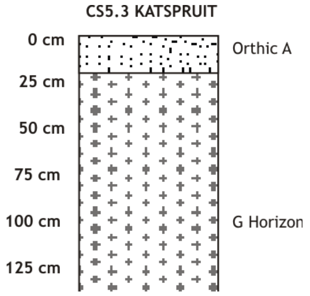
Appendix 4.1 (Continued) Diagnostic characteristics of Craigieburn soil profiles

Sample	Location	Depth (cm)	Munsell Colour (moist soil)	Dry soil Feel	Plasticity[*]	Mottling	Organisms	Sample Profile
CS4.2	24^0 40.073‘S 30^0 59.137‘E	0 - 18	7.5YR 4/1	Gritty	40/2[#]	None	Many tiny roots	
		18 - 95	7.5YR 7/1	Very gritty	No	None	None	
		95 - 173	7.5YR 6/6	Very gritty	No	None	None	
CS4.3	24^0 40.085‘S 30^0 59.136‘E	0 - 27	7.5YR 4/2	Gritty	No	Many reddish yellow	Many roots, earthworms & dead leaves	
		27 - 53	7.5YR 5/2	Very gritty	No	Many reddish yellow	Few roots	
		53 - 109	7.5YR 7/1	Very gritty	No	Many reddish yellow	None	
		109 - 159	7.5YR 8/2	Very gritty	No	None	None	
CS4.4	24^0 40.103‘S 30^0 59.118‘E	0 - 10	7.5YR 4/6	Very gritty	40/4	None	Many roots	
		10 - 60	2.5YR 4/2	Gritty	40/2	None	None	
		60 - 173	2.5YR 4/2	Gritty	40/4	None	None	

[*] Plasticity refers to the ability of a moist or wet soil to be molded and rolled into a thread of different diameters without breaking (Fitzpatrick, 1986).

[#] 40/2 refers to a thread of moist soil molded and rolled to a length of 40 mm with a diameter of 2 mm without breaking (Dackombe & Gardiner, 1983).

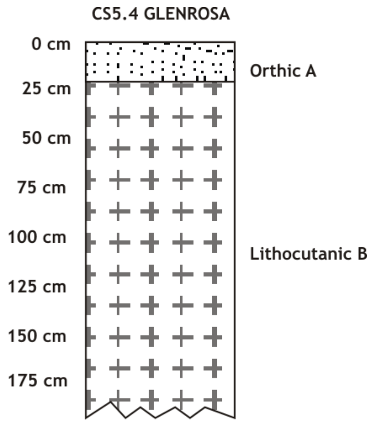
Appendix 4.1 (Continued) Diagnostic characteristics of Craigieburn soil profiles

Sample	Location	Depth (cm)	Munsell Colour (moist soil)	Dry soil Feel	Plasticity*	Mottling	Organisms	Sample Profile
CS5.1	24^{0} 40.015ʻS 30^{0} 59.779ʻE	0 - 26	7.5YR 4/3	Gritty	40/2#	None	Many tiny roots & some pores	
		26 - 92	2.5YR 4/8	Gritty	40/2	None	Few tiny roots & some pores	
		92 - 151	7.5YR 5/8	Gritty	40/2	None	Few pores	
CS5.2	24^{0} 40.055ʻS 30^{0} 58.546ʻE	Characteristics not recorded as this profile is stratified alluvium, a depositional terrace						
CS5.3	24^{0} 40.099ʻS 30^{0} 58.780ʻE	0 - 19	7.5YR 3/3	Gritty	40/6	Few strong brown	Many tiny roots	
		19 - 29	7.5YR 6/1	Very gritty	No	None	Few tiny roots	
		29 - 71	7.5YR 7/2	Very gritty	No	Moderate reddish yellow	None	
		71 - 156	7.5YR 7/1	Gritty, gravely	No	None	None	

* Plasticity refers to the ability of a moist or wet soil to be molded and rolled into a thread of different diameters without breaking (Fitzpatrick, 1986).

40/2 refers to a thread of moist soil molded and rolled to a length of 40 mm with a diameter of 2 mm without breaking (Dackombe & Gardiner, 1983).

