SECTION 2: MEASURED RAINFALL ATTRIBUTES, SURFACE TEMPERATURES AND GEOMORPHIC IMPLICATIONS

PREFACE

Section 2 comprises six Chapters and one Appendix that present and discuss measured data from the study area. They appear as follows:

Nel, W. and Sumner, P.D. 2005. First rainfall data from the KZN Drakensberg escarpment edge (2002 and 2003), *Water SA,* 31, 399-402.

Nel, W. Submitted. Observations on daily rainfall events in the KwaZulu-Natal Drakensberg. *Water SA.*

Nel, W. and Sumner, P.D. Submitted. Intensity, energy and erosivity attributes of storm events in the Drakensberg, South Africa. *Catena*.

Nel, W. Submitted. Intra-storm attributes of extreme storm events in the Drakensberg, South Africa. *Physical Geography*.

Sumner, P.D. and Nel, W. 2006. Surface-climate attributes at Injisuthi Outpost, Drakensberg, and possible ramifications for weathering. *Earth Surface Processes and Landforms,* 31, 1445-1451.

Nel, W. and Sumner, P.D. Submitted. Rainfall and temperature attributes on the Lesotho-KwaZulu-Natal Drakensberg escarpment edge, southern Africa. *Geografiska Annaler: A.*

APPENDIX:

Sumner, P.D., Meiklejohn, K.I., Nel, W. and Hedding, D.W. 2004. Thermal attributes of rock weathering: zonal or azonal? A comparison of rock temperature data from different environments. *Polar Geography,* 28, 79-92.

The first (Nel and Sumner; published in *Water SA* in 2005)[2] and second (submitted to *Water SA*) Chapters present the first measured contemporary rainfall data from the southern and northern KwaZulu-Natal Drakensberg escarpment. The first chapter introduces the reader to previous rainfall estimations on the escarpment as well as rain-catch deficiency that could exist in the mountains. It also presents findings on calibration issues between the D-MCS automatic gauges used by the author and the standard SAWS manual rain gauges. Rainfall measured suggests that earlier estimates for rainfall totals at the escarpment may be an over-estimation and that rainfall totals from the D-MCS automatic gauges and the standard SAWS manual rain gauge are comparable. The second chapter presents an analyses of rainfall totals generated from individual rainfall events at all altitudes. Daily rainfall and mean rainfall from individual events is less on the escarpment, but the number of rain days as well as the number of rainfall events increases with altitude. A high percentage of rain days recording single rainfall events are evident in the Drakensberg and these events contribute a high proportion of the total daily rainfall.

Chapter three (Nel and Sumner, submitted to Catena)[3] and Chapter four (submission to *Physical Geography*) of this section presents the first data and discussions on storm erosivity in the KwaZulu-Natal Drakensberg summit area and in the foothills east of the escarpment. Chapter three analyses the characteristics of individual storms as well as the rainfall intensity, kinetic energies, rainfall frequency and erosivity of storm events. Erosive events are shown to be a summer phenomena and the attributes of these storms; rainfall intensity, kinetic energy and erosivity are positively correlated with storm depth. A clear altitudinal trend when comparing maximum intensity, depths of erosive storms, cumulative kinetic energy and cumulative erosivity is found. Chapter four analyses the within-storm distribution of rainfall and kinetic energy attributes of extreme erosive rainfall events in the Drakensberg.

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[2] Paul Sumner provided inputs on the text as well as inputs on methodology. The original idea for the paper was mine, and I undertook the text compilation, submission and revision.

[3] The original idea for the paper was mine, and I analysed the data, undertook the text compilation and submission. Paul Sumner provided inputs on the text and discussion.

An exponential distribution of cumulative kinetic energy content of storm rainfall over time exists and most storms indicate a high proportion of rainfall and peak intensity being generated within the first half of the storm duration. This Chapter also highlights the need for further research to supplement the understanding of the relationship between rainfall and the subsequent soil loss dynamics from rainfall events in the Drakensberg.

The fifth Chapter (Sumner and Nel, published in *Earth Surface Processes and Landforms* in 2006)[4] presents general surface-weather conditions in the Drakensberg foothills and therefore adding to the very scarce database on temperatures in the Drakensberg. A predominance of summer rainfall is clearly evident extending from November towards the end of March and rainfall frequency and rock temperature records suggest an environment conducive to thermal fatigue and wetting a drying with potential for frost action. The differences in air, rock and soil surface temperatures underline the dissimilarity in environmental conditions experienced by the different mediums in the field as well as the problem in using air temperatures as a surrogate for rock temperatures in weathering studies. The data from this study are compared with similar data at higher altitude and it appears that with an increase in altitude up to the escarpment, air temperature decreases more rapidly than soil temperature.

The final Chapter of the thesis (submitted to *Geografiska Annaler: A*)[5] presents the longest contemporary rainfall, air and soil temperature data recorded on the Drakensberg escarpment edge. Rainfall totals less than records for the same period lower down the escarpment and challenges, the assumption of an increase in rainfall up to the escarpment, and the data show that earlier estimates for January and annual rainfall have been over-

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[4] The idea for the paper was mine and I initiated the methodological approach used in the paper. Paul Sumner was responsible for the first draft as well as the submission and revision. I was directly involved in data collection in the field and comments and discussions on the draft.

[5] Paul Sumner provided inputs on the text and on methodology. The original idea for the paper was mine, and I undertook the text compilation and submission.

estimated. Mean air temperature measured at the escarpment falls within the estimated range for the area, but is somewhat higher than the 3° to 4° MAAT postulated for the plateau peaks immediately behind the escarpment. Frost cycles in air and soil surface are found to be frequent in winter, but no long-duration, or seasonal freeze was found for the soil surface. In general the soil temperatures are higher than that of air and this chapter notes that air temperature cannot be convincingly used as a proxy to study soil frost.

The appended paper (Sumner *et al*. published in *Polar Geography* in 2004)[5] investigates the specific attributes of thermal conditions in four distinct climatic zones (including the Drakensberg) and analyses rock thermal conditions, with respect to mechanical disintegration in these environments. Findings recommend that although the settings differ greatly in terms of absolute air temperatures, they experience many similarities in terms of rock temperature changes; thereby nullifying the notion of zonality with regards to rock weathering.

FIRST RAINFALL DATA FROM THE KZN DRAKENSBERG ESCARPMENT EDGE (2002 AND 2003)

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ABSTRACT

Rainfall data for the KwaZulu-Natal Drakensberg escarpment, the first from above 2800 m a.s.l., are presented. Rainfall at the top of Sani Pass (2850 m a.s.l.) in the southern Drakensberg was 742 mm in 2002, while totals in the January months of 2002 and 2003 averaged 109 mm. Rainfall on Sentinel Peak (3165 m a.s.l.) in the northern KZN Drakensberg during 2003 was 765 mm and in January 2003 totalled 145 mm. Recorded rainfall at the two sites on the escarpment was marginally lower than, but within 6% of rainfall recorded at adjacent lower altitude Drakensberg stations over the same period. In the southern and northern Drakensberg, the number of rain days increased slightly with altitude and the data suggest that even though the amount of rainfall on the escarpment is similar to that at lower altitude, the frequency of rainfall events is higher on the escarpment. Even though 2002 and 2003 were dryer than normal years in the region, comparisons between this preliminary data with prior estimations where rainfall is expected to range between 1500 and 2000 mm p.a, it is possible that mean annual totals, and mean January rainfall, for the summit of the escarpment have been over-estimated in the past. Measurements to verify these data are ongoing.