Appendix 4.1 (Continued) Diagnostic characteristics of Craigieburn soil profiles

Sample	Location	Depth (cm)	Munsell Colour (moist soil)	Dry soil Feel	Plasticity[*]	Mottling	Organisms	Sample Profile
CS5.4	24^{0} 40.139‘S 30^{0} 58.772‘E	0 - 20	7.5YR 4/6	Gritty	40/2[#]	None	Many tiny roots & pores	
		20 - 60	7.5YR 6/6	Gritty	40/2	None	Few tiny roots	
		60 - 100	7.5YR 7/6	Gritty	40/4	None	None	
		100 - 150	7.5YR 7/2	Gritty	No	None	None	

[*] Plasticity refers to the ability of a moist or wet soil to be molded and rolled into a thread of different diameters without breaking (Fitzpatrick, 1986).

[#] 40/2 refers to a thread of moist soil molded and rolled to a length of 40 mm with a diameter of 2 mm without breaking (Dackombe & Gardiner, 1983).

Appendix 5.1a Correlation matrix (R^2 values) between variables affecting the upper gully

	Upper Gully	**Dirt Roads**	**Footpaths/ Animal Tracks**	**Total Roads**	**Adjacent Gullies**[#]	**Individual Homes**	**Year**
Upper Gully	1.00	0.78	0.39	0.49	0.68	0.61	0.86
Dirt Roads	0.78	1.00	0.05	0.10	0.75	0.33	0.84
Foot paths/ Animal Tracks	0.39	0.05	1.00	0.99	0.02	0.66	0.16
Total Roads	0.49	0.10	0.99	1.00	0.06	0.73	0.24
Adjacent Gullies	0.68	0.75	0.02	0.06	1.00	0.10	0.83
Individual Homes	0.61	0.33	0.66	0.73	0.10	1.00	0.28
Year	0.86	0.84	0.16	0.24	0.83	0.28	1.00

Appendix 5.1b Correlation matrix (R^2 values) between variables affecting the lower gully

	Lower Gully	**Dirt Roads**	**Footpaths/ Animal Tracks**	**Total Roads**	**Adjacent Gullies**[#]	**Individual Homes**	**Year**
Lower Gully	1.00	0.94	0.40	0.60	0.97	0.30	0.98
Dirt Roads	0.94	1.00	0.58	0.77	0.97	0.49	0.93
Footpaths/ Animal Tracks	0.40	0.58	1.00	0.96	0.44	0.95	0.44
Total Roads	0.60	0.77	0.96	1.00	0.64	0.88	0.63
Adjacent Gullies	0.97	0.97	0.44	0.64	1.00	0.33	0.98
Individual Homes	0.30	0.49	0.95	0.88	0.33	1.00	0.30
Year	0.98	0.93	0.44	0.63	0.98	0.30	1.00

[#] Adjacent gullies in this context are scars left behind by earthflows

Appendix 6.1 Soil particle size distribution and pH

Soil Sample/Soil Form	Depth (cm)	% Sand 2.0 – 0.05 mm	%Silt 0.05 – 0.002 mm	%Clay < 0.002 mm	pH.H_2O
CS1.1 Hutton	O - 2	34	13	53	5.9
	2 - 22	29	14	57	5.6
	22 - 90	13	10	77	5.5
	90 - 150	22	11	67	6.0
CS1.2 Hutton	0 - 13	52	4	44	5.2
	13 - 53	44	3	53	5.2
	53 - 78	39	6	55	5.2
	78 -153	47	15	38	5.3
CS1.3 Kroonstad	0 - 40	60	4	36	5.4
	40 - 80	68	5	27	5.8
	80 - 180	53	5	42	5.8
CS1.4 Katspruit	0 - 39	56	6	38	5.2
	39 - 50	59	5	36	5.5
	50 - 150	73	5	21	6.2
CS1.5 Glenrosa	0 - 50	77	2	20	5.2
	50 - 90	68	10	22	5.6
	90 - 150	66	12	22	5.7
CS1.6 Glenrosa	0 - 25	61	2	37	4.9
	25 - 37	58	12	30	4.9
	37 - 150	68	10	22	5.6
CS2.1 (Hutton)	0 - 80	30	3	67	5.0
	80 - 150	51	12	37	5.3
CS2.2 Dundee	0 – 20	76	6	18	5.5
	20 – 34	84	5	11	5.6
	34 – 59	87	1	11	5.9
	59 - 150	90	6	4	5.9
CS2.3 Dundee	0 – 21	48	4	49	5.2
	21 – 65	83	5	12	5.4
	65 – 87	65	14	21	5.3
	87 - 99	55	25	20	5.4
	99 - 150	68	8	24	5.4
CS3.1 Hutton	0 - 13	36	26	38	4.9
	13 - 60	37	7	56	5.2
	60 - 150	51	11	38	5.5
CS3.2 Kroonstad	0 - 18	80	5	15	5.2
	18 - 63	84	5	11	5.2
	63 - 150	61	3	36	5.7
CS3.3 Katspruit	0 - 29	60	5	35	5.3
	29 - 140	71	2	27	5.8
	140 - 190	82	5	13	5.1
	190 - 215	87	5	8	6.6
CS3.4 Hutton	0 - 7	53	1	46	5.3
	7 - 45	44	1	55	5.0
	45 - 143	34	8	58	5.6
	143 - 150	63	6	32	5.6

Appendix 6.1 (Continued) Soil particle size distribution and pH

Soil Sample/Soil Form	Depth (cm)	% Sand 2.0 – 0.05 mm	%Silt 0.05 – 0.002 mm	%Clay < 0.002 mm	pH.H$_2$O
CS4.1 Glenrosa	0 - 15	58	6	36	5.0
	15 - 72	37	5	58	5.2
	72 - 150	47	8	45	5.1
CS4.1a Kroonstad	0 - 35	58	9	33	4.8
	35 - 72	78	5	17	5.5
	72 - 154	57	6	37	5.7
CS4.1b Katspruit	0 - 23	72	5	23	5.5
	23 - 84	63	8	28	5.9
	84 - 150	80	4	16	6.1
CS4.2 Glenrosa	0 - 18	81	6	13	5.2
	18 - 95	78	2	20	6.9
	95 - 173	85	1	13	7.0
CS4.3 Katspruit	0 - 27	18	68	14	5.5
	27 - 53	66	4	30	5.9
	53 - 109	89	4	7	7.6
	109 - 159	89	1	9	7.9
CS4.4 Katspruit	0 - 10	44	4	52	5.5
	10 - 60	33	7	60	5.6
	60 - 173	68	14	18	5.8
CS5.1 Oakleaf	0 - 26	51	9	40	5.1
	26 - 92	33	6	61	5.3
	92 - 151	62	5	33	4.9
CS5.2 Dundee	0 - 5	79	5	16	5.6
	5 - 60	83	6	11	5.6
	60 - 80	62	12	26	5.4
	80 - 100	75	7	18	5.4
	100 - 120	44	26	30	5.3
	120 - 140	87	5	8	6.0
	140 - 146	32	24	44	5.5
	146 - 160	72	12	16	5.3
CS5.3 Katspruit	0 - 19	77	1	22	5.2
	19 - 29	74	7	18	5.1
	29 - 71	72	7	16	5.8
CS5.4 Glenrosa	0 - 20	43	5	52	5.5
	20 - 60	16	42	41	5.8
	60 - 100	77	13	10	6.1
CRVS1 Not determined	0 - 45	74	6	20	nd
	45 - 55	51	14	35	nd
CRVS2 Not determined	0 - 10	46	7	46	4.9
	10 - 50	84	3	13	5.3
	50 - 100	80	3	17	5.4

Note: nd refers to “not determined”