INTRODUCTION

Rainfall data and accurate rainfall estimation in the Drakensberg and adjacent Lesotho highlands are of fundamental importance in geomorphological, hydrological and botanical research and form a basis for palaeoenvironmental reconstruction. For example, Partridge (1997) predicts precipitation at the Last Glacial Maximum (approx. 18 000 B.P.) to be in the region of 70% of current values. However, contemporary meteorological data are sparse (Boelhouwers and Meiklejohn, 2002) and measured rainfall data for the Drakensberg escarpment region (above 2500 m a.s.l.) do not exist on record. Rainfall estimation for the escarpment zone has been a topic of research in the past, notably by Tyson *et al*. (1976) and Schulze (1979). All rainfall data for the high Drakensberg are derived by projection from stations at lower altitudes. No rainfall records from the top of the escarpment have been forthcoming in recent years to verify these estimates, and most contemporary geomorphological research in the Drakensberg cite the values given by Tyson *et al*. (1976) and/or Schulze (1979) (e.g. Boelhouwers, 1988; 1991; 1994; Grab, 1994; 1996; 1999; 2002; Sumner, 2003). This paper presents the first measured rainfall data from the southern and northern KwaZulu-Natal Drakensberg escarpment as part of ongoing meteorological monitoring in the high mountain regions at the South Africa-Lesotho border.

PREVIOUS RESEARCH

The most comprehensive and most cited rainfall analyses for the escarpment area come from the 1970s. Tyson *et al*. (1976) indicate that mean annual rainfall increases with altitude, and that the top of the escarpment should receive over 2000 mm of rain annually. Stations in the Drakensberg are noted to experience an average of 16 to 18 rainy days in December and January, and the summer months November to March account for 70% of the annual rainfall, while May to August for less than 10%.

Schulze (1979) sketched a transect through the Central Drakensberg depicting mean annual rainfall and mean January rainfall from Hoffenthal in KZN to Mothelsessane in Lesotho. At Cleft Peak, situated on a transect and on the escarpment edge at 2880 m a.s.l., rainfall was only recorded for an unspecified short duration, and the monthly data synthesised to 21 years using Cathedral Peak 2A as base station. Schulze (1979) found a clearly defined relationship between altitude and rainfall, with the rainfall attaining a maximum before the highest altitude is reached. On the escarpment, mean annual rainfall is predicted at over 1800 mm, just 200 mm less than the estimate from Tyson *et al*. (1976). Mean January rainfall is estimated at over 250 mm (Schulze, 1979). From these two studies, contemporary rainfall exceeding 1500 mm p.a is typically quoted for the escarpment (e.g. Boelhouwers, 1991; Grab, 2002) and the value applied as a basis for palaeoenvironmental extrapolations.

EQUIPMENT AND CALIBRATION

In this study, rainfall at the escarpment edge is currently being measured at two locations using a Davis-MC Systems (D-MCS) automated tipping-bucket rain-gauge. The two sites are at the top of Sani Pass in the southern Drakensberg, and on Sentinel Peak in the northern Drakensberg. Both sites have established South African Weather Service stations at lower altitudes using standard SAWS manual-recording rain-gauges. As with the SAWS stations, daily rainfall is measured over a 24h cycle from 08h00 to 08h00 the following day. A rain day is defined as one on which at least 0.5 mm of rainfall is measured (Schulze, 1979).

The D-MCS gauge has a 163 mm collection diameter and logs total rainfall every 5min on a tipping resolution of 0.2 mm rainfall. Snowfalls are not recorded although some snow falls into the bucket and subsequent melt will be reflected in the records. No continuous snowfall records are available for the escarpment area. Rough estimates from observations in the area during 2002 and 2003, the beginning of the monitoring period, are that less than 0.5 m of snow fell on the escarpment each year, which translates into a water equivalent of approximately 50 mm (10%). In general, observations by the authors are that annual average snowfall cumulative depth is unlikely to exceed 1 m on horizontal surfaces during any calendar year, and the water equivalent will generally be less than 100 mm contribution to total precipitation.

Fundamental inaccuracies in the rain-catch by standard rain-gauges are well documented (e.g. Ward, 1975; Schulze, 1975; 1979). To test the difference in rain-catch between the standard SAWS rain-gauge and the D-MCS automatic rain-gauge, two D-MCS gauges were installed within a few metres from manual gauges at established SAWS stations; Glenisla Farm near Winterton in the central Drakensberg foothills (1060 m) and at the Royal Natal National Park office complex in the northern Drakensberg (1392 m). During the period from November 2001 to April 2003 the manual SAWS rain-gauge at Glenisla recorded 1471 mm of rainfall and the automatic rain-gauge recorded 1266 mm, a deficit of 14% from the SAWS data. The monthly rainfall totals measured by the two rain-gauges shows a similar trend (Fig. 1), however the deficit is apparent especially when rainfall is higher. In contrast, at the Royal Natal National Park station the D-MCS logger measured 3% more than the SAWS station records. Differences at stations could be attributed to gauge calibrations and human error, while the effect of varying intensities (possibly related to altitude and location) on accuracy may be a factor. Rain-catch deficiency is also exaggerated by windy conditions because of the formation of turbulent fields (Schulze, 1979) and it has been estimated that on the windswept higher altitudes of the Drakensberg, deficiencies in rain-catch are in excess of 8.1% (Schulze, 1979), possibly approaching 20% as reported by Rodda (1967) for windy sites (Schulze, 1979). Since the Royal Natal National Park station is located at a higher altitude and nearer to an escarpment monitoring site, more details on those comparative data are also provided in Table 1. Although the totals are similar at Royal Natal National Park, four fewer rainfall days are apparent from the manually recorded (SAWS) data, which could represent human error in records. This may apply only to small rainfall events recorded by the logger but not noted by observers and thus will not significantly affect totals. The difference in measured rainfall at Glenisla (Fig. 1) can only be contributed to gauge calibration, and between- gauge calibration still requires more detailed investigation given a larger data set. Notwithstanding this, the totals are deemed similar enough for direct comparison between SAWS and D-MCS data.

Rainfall Station	**Rainfall in 2003 (mm)**	**Rain Days**	**Rain Days (Dec-Jan)**	**Rain Days (May-Aug)**
Royal Natal National Park (SAWS)	774	100	26	10
Royal Natal National Park (D-MCS)	798	104	26	10
Sentinel Peak	765	107	26	8

Table 1: Rainfall and rain days in the northern Drakensberg during 2003

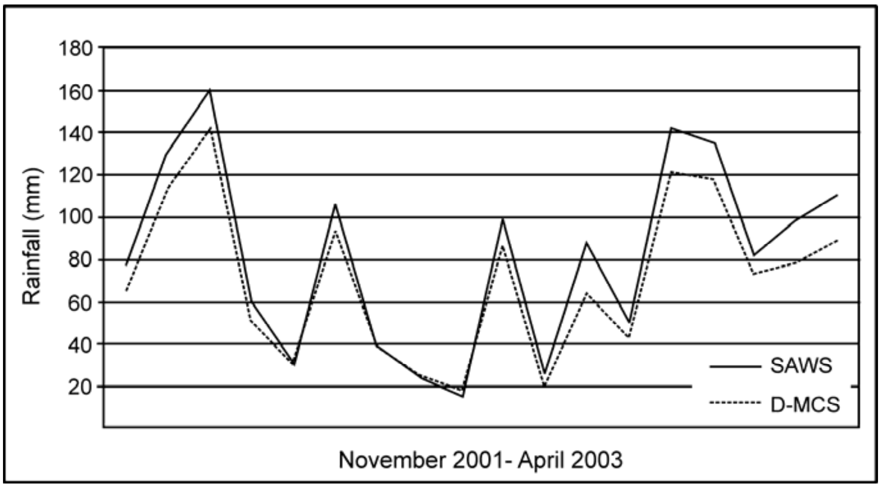

Figure 1: Monthly rainfall measured at Glenisla from November 2001 to April 2003

NEW RAINFALL DATA FROM 2002 AND 2003

At the southern Drakensberg escarpment edge site, monitoring of rainfall at the top of Sani Pass (2850 m a.s.l. 29.57° S, 29.27° E) adjacent to the chalet complex at the top of Sani Pass commenced from October 2001. High wind speeds caused the logger support platform to be damaged in mid-2003 and records for that year are incomplete. Data presented here are for the calendar year 2002 and for the two January months of 2002 and 2003. The logger has been subsequently re-established and monitoring is ongoing. Total rainfall recorded for the calendar year 2002 was 742 mm, while the rainfall in January 2002 and 2003 gave a mean of 109 mm (Tables 2 and 3).