Appendix 6.1 (Continued) Soil particle size distribution and pH

Soil Sample/Soil Form	Depth (cm)	% Sand 2.0 – 0.05 mm	%Silt 0.05 – 0.002 mm	%Clay < 0.002 mm	pH.H_2O
CRVS3 Not determined	0 - 10	68	3	29	5.3
	10 - 50	64	7	29	5.3
	50 - 70	82	9	9	nd
	70 - 100	85	6	9	5.7
	100 - 150	86	3	11	nd
	150 - 200	87	1	12	5.1
	200 - 250	88	3	9	5.0
	250 - 270	85	1	14	5.1
CRVS4 Not determined	0 - 10	82	2	16	5.2
	10 - 50	84	4	12	4.9
	50 - 100	80	4	17	nd
	100 - 150	80	4	16	5.1
	150 - 200	86	4	10	5.3
	200 - 250	79	9	13	nd
	250 - 300	87	1	12	5.9
CRVS5 Not determined	0 - 10	79	6	15	4.9
	10 - 50	nd	nd	nd	4.6
	50 - 70	74	4	22	4.8
	70 - 100	85	1	14	5.5
	100 - 150	83	8	9	nd
CRVS6 Not determined	0 - 10	nd	nd	nd	nd
	10 - 50	73	11	16	nd
	50 - 160	80	6	15	nd
	160 - 250	82	2	16	nd
	250 - 300	40	51	9	nd
	300 - 320	91	2	7	nd
CRVS7 Not determined	0 - 10	50	32	18	5.4
	10 - 50	nd	nd	nd	4.4
	50 - 80	59	11	30	nd
	80 - 90	71	8	21	nd
	90 - 100	48	24	28	nd
	100 - 140	81	5	14	4.5
	140 - 150	83	1	16	nd
	150 - 180	88	4	8	4.8
	180 - 200	84	0	16	nd
	200 - 250	86	1	13	4.8
CRVS8 Not determined	0 - 10	76	5	19	nd
	10 - 50	66	4	30	nd
	50 - 100	56	10	34	nd

Note: nd refers to “not determined”

Appendix 6.1 (Continued) Soil particle size distribution and pH

Soil Sample/Soil Form	**Depth (cm)**	**% Sand 2.0 – 0.05 mm**	**%Silt 0.05 – 0.002 mm**	**%Clay < 0.002 mm**	**pH.H_2O**
1st HCT Dundee	0 - 10	64	7	29	4.7
	10 - 40	67	6	27	nd
	40 - 50	76	2	22	4.6
	50 - 90	74	7	19	5.0
	90 - 120	nd	nd	nd	5.4
	120 - 145	64	5	31	5.3
	145 - 160	47	10	43	5.2
	160 - 190	70	5	25	nd
	190 - 215	24	18	59	nd
	215 - 220	90	1	9	nd
	220 - 230	17	25	58	5.0
	230 - 320	27	27	46	4.6
	320 - 435	24	23	53	4.7
2nd HCT Dundee	0 - 70	65	5	30	4.6
	70 - 80	68	16	15	6.0
	80 - 110	35	11	55	5.3
	110 - 140	94	1	5	5.3
	140 - 160	55	8	37	4.9
	160 - 170	89	3	8	5.2
Below HCT2 Not determined	0 - 10	83	3	14	5.0
	10 - 40	80	2	18	5.0
	40 - 80	87	4	9	6.4
	80 - 100	50	8	41	nd
	100 - 110	81	11	8	nd
	110 - 150	90	1	9	5.5
	150 - 160	81	6	13	nd
	160 - 200	78	7	15	nd
	200 - 210	88	1	11	5.9

Note: nd refers to “not determined”

Appendix 7.1 Monthly rainfall data (1908 – 1999) from Wales Station (ICFR, 2005) ~ 2 km south of Craigieburn

Year	January	February	March	April	May	June	July	August	September	October	November	December	Annual Total
1908	78.2	56.1	138	41.5	10.4	3.4	13.2	2	3.4	19.9	108.4	139	613.5
1909	762.4	237.2	40.3	98.8	46.5	24.5	3.1	56.9	22.4	49.9	53.9	139	1534.9
1910	175.8	108	312.1	22.5	4.7	19.2	10.5	2.5	34.5	41.5	28.9	134.8	895
1911	74.6	81.9	142.3	79.1	44	1.6	35.9	10	9.5	196.8	86.9	82.1	844.7
1912	64.7	96.2	31.2	115.4	52.1	3.6	6.3	12.5	14.1	28.1	8.5	77.3	510
1913	21.1	51.3	18	125.6	26.9	15	18.6	53	17.1	21.2	131.4	97.7	596.9
1914	148.2	231.8	133	15.5	71.9	3.7	2.5	1.8	0.6	60.2	113.9	388	1171.1
1915	889	47.5	11.2	14.4	6.9	0.1	106.8	20.1	25.7	97.2	190.1	31.8	1440.8
1916	92.9	122.6	135.4	33.7	8.2	0.7	0	17.1	0.4	9.3	330	198.2	948.5
1917	42.7	70	19.1	22.8	92.1	52.5	5.7	83.4	87	137.6	58.9	154.6	826.4
1918	96.5	89.1	296.1	68.5	6.3	3.5	13.3	68.4	47.1	35.1	58.5	85.1	867.5
1919	69.2	260.6	24.9	27.7	43.6	11	2.7	10.9	31.7	64.8	161.5	95	803.6
1920	277.5	95.9	210.7	81.8	17.1	1.5	9.7	15.3	20.7	177.8	69.8	170.4	1148.2
1921	186.7	65.6	147.5	54.2	9.3	4.7	4.7	6	42.2	139.9	312.6	79.6	1053
1922	53	75.4	135.5	20.2	25	37.5	1.3	39.3	11	124.8	188.6	25.2	736.8
1923	425.8	99.1	27.8	17.7	4.8	0.2	2.8	0.2	11.1	24.4	16.9	100.5	731.3
1924	108	92.6	69.9	33.4	65.8	2.8	5.1	47.3	33.6	85.6	104.1	134.6	782.8
1925	149.6	102.3	656.2	71.7	63.7	15.9	30	2.6	48.6	98	64.7	46.3	1349.6
1926	62	139	126.2	11.6	36.1	13.7	54.8	4	19.7	1.5	111.5	143.7	723.8
1927	125.9	94.5	72.7	30.9	7.7	16.4	122.8	17.4	34.2	115.8	48.8	88.7	775.8
1928	168.7	78.5	95.6	49.5	10.8	0.8	14.8	5.9	12.7	55.5	57.5	114.1	664.4
1929	151.2	212.9	131.2	21.7	22.8	10.8	7.7	18.2	36.6	126.9	204.4	120	1064.4
1930	97.6	160.8	259.4	85.1	11.2	6.1	9.6	2.5	13	0.9	73.8	289.5	1009.5
1931	51.5	117	97.9	84.1	0.2	7	32.6	0.2	11.9	17.9	152.1	108	680.4
1932	130	51	72.1	45.7	23.1	2.7	0	0	12	17.5	85.8	135.4	575.3
1933	187.8	163.2	116.2	36.9	0.3	1.4	5.5	7.6	8.2	24.7	210.5	157.2	919.5
1934	182.7	72.2	90.4	63.6	12.6	16.8	1	3	16.6	94.3	66.6	132.5	752.3
1935	142.8	114.5	96.9	28	13.9	19.7	4.7	3.6	18.4	33	30.7	59.9	566.1
1936	209.6	180.9	152.7	39.2	33	10.7	11.3	4.4	85.7	160.6	148.5	268.6	1305.2
1937	199	298.8	113.2	56.4	0.9	0	1.9	16	32.1	16.3	77.3	186.8	998.7
1938	248.3	86.6	63.2	148.9	4.7	16	7.9	2.1	86.7	57.1	156.5	471.4	1349.4
1939	202.8	671.8	232.1	60.4	63.9	9.4	59.3	34.3	63.8	39.9	344.2	205.6	1987.5
1940	101.8	63.3	162.9	118.4	39.1	79.8	3.3	24.6	75.2	70.7	245.6	167.1	1151.8