Rainfall Station	**Rainfall in 2002 (mm)**	**Rain Days**	**Rain Days (Dec-Jan)**	**Rain Days (May-Aug)**
Himeville	799	83	32	9
Sani Pass Border Post	787	107	36	18
Sani Pass Top	742	141	44	28

Table 2: Rainfall and rain days in the southern Drakensberg during 2002

For comparative purposes, monthly rainfall data from 1970 to 2002 were obtained from the SAWS stations at lower altitude, namely the Sani Pass Border Post (2055 m a.s.l. 29.60° S, 29.35° E) and Himeville (1524 m a.s.l. 29.75° S, 29.53° E). These three stations depict rainfall trends with changing altitude in the southern Drakensberg (Table 3). The number of rain days increases with altitude, but the rainfall totals for 2002 show that rainfall on the escarpment was slightly less than at the lower altitude stations (e.g. 6% less than the Sani Pass Border Post station for the same period) (Table 2).

Rainfall Station	**Altitude (m)**	**Record**	**Mean Annual Rainfall (mm)**	**Mean January Rainfall (mm)**
Southern Drakensberg				
Himeville	1524	1970-2002	912	166
Sani Pass Border Post	2055	1970-2002	1176	221
Sani Pass Top	2850	2002	742	109 (2002, 2003)
Northern Drakensberg				
Royal Natal National Park (SAWS)	1392	1970-2002	1311	244
Sentinel Peak	3165	2003	765	145

Table 3: Altitudinal transect through the southern and northern Drakensberg

At the northern Drakensberg escarpment edge site, the freestanding Sentinel Peak (28.74º S, 28.89º E) is the highest point where rainfall is currently measured in Southern Africa (3165 m). Monitoring commenced in November 2001 although the D-MCS rain-gauge was either blown off the site or stolen during 2002 and the data lost. Data presented here are from the calendar year 2003. Rainfall for the year totalled 765 mm, a similar value to that obtained the previous year at the top of Sani Pass. Rainfall in January 2003 was 145 mm (Table 3), 36 mm more than the Sani average for 2002 and 2003 but substantially less than the estimate by Schulze (1979) of 250 mm. For comparison with lower altitudes data, long-term data from the SAWS station at Royal Natal National Park were obtained and, as noted above, a D-MCS rain-gauge logged during this period. As recorded at the top of Sani Pass, slightly less precipitation fell on the escarpment edge than at the next-lowest station, Royal Natal National Park (4% less than the D-MCS record) and three more rain days were recorded at the higher altitude.

In comparison to mean annual rainfall totals from established stations since 1970, years 2002 and 2003 were dryer than normal. Analysis of rainfall measured in 2002 at eight stations in the Drakensberg, all with well-established weather stations, ranges from 78 to 100% of the mean annual rainfall (33 years) and analysis of rainfall in 2003 at four stations ranges from 60 to 82% of the MAR (33 years). The totals measured at the top of Sani Pass in 2002 (742 mm) and on the Sentinel in 2003 (765 mm) are thus probably below long-term rainfall averages for the sites. Both escarpment edge sites recorded totals that were less than the next-lowest SAWS sites for the corresponding year, namely the Sani Pass Border Post (787 mm) in 2002 and the Royal Natal National Park station (774 mm) in 2003. Long-term averages for these two SAWS stations are 1176 mm p.a and 1311 mm p.a respectively (Table 3). It is thus unlikely that long-term averages for the high-altitude sites will exceed these lower station mean values and earlier estimates (Tyson *et al*., 1976; Schulze, 1979) for rainfall totals at the escarpment of between 1500 mm and 2000 mm p.a may thus be an over-estimation. The lower precipitation values at the escarpment edge also challenges the assumption of increasing rainfall with altitude in the Drakensberg. This is supported by recent research elsewhere that suggest altitude is not necessarily the only important factor influencing rainfall in mountainous areas (e.g. Prudhomme and Reed, 1998; Johansson and Chen, 2003; Konrad, 1996).

SUMMARY AND ONGOING RESEARCH

Limited data collected from above 2800 m in the southern and northern Drakensberg are the first records from high-altitude sites in Southern Africa at the escarpment. The data are part of an ongoing monitoring programme and the first complete calendar years are presented here. Although 2002 and 2003 were dryer than average years, estimates based on corresponding stations suggest that earlier estimates for rainfall totals at the escarpment of between 1500 mm and 2000 mm p.a may be an over-estimation. A similar scenario apparently exists for January estimates. More long-term data are required to verify findings.

Inherent and apparent errors also need to be considered further. Rain-gauge calibration requires detailed investigation where different gauge-types are used for comparison. Rain-catch deficiency is also exaggerated by windy conditions and recording errors in manual measurements are also apparent given the difference in rain days recorded with the two instruments at the Royal Natal National Park station in 2003. Since no snowfall records exist, the contribution of snow to precipitation totals is still largely unknown.

ACKNOWLEDGEMENTS

The Department of Geography, Geoinformatics and Meteorology at the University of Pretoria supplied the Davis-MC Systems (D-MCS) equipment. Ross and Julia Stockill from Glenisla are thanked for their meticulous rainfall records at the SAWS station and provision of accommodation. Mrs Glenda Swart at the South African Weather Service is gratefully acknowledged for the rainfall data provided. The support of the project by KZN Wildlife, and particularly that from management at Royal Natal National Park, is appreciated.

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OBSERVATIONS ON DAILY RAINFALL EVENTS IN THE KWAZULU-NATAL DRAKENSBERG

Werner Nel

Submitted: Short communication to *Water SA*

ABSTRACT

Five-minute rainfall data measured at different stations in the KwaZulu-Natal Drakensberg are presented and although the data is limited this paper is the first to analyse individual rainfall events in the area. The occurrence of rain days in the Drakensberg shows strong seasonality with most rain recorded during the summer months. Although the number of rain days as well as the number of rainfall events increases with an increase in altitude, the mean daily rainfall and mean rainfall generated from individual events is less on the escarpment than in the foothills. All stations show a high percentage of rain days with single rainfall events as well as a high proportion of rainfall received from events generating more than 10 mm, but the escarpment station receives less rainfall from these events than the stations in the foothills. It is known that rainfall in the Drakensberg is mostly generated from thunderstorms, and data presented here indicate that rainfall predominately occur in the late afternoon/early evening when sufficient cooling has possibly taken place for condensation and cloud formation to occur.

INTRODUCTION

Recently declared a Trans-Frontier National Park, the Drakensberg is part of the Main Escarpment of southern Africa, which extends as a passive margin around the sub-continent and reaches above 3000 m on the watershed border between KwaZulu-Natal and Lesotho. Rain producing systems in the Drakensberg consist of two types (Tyson *et al*., 1976). Large-scale line thunderstorms and orographically induced storms provide the major source of rainfall over the Drakensberg in the extended summer period. While frontal systems develop as closed low-pressure cells in the western Atlantic and move across southern Africa in a west-northwest to east-southeast direction bringing widespread rainfall in winter (Tyson *et al*., 1976). Mean annual rainfall is estimated to vary between 700 mm in the northeast and south (Schulze, 1979) to over 1800 and 2000 mm on top of the escarpment (Tyson *et al*, 1975; Schulze, 1979). Recently however, data collected by Nel and Sumner (2005) from the southern and northern Drakensberg suggest that these earlier estimates of rainfall totals at the escarpment may be an over-estimation. Stations in the Drakensberg are known to experience an average of 16 to 18 rain days in the months of December and January (Tyson *et al.*, 1976), and the summer months November to March account for 75% of the annual rainfall, whilst May to August accounts for less than 10% (Nel and Sumner, 2006).

Given the remoteness of the area, especially the escarpment region, high-resolution rainfall data are sparse. Most of the above-mentioned rainfall analysis and estimations were done with daily or monthly rainfall totals, which is insufficient to assess the characteristics of individual rainfall events. This paper presents the first effort to analyse individual rainfall events in the KwaZulu-Natal Drakensberg as part of ongoing meteorological monitoring in the high mountain regions of the South African eastern escarpment.

STUDY SITES AND DATA COLLECTION

Davis-MC Systems (D-MCS) automated tipping-bucket rain gauges were installed at five locations within the Drakensberg. The D-MCS rainfall gauges have a 163 mm collection diameter and log total rainfall every 5 minutes on a tipping resolution of 0.2 mm. Records by the D-MCS are deemed comparable against manual recording rain-gauges used at the South African Weather Service stations (Nel and Sumner, 2005). Two sites on the escarpment edge are at the top of Sani Pass (29.57° S, 29.27° E, 2850 m a.s.l.) in what is known as the southern Drakensberg and at the Sentinel Peak (28.74° S, 28.89° E, 3165 m) in the northern Drakensberg. Rainfall gauges where also installed in the foothills at the Royal Natal National Park (RNNP) (28.68° S, 28.95° E, 1392 m) also in the north, and on the farm Glenisla (29.02° S, 29.49° E, 1060 m) and the Injisuthi Outpost (29.13° S, 29.45° E, 1920 m) both in the central Drakensberg. Five-minute rainfall data that have been analysed here were recorded over a 17-months (516 days) period between December 2001 and April 2003 at four stations (Sani Pass, Glenisla, Injisuthi Outpost and Royal Natal National Park) and during 2003 at the Sentinel Peak, Injisuthi Outpost and Royal Natal National Park.

DAILY RAINFALL

In this study daily rainfall is measured over a 24h cycle from 00h00 to 00h00 the following day and a rain day is defined as one on which at least 0.5 mm of rainfall is measured (Schulze, 1979). Royal Natal National Park (RNNP) measured 1559.4 mm of rainfall from December 2001 to April 2003 in 166 rain days, while Sani Pass, Injisuthi Outpost (Outpost) and Glenisla measured 1303.6 mm, 1345.6 mm and 1139.0 mm in 210, 205 and 139 rain days respectively (Table 1). Glenisla recorded the highest rainfall per day of 62.4 mm, while Royal Natal National Park (RNNP), Sani Pass and the Outpost measured maximum daily rainfall of 59.8 mm, 55.6 mm and 44.4 mm respectively. Daily rainfall measured at RNNP shows that an average of 9.4 mm of rain is recorded per rain day. Glenisla, Outpost and Sani Pass measured lower rainfall per rain day of 8.2 mm, 6.7 mm and 6.2 mm respectively (Table 1). Differences can also be discerned when comparing rainfall totals and number of rain days measured during 2003 at RNNP (1392 m) and Sentinel Peak (3165 m) (Table 1). Even though these stations are in close proximity of each other, they have an altitude difference of 1773 m. During 2003, Sentinel Peak recorded 754.4 mm of total daily rainfall that were measured in 115 days. RNNP measured 773.0 mm but in only 96 days, giving a mean of 8.1 mm of rainfall per rain day for 2003 (Table 1).

Station	**Recording period**	**Total daily rainfall (mm)**	**No. of rain days**	**Maximum daily rainfall (mm)**	**Mean rainfall/rain day**
Sani Pass (2850 m.a.s.l.)	Dec 2001 to Apr 2003	1303.6	210	55.6	6.2
Outpost (1920 m.a.s.l.)	Dec 2001 to Apr 2003	1345.6	205	44.4	6.7
RNNP (1392 m.a.s.l.)	Dec 2001 to Apr 2003	1559.4	166	59.8	9.4
Glenisla (1060 m.a.s.l.)	Dec 2001 to Apr 2003	1139.0	139	62.4	8.2
Sentinel Peak (3165 m.a.s.l.)	2003	754.4	115	50.0	6.6
Outpost (1920 m.a.s.l.)	2003	724.2	123	44.0	5.9
RNNP (1392 m.a.s.l.)	2003	773.0	96	59.8	8.1

Table 1: Daily rainfall characteristics measured at the recording stations in the KZN Drakensberg.

The monthly distribution of rain days measured at the different stations was calculated and all stations show that rain days predominate during the summer months (Fig. 1), with the highest number of rain days measured in December and the lowest in July. The high altitude station, Sani Pass, has a higher number of rain days in total and also measured more rain days during the winter of 2002 (May to September) and the summer of 2002/2003 than the stations at lower altitude (Fig. 1).

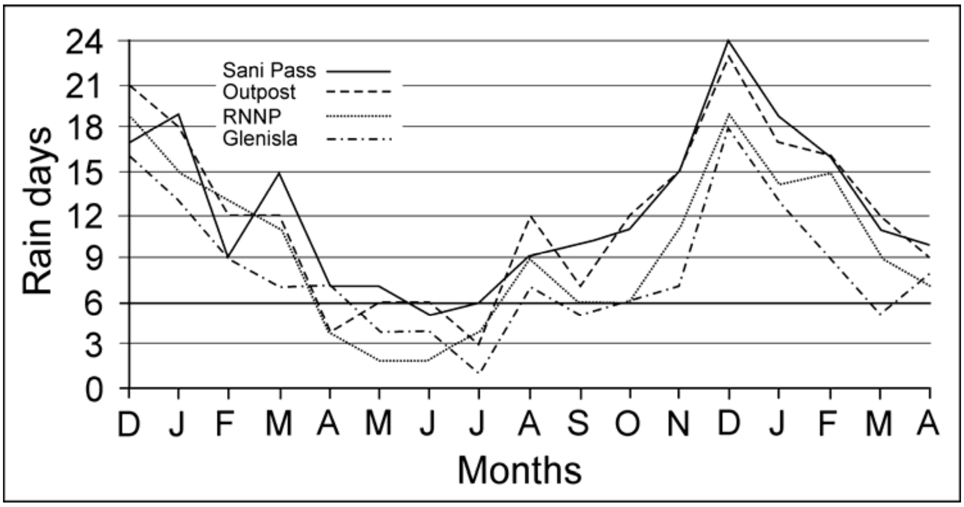

Figure 1: Number of monthly rain days recorded at the stations from December 2001 to April 2003.

The amount of rainfall recorded in a certain hour as a percentage of total rainfall at the different stations was also considered (Fig. 2). Rainfall at all four stations predominantly falls in the latter part of the day with 75% of the total rainfall falling between 12h00 and 24h00. Most stations show peak rainfall in the late afternoon/early evening between 19h00 and 21h00 and 46% of the total rainfall were measured between 16h00 and 22h00 (Fig. 2).

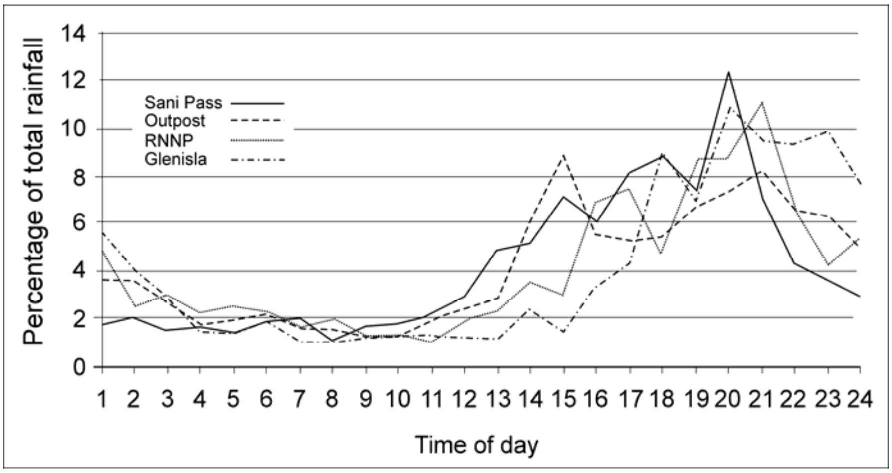

Figure 2: Timing of daily rainfall measured at the respective stations.

RAINFALL EVENTS

For this study a discreet rainfall event is defined as one that generates more than 0.5 mm of rain and is separated from the next event by more than three hours. Sani Pass measured 231 rainfall events during the recording period, while Injisuthi Outpost, RNNP and Glenisla measured 223, 205 and 161 respectively (Table 2). Rainfall measured from each individual events recorded at the different stations indicate that RNNP has on average the highest rainfall generated by each event with 7.6 mm per event. The high altitude station at Sani Pass has the lowest mean event rainfall with 5.5 mm per event. All stations show that a high percentage of rain days only record a single rainfall event. At Sani Pass of the 210 rain days that were recorded, 162 days only measured single rainfall events. Injisuthi Outpost, RNNP and Glenisla recorded single events on 156, 127 and 117 days respectively (Table 2). Of the total rainfall recorded at Glenisla, 81% is generated during days that only record a single discreet rainfall event (Table 2). Sani Pass has the lowest percentage of total rainfall generated during days with single rainfall events with 61%. Sani Pass and RNNP also have the highest number of days (5) measuring three rainfall events, while the Outpost only measured three discreet rainfall events on three days and Glenisla did not record a single day with three rainfall events. No station recorded more than three discreet rainfall events per day.

The number of rainfall events that generate more than 10 mm was also considered at each station (Table 2). Rainfall events above this threshold measured at Royal Natal National Park generate approximately 70% of the total rainfall measured at that station. Rainfall events at Sani Pass with rainfall above 10 mm only generate 47% of the total rainfall.

Station	No of rainfall events	Mean event rainfall (mm)	Days with 1 event	Rainfall from 1 event/day (mm)	Percentage of total rainfall	No events> 10mm	Rainfall from events >10mm	Percentage of total rainfall
Sani Pass	231	5.5	162	795.4	61	29	594.8	47
Outpost	223	5.9	156	835.2	62	34	705.6	54
RNNP	205	7.6	127	1172.4	75	50	1082.2	69
Glenisla	161	7.1	117	922.6	81	36	741.8	65

Table 2: Rainfall event characteristics measured at the recording stations for the period December 2001 to April 2003.

DISCUSSION

Rainfall measured in 2002 at eight stations in the Drakensberg, all with well-established weather stations, ranges from 78 to 100% of the mean annual rainfall (MAR) (33 years) and analysis of rainfall in 2003 at four stations ranges from 60 to 82% of the MAR (33 years) (Nel and Sumner, 2005). The totals measured from December 2001 to April 2003, and for the year 2003, at the respective stations in this study are thus probably slightly below long-term rainfall averages for the sites. Even though there are latitudinal differences in station positions, latitude is found to play no significant role in influencing rainfall totals (Nel and Sumner, 2006). Below 2100 m a.s.l. in the Drakensberg, mean annual rainfall is strongly related to altitude and eastward distance from the escarpment (Nel and Sumner 2006). Above 2100 m a.s.l. where no long-term data are available, the trend of increasing precipitation has been assumed to extend to the escarpment summit, where rainfall is anticipated to exceed 1500 mm p.a. (Tyson *et al*., 1976; Schulze, 1979). During the recording period in this study, the two escarpment sites, Sani Pass and Sentinel Peak, recorded less total and mean daily precipitation than the lower altitude stations and the precipitation values at the escarpment edge, therefore, challenges the assumption of increasing rainfall with altitude in the Drakensberg up to the escarpment. Rainfall in the Drakensberg is highly seasonal (Nel and Sumner, 2006) and the monthly distribution of rain days indicates the predominance of rain during the summer months. Even though daily rainfall is less on the escarpment, the number of rain days recorded increases with altitude.

Line and orographically induced thunderstorms provide the major source of rainfall over the Drakensberg, and most rainfall events in the high Drakensberg occur in the late afternoon/early evening with most stations showing peak rainfall occurring between 19h00 and 21h00 when sufficient cooling has occurred for condensation and cloud formation. An increase in the number of rain events also exists with altitude, but less rain falls per event on the escarpment than at the stations at lower altitude. All stations show a high percentage of rain days that record single rainfall events only and these events contribute between 61 and 81% of the total daily rainfall with a decrease in contribution with altitude. The high altitude station also record higher contributions to the overall rainfall totals from rain days that record two or three events. The number of rainfall events that generate more than 10 mm show that altitudinal difference can also be discerned with regards to the amount of rainfall generated by these high rainfall events. Rainfall events that generated precipitation above this threshold are less on the escarpment than stations in the foothills with Sani Pass only measuring 47% of the total rainfall from these events. At Sentinel Peak rainfall events above 10 mm generated 60% of the total rainfall measured during 2003. This compares well to the figure of Berding (1981) for northern Lesotho, where 50% of the annual rainfall was received by events of 10 mm or more.

SUMMARY

The rainfall records presented here are the first data that analysis specific rainfall events in KwaZulu-Natal Drakensberg. The rainfall records challenges the assumption of an increase in rainfall with altitude in the Drakensberg up to the escarpment. Even though daily rainfall and mean rainfall from individual events is less on the escarpment, the number of rain days as well as the number of rainfall events increases with altitude. All stations also show a high percentage of rain days recording single rainfall events and these events contribute between 61 and 81% of the total daily rainfall. However, the station on the escarpment has a lower contribution to the overall rainfall totals from rain days with single rainfall events than the low altitude stations.

Clear altitudinal differences also exists with regards to the amount of rainfall generated by events of 10 mm or more, with the escarpment stations receiving less rainfall from high rainfall events than the stations in the foothills. Most rainfall events in the high Drakensberg occur in the late afternoon/early evening when sufficient cooling would have occurred for condensation and cloud formation.

ACKNOWLEDGEMENTS

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INTENSITY, ENERGY AND EROSIVITY ATTRIBUTES OF STORM EVENTS IN THE DRAKENSBERG, SOUTH AFRICA

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ABSTRACT

Rainfall intensity, kinetic energy and erosivity were analysed for 106 erosive storm events at five locations from the end of 2001 to the beginning of 2006 in the KwaZulu-Natal Drakensberg, a portion of the eastern escarpment of southern Africa. Three stations located in the escarpment foothills and two stations sited on the escarpment edge above 2800 m a.s.l. provide the first detailed rainfall data for the Drakensberg escarpment summit areas. Erosive storm events, defined as a total rainfall exceeding 12.5 mm and a maximum 5-minute intensity exceeding 25 mm/hour, are found to vary in duration and in depth, but that the distribution is biased towards shorter shallower storms. Erosive events are also almost exclusively a summer phenomena and the attributes of these storms; rainfall intensity, kinetic energy and erosivity are positively correlated with storm depth but not the duration of the storm. Inter-station similarities exist when comparing rainfall totals, mean kinetic energies and erosivities from individual storm events. However, this study has found a clear altitudinal trend when comparing maximum intensity, depths of erosive storms, cumulative kinetic energy and cumulative erosivity. An increase in altitude gives a decrease in maximum rainfall intensity, number of high intensity events and the cumulative kinetic energy and erosivity. Potential to detach soil does exist on the escarpment, but the frequency of erosive events as well as the extent of collective erosive effect decreases with an increase in altitude. Analysis of the monthly distribution of erosive events suggest that the differences in cumulative kinetic energy and cumulative erosivity can be explained by the lack of erosive events during early and late summer at the escarpment, and significant erosive rains during this period at lower altitudes in the foothills.

INTRODUCTION

The KwaZulu-Natal Drakensberg in the east of South Africa is part of the Main Escarpment of southern Africa that extends as a passive margin around the sub-continent. South Africa is predominantly a semi-arid country; and it is only primarily areas in the east that record rainfall above 600 mm (Schulze, 1979). In the high mountains, that reaches up to 3482 m a.s.l., annual rainfall totals have been estimated to exceed 1500mm although recent records show this could be an overestimate (Nel and Sumner, 2005). The Drakensberg is considered South Africa's most important source of runoff and was recently declared a World Heritage site. Typically, the escarpment reaches above 2800-3000 m and defines the watershed between the interior catchments of Lesotho that feed into the Orange river, and the shorter and steeper catchments of the rivers in the province of KwaZulu-Natal (Fig. 1). KwaZulu-Natal contributes nearly twice as much total runoff per unit of rainfall than in South Africa as a whole and a quarter of South Africa's streamflow (Whitmore, 1970). Rainfall in the Drakensberg is highly seasonal with the five summer months (November to March) accounting for 75% of the annual rainfall, whilst winter months (May to August) contribute less than 10% (Nel and Sumner, 2006). The major source of precipitation over the Drakensberg is large-scale line thunderstorms and orographically induced storms that develop mostly over the extended summer period (Tyson *et al*., 1976). During winter, just over 40 cold fronts affect KwaZulu-Natal annually (Grab and Simpson, 2000). These develop as closed low-pressure cells in the western Atlantic and move across southern Africa in a west-northwest to east-southeast direction (Tyson *et al*., 1976) bringing widespread rainfall to the Drakensberg. Occasional snowfalls are thought to contribute around 100 mm water equivalent to precipitation totals (Nel and Sumner, 2005), or less than 10% of the rainfall total, but the precise contribution remains unmeasured.

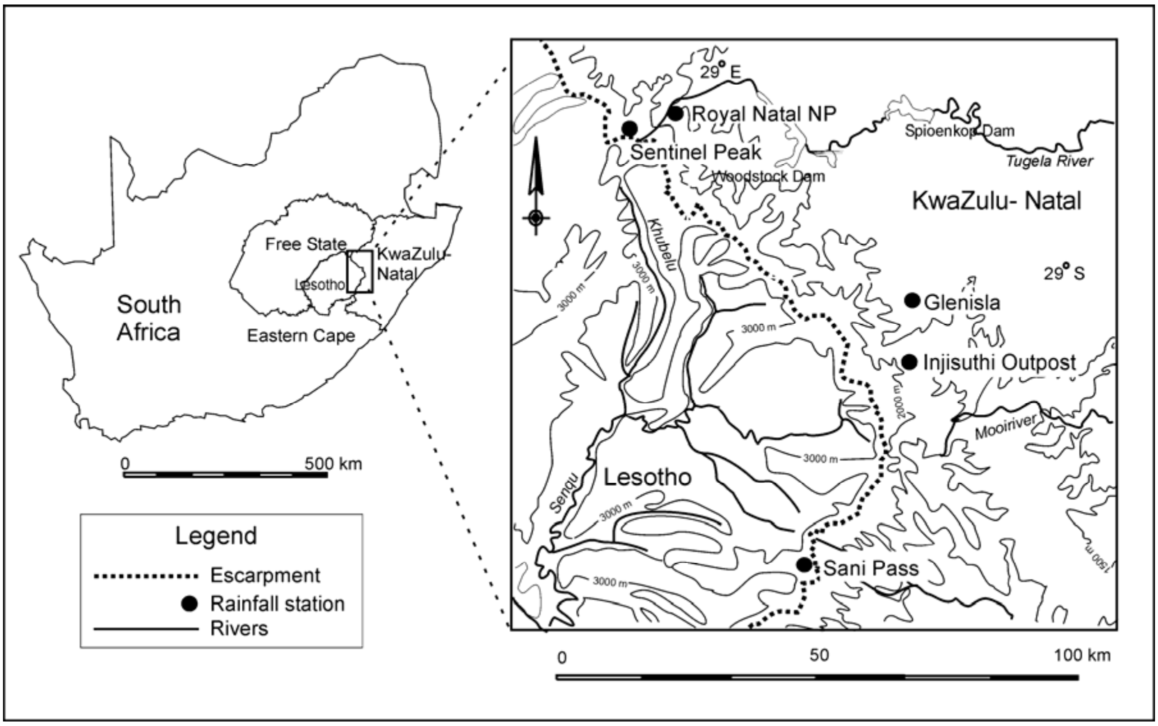


Figure 1: Map of the KwaZulu-Natal Drakensberg and the location of rainfall stations. The escarpment edge corresponds closely to the international border.

Rainfall in the Drakensberg is of primary significance because of the mountain's ecological importance, and also since the high altitude sub-catchments regulate discharge, particularly during low-flow conditions. Rainfall influences the creation of surface runoff and detachment of soil particles (Moore, 1979) and the erosivity of rainfall in the Drakensberg is a major driving force of many of the hydrological and erosional processes. The key process in water erosion and the amount of soil that is detached by a particular depth of rain is related to the intensity at which this rain falls (Van Dijk *et al*., 2002). The combination of rainfall intensity and raindrop fall velocity influence soil splash rate (Ellison, 1944) and the amount of erosion caused by rainfall from a certain storm is a function of the rainfall physical characteristics including intensity, amount (or rain depth), drop size distribution, terminal fall velocity, wind speed and rain inclination (Obi and Salako, 1995). In particular, rainfall kinetic energy has been suggested as an indicator of rainfall erosivity (Free, 1960). Direct measurements of kinetic energy and raindrop sizes are in most cases not readily available, unlike rainfall intensity; hence the development of empirical relationships between rain intensity and kinetic energy (Nyssen *et al*., 2005).

Few studies have investigated contemporary rainfall erosivity in the KwaZulu-Natal Drakensberg area. Schulze (1979) undertook a preliminary investigation into the kinetic energy of rainfall using two low altitudinal stations in the Central Drakensberg (Cathedral Peak at 1854 m and Ntabamhlope Research Station at 1457 m a.s.l.). More recently, in a study of rainfall erosivity of southern Africa, Seuffert *et al*. (1999) used one station in the central Drakensberg foothills as representative of the mountainous area. Given the paucity of existing data the aim of this study is to investigate storm erosivity in the KwaZulu-Natal Drakensberg summit area and in the foothills east of the escarpment. First, the study analyses the characteristics of individual storms. Second, rainfall intensity and kinetic energies of the storm events are examined, and finally, rainfall frequency and magnitude of the erosivity of storm events is determined.

STUDY SITES AND DATA COLLECTION

Davis-MC Systems (D-MCS) automated tipping-bucket rain gauges were installed at five locations within the Drakensberg. The D-MCS rainfall gauges have a 163 mm collection diameter and log total rainfall every 5min on a tipping resolution of 0.2 mm rainfall. Two sites are on the escarpment edge, one at the summit of Sani Pass (2850 m a.s.l.) in what is known as the southern Drakensberg and on the Sentinel Peak (3165 m) in the northern Drakensberg. Rainfall gauges where also installed in the foothills at the Royal Natal National Park (RNNP) (1392 m), also in the north, and on the farm Glenisla (1060 m) and the Injisuthi Outpost (1920 m) both in the central Drakensberg (Fig. 1, Table 1). The two high altitude stations are the first that attempt to record detailed and long-term rainfall data from the upper reaches of the catchments.

Station	**Recording days**	**Number of erosive storms**	**Total rainfall (mm)**	**Total storm depth (mm)**	**Total storm duration (min)**	**No. $I_5 >$ 50mm/h**
Sani Pass (Altitude 2850m)	1425	9	3172	252.2	3465	5
Sentinel Peak (Altitude 3165m)	1201	11	2660.8	321.2	4170	6
Royal Natal NP (Altitude 1392m)	1147	49	3145	1249.6	29756	29
Injisuthi Outpost (Altitude 1920m)	806	14	1917	348.4	4035	7
Glenisla (Altitude 1060m)	528	23	1270	515.8	3840	14

Table 1: General characteristics of erosive events measured at the rain gauge stations in the KwaZulu-Natal Drakensberg.

Rainfall at the top of Sani Pass was monitored from September 2001 to mid April 2003. Then some data were lost due to wind damage but records commenced again from early September 2003 to early January 2006. Total records for this station span over 1425 days. Monitoring on the summit of the Sentinel Peak commenced in late November 2002 and data presented here are for 1201 days from the 28th of November 2002 to the 12th of March 2006. At the RNNP rainfall recording began on the 21st of November 2001 and ended on the 10th of January 2005 (1147 days). Data presented here for the Injisuthi Outpost are from the 29th of October 2001 to the 12th of January 2004 (828 days) and at Glenisla from the 29th of October 2001 to the 30th of April 2003 (528 days) (Table 1, Table 2).

Station	**Recording period**	**Total rainfall (mm)**	**Erosive rainfall (mm)**	**(%)**	**Kinetic Energy (J m^{-2})**	**Erosivity (J mm m^{-2} h^{-1})**
Sani Pass (2850 m.a.s.l.)	December 2001 to April 2003	1330.8	182.4	13.7	3556	155 256
Outpost (1920 m.a.s.l.)	December 2001 to April 2003	1363.0	238	17.5	4409	124 985
RNNP (1392 m.a.s.l.)	December 2001 to April 2003	1591.4	536.8	33.7	11542	351 370
Glenisla (1060 m.a.s.l.)	December 2001 to April 2003	1202	473.6	39.4	10212	360 460
Sentinel Peak (3165 m.a.s.l.)	2003	764.8	40.6	5.3	705	11 976
Outpost (1920 m.a.s.l.)	2003	741.8	99	13.3	1656	34 572
RNNP (1392 m.a.s.l.)	2003	798.8	242.4	30.3	5021	152 451

Table 2: Erosive rain attributes as measured for selected periods in the KwaZulu-Natal Drakensberg

DATA ANALYSIS AND RESULTS

Stocking and Elwell (1976) classify a distinct erosive rainfall event as a storm when total rainfall exceeds 12.5 mm, maximum 5-minute intensity exceeds 25 mm/hour and the event is isolated by at least a two-hour period of no rain. With this definition, the data series from the five gauge locations used in this study contain 106 individual erosive storm events.

Storm characteristics

Of the 106 individual erosive storm events the Royal Natal National Park station measured 49 storms. At Glenisla farm 23 storms were measured, at Injisuthi Outpost 14 and at Sani Pass and at the Sentinel Peak, 9 and 11 storms with erosive energy were measured respectively (Table 1). The shortest erosive storm that was recorded had a duration of 20 minutes and the longest had a duration of 26 hours. Erosive storm events had an average duration of 279 minutes (4 hours and 36 min) but the distribution is noticeably skewed (CV =

1.0) with 25% of the storms being shorter than 106 minutes (1 hour and 46 min) and 75% shorter than 335 minutes (5 hours and 36 min). The mean amount from all measured individual storm events is 25.3 mm with the lowest totaling 12.6 mm and the highest 72.0 mm. This distribution is also skewed (CV = 0.5) with 25% of all storms having a rainfall depth of between 12.6 and 15.7 mm, 75% of the events have rainfall of less than 29.5 mm and 90% of all storms have a rainfall depth of less than 47.3 mm. A comparison between storm depth and storm duration shows a statistically significant ($P> 0.001$) positive correlation ($R= 0.61$) (Fig. 2).

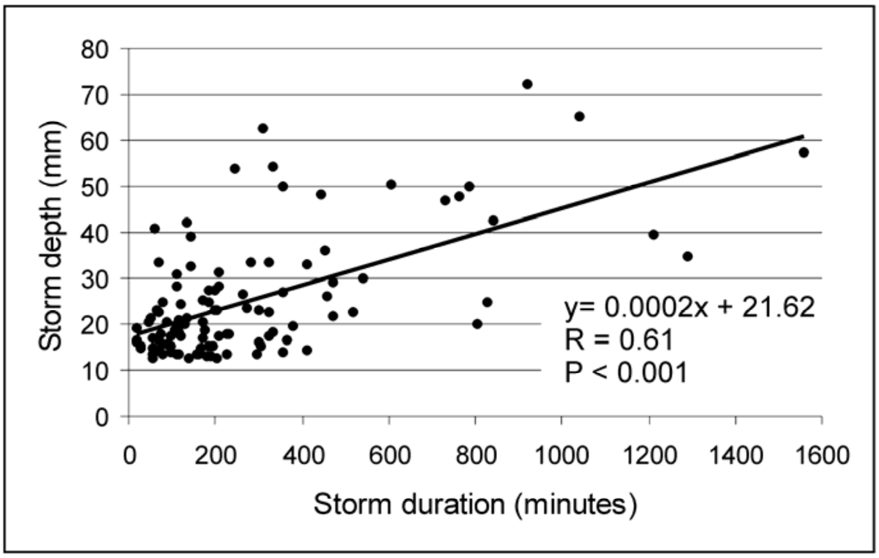


Figure 2: Correlation between storm depth and storm duration.

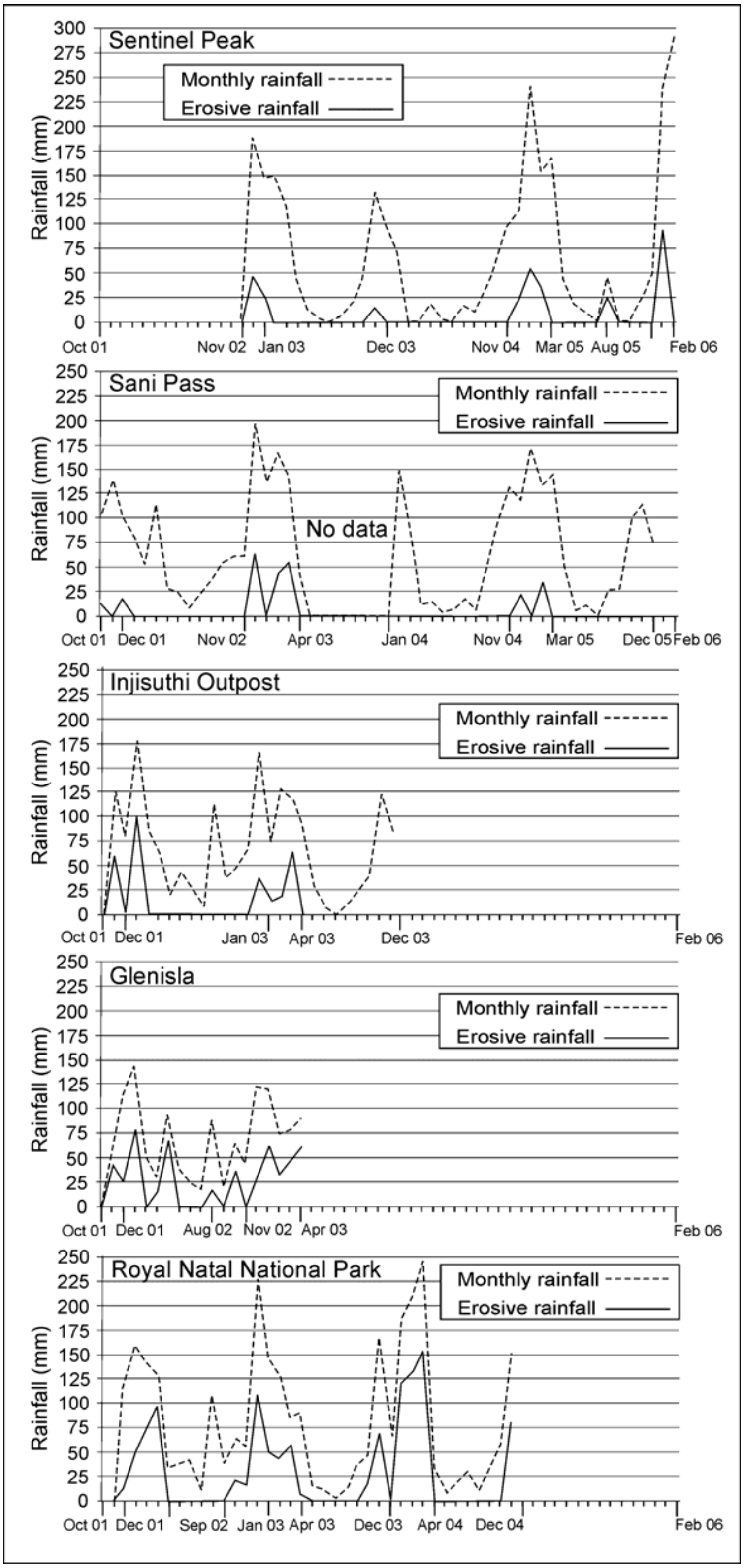


Figure 3: Monthly rainfall and erosive rainfall as measured at stations in the Drakensberg.

Given the seasonality of rainfall in the Drakensberg (Nel and Sumner, 2006) monthly rainfall (in mm) for the recorded period at each station was compared to monthly erosive rainfall (in mm) (Fig. 3). At Royal Natal National Park and Glenisla stations approximately 40% of the total rainfall measured at these stations are derived from erosive rainfall events. The high altitude stations, Sani Pass and Sentinel Peak, have the lowest percentage of rainfall generated from erosive events to total rainfall with 8 and 12 percent respectively. No erosive storms occurred at the recording sites during the months of May, June, July and September (Fig. 3) even though collectively 907.4 mm of rainfall were recorded at the sites during these months. Glenisla and Sentinel Peak recorded one erosive event each during August, and all other erosive rainfall events at the stations occurred from October to April with the highest number of erosive storms during January. Comparing monthly rainfall and erosive rainfall measured during 2003 at Royal Natal National Park (1392 m) and Sentinel Peak (3165 m) that are in close proximity of each other (Fig. 1), but have an altitude difference of 1773 m, a difference in the distribution and magnitude of monthly erosive events is evident (Table 2). During 2003, Sentinel Peak recorded 764.8 mm of total rainfall, from which 40.6 mm fell as erosive events (5%). At the Royal Natal National Park 798.8 mm were recorded from which 242.4 mm fell as erosive events (30%). Comparatively, during 2003 at the Injisuthi Outpost at an altitude of 1920 m, 741.8 mm of rainfall fell from which 99 mm was during erosive events (13%). Although all three stations only recorded erosive events during the summer months some difference do exist in the intra-annual distribution of erosive events. During the early and late summer months of 2003 (February, March and October) at the Sentinel, 313.2 mm of rainfall fell but no erosive events were recorded. For the same period at Injisuthi Outpost 285.2 mm fell from which 85.6 mm were from erosive events (30%) and at the Royal Natal National Park 256.8 mm fell from which 115.8 mm were from erosive events (45%). When comparing 17 months of 5-minute rainfall data from December 2001 to April 2003 at Sani Pass, Glenisla, Injisuthi Outpost and Royal Natal National Park (Table 2) an altitudinal difference in the rainfall generated during erosive events as a percentage of total rainfall is apparent. At Glenisla (1060 m) 1202 mm fell from which 473.6 mm are from erosive events

(39%). At Royal Natal National Park (1392 m), 1591.4 mm fell and 536.8 mm were during erosive events (34%). Injisuthi Outpost (1920 m), which is close to Glenisla but at higher altitude (Fig. 1) recorded 1363 mm from which 238 mm fell as erosive events (18%) and at Sani Pass (2850 m) 1330.8 mm of rainfall were recorded but only 182.4 mm was generated by erosive events (14%). The main differences between stations is that the higher altitude stations (Injisuthi Outpost and Sani Pass) recorded no erosive events during the early and late summer months of 2002 (March, April and October) while the lower altitude stations did record substantial erosive rains during this period (Fig. 3).

Rainfall intensity

Five-minute rainfall intensity (I_5) of erosive events measured at the different stations, range from 26.4 mm/h to 144 mm/h and 30-minute rainfall intensity (I_{30}) range from 8 mm/h to 70.4 mm/h (Table 3). At Glenisla rainfall intensity of 144 mm/h in 5 minutes was recorded (Table 3, Fig. 4) and this was the maximum 5-minute rainfall intensity measured in the Drakensberg during the recording period. At RNNP 120 mm/h in 5 minutes was recorded and at the Injisuthi Outpost, Sani Pass and Sentinel Peak the maximum I_5 measured during an individual storm was less with 93.6 mm/h, 79.2 mm/h and 69.6 mm/h respectively (Table 3, Fig. 4). Again altitude appears to have an influence, but mean 5 minute and 30 minute rainfall intensities measured at the different locations for individual events, show no measurable differences (Table 3). A comparison between storm depth and mean storm intensity, maximum intensities for 5 minutes (I_5) and 30 minutes (I_{30}) were attained for all erosive events (Fig. 5). There is a statistically significant, positive correlation between storm depth and maximum 5-minutes intensity (I_5) ($R= 0.25$, $P= 0.01$) and storm depth and maximum 30-minutes intensity (I_{30}) ($R= 0.54$, $P< 0.001$). However, no statistically significant correlation exists between mean intensity and storm depth (Fig. 5).

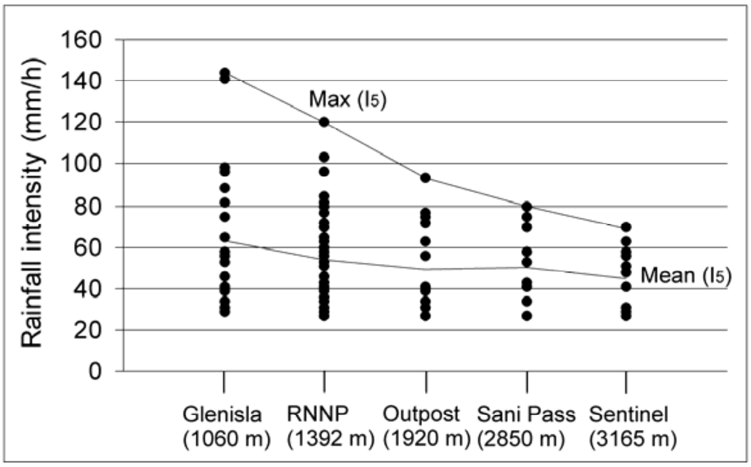