Appendix 7.1 (Continued) Monthly rainfall data (1908 – 1999) from Wales Station (ICFR, 2005) ~ 2 km south of Craigieburn

Year	January	February	March	April	May	June	July	August	September	October	November	December	Annual Total
1941	115.4	93.2	145	210.4	0.7	0	6.6	16	9.2	50.6	73.2	315.8	1036.1
1942	204.3	120	163	22	56.5	72.4	3.6	55.5	77.5	126.4	122.8	127.6	1151.6
1943	135.5	148.8	167.7	195.6	23.9	0.4	41.8	40.8	54.4	36.3	109.2	69.1	1023.5
1944	137.6	328.9	59.2	19.8	0.5	22.8	0	17.5	26.2	106.9	167.3	62.7	949.4
1945	168.3	179.5	130.8	62.5	0.2	0	0	0	15.9	111.1	57.4	81.6	807.3
1946	473.4	284.9	141	35	21.4	5.2	0	8.6	0	42.7	115.9	115.2	1243.3
1947	147.2	225.2	118	108.7	12.7	29.7	20.7	0	18.1	48.1	261.4	291.3	1281.1
1948	153	126.9	318.7	98.8	24	0	11.4	0.1	36.2	83.6	62.8	77.8	993.3
1949	326.9	210.1	93	56.9	27.8	20.2	17.6	5.1	23.7	40.5	207	311	1339.8
1950	139.3	108	239.2	61.9	64.5	19.8	8.3	30.5	20.8	14.6	64	292.9	1063.8
1951	125	77	133.1	138.8	59.7	0.8	7.9	61.7	47.5	122	83.8	192.8	1050.1
1952	88	135	164.2	66	8.7	17.3	28	10.4	0.8	71.6	311.3	200.7	1102
1953	209.4	333.1	223.7	124.3	21.8	0	8.5	10.4	21.5	103	173.6	230.9	1460.2
1954	219.8	259.6	122.7	103.9	26.1	4.1	0	45.6	7.5	67.8	136.9	122.3	1116.3
1955	549.1	345.2	237.4	107.4	47	6.3	0.5	3.8	11.6	127.5	237	316.2	1989
1956	116	557.3	281.5	11.4	56.6	54.2	18.1	6.3	78.5	45.2	58.4	167	1450.5
1957	100.8	266.9	232	92	48.2	0.5	39.4	40.4	50.5	138.3	76.7	181.8	1267.5
1958	563.5	73.9	69.8	82.2	0.2	11.5	3.6	0	82.2	58.1	174	149.6	1268.6
1959	220.2	298.7	62.1	21.6	11.4	0	40	0.9	66.4	73.6	175.5	241.6	1212
1960	84	474.1	103.6	108.5	5.9	3.1	2.1	21.1	24.6	33.2	280	424.9	1565.1
1961	142	233.7	148.8	93.8	36.3	98.6	42	29.9	41.8	57.1	128.3	196.2	1248.5
1962	161.1	135.9	65.7	74.8	33	3.4	1	13.4	18.6	29.7	315.7	240.5	1092.8
1963	120.1	100.5	97.4	43.5	40.6	66.2	45.5	2.3	5.2	57	198.1	98.6	875
1964	277.9	124.9	70.5	44.6	40.4	3.6	1.4	7.3	5.5	119.8	93.2	226.8	1015.9
1965	220.9	219.2	58	50.8	13.6	2.4	0.6	2.8	56.5	42.5	146.6	56.2	870.1
1966	233	280.3	45.1	28.4	21	30	4.6	13.7	14.3	132.1	46.5	191.7	1040.7
1967	313.6	280.1	105.8	226.3	9.5	3.6	23.1	31.2	4.1	47.5	101.5	92.7	1239
1968	160.8	188.6	160.3	80.9	42.9	34.5	4.7	17.8	12.6	74.6	145.4	163.6	1086.7
1969	180.2	189	256.7	69.3	6.5	4.2	11.1	1.7	40.2	180.6	90.8	171.2	1201.5
1970	23.5	94.8	28.2	28.2	23.3	61.6	27.6	4.9	20.6	79.4	147.9	211.6	751.6
1971	280	116.1	121.1	151.5	30.6	22.1	0.5	5.5	40.1	125.6	143.4	199.8	1236.3
1972	449.1	304	291.6	85.1	49.9	5.4	2.9	9.1	10.1	112.2	119.7	91.6	1530.7

Appendix 7.1 (Continued) Monthly rainfall data (1908 – 1999) from Wales Station (ICFR, 2005) ~ 2 km south of Craigieburn

Year	January	February	March	April	May	June	July	August	September	October	November	December	Annual Total
1973	123.4	88.6	98.2	139.5	23.9	4.7	7.6	33.6	210.1	112.9	118.9	410.8	1372.2
1974	381.7	219.2	106.6	82.6	11.5	0.9	42.9	4.4	34.9	61.8	146.8	160.9	1254.2
1975	330	217.5	102.3	54.9	40.9	27.6	2	16.3	20.2	32	66.4	291.3	1201.4
1976	591.5	351.3	236.5	54.2	42	0	4.8	9.6	5	50.1	99.8	116.1	1560.9
1977	297.4	260	189.2	138.6	15.2	2.1	3.3	5.5	108.2	38	127	241.8	1426.3
1978	328.7	277.6	330.3	34	8	0.5	10.3	5.9	0.3	103.8	172	180.3	1451.7
1979	178.3	44.8	169.5	16.4	19.2	1.6	11.4	44.1	38.6	71.5	102	158.8	856.2
1980	143.9	215.1	170.6	24.5	18	0	6.6	28	58.9	75.4	227.3	197.8	1166.1
1981	368.2	348.8	146.3	39.5	29.6	2	0	34.9	19.4	74	98.6	84.2	1245.5
1982	164.7	26.6	57.3	140.9	21.5	0	67.5	17.4	26.2	44.8	61	42.5	670.4
1983	103.8	74.4	118.1	90.7	47.1	5.8	6.7	14.2	21.5	93.3	239.1	150.6	965.3
1984	92.2	66.7	192.9	47.4	4.9	7.7	109.9	15	40.1	118.8	122.1	67.3	885
1985	182.1	444.8	123	3.9	34.6	15.6	0.3	1.3	15.9	97	28	104.8	1051.3
1986	195	263	124	216	30	0	0	34	5	42.3	94	149.6	1152.9
1987	176.5	34.1	114	51	8.1	10.5	0	34	123.6	57.6	37.2	560	1206.6
1988	118	344	150	62.5	20	13	2.5	18	24.3	99.3	0	29.9	881.5
1989	0	0	0	0	0	52.4	0	10	10.9	86.1	222.5	190.3	572.2
1990	121.8	205.1	97.9	57	16.4	0	28.9	16.7	7	108	55.3	225.4	939.5
1991	171.4	149.3	186.1	4.2	24.8	73.5	0	6.8	25.3	35.1	85.7	119	881.2
1992	71.3	25	55.2	40.6	1.4	2	1.1	21.3	11	29.1	101.5	315.2	674.7
1993	138.6	150	363.9	56.5	14.6	17.6	1.5	18.6	7.1	87.9	124.7	238.5	1219.5
1994	197.6	86.4	122.4	13.3	0	0.5	1.1	1.5	9.1	102.2	47.2	131.9	713.2
1995	182.8	116.9	99.7	84.9	33.1	0	0.7	22.5	7.8	67.4	161.1	236.1	1013
1996	325.7	448.5	134.4	92.7	136.1	9.7	30.1	47.9	6.2	84.6	73.1	157.2	1546.2
1997	183.5	185.7	266.6	99.5	26.7	5.8	10.7	11.6	87.6	72.1	111.4	137.5	1198.7
1998	271.1	60.5	106	57.6	0	0.2	18.5	0	42.5	70.5	212.8	421.3	1261
1999	354.3	217	262.3	68.5	16	0.8	9.7	23.6	110.8	56.9	199.7	239.2	1558.8

Figure 5.1 Spatial distribution of homesteads and individual homes at Craigieburn from 1954 – 1997.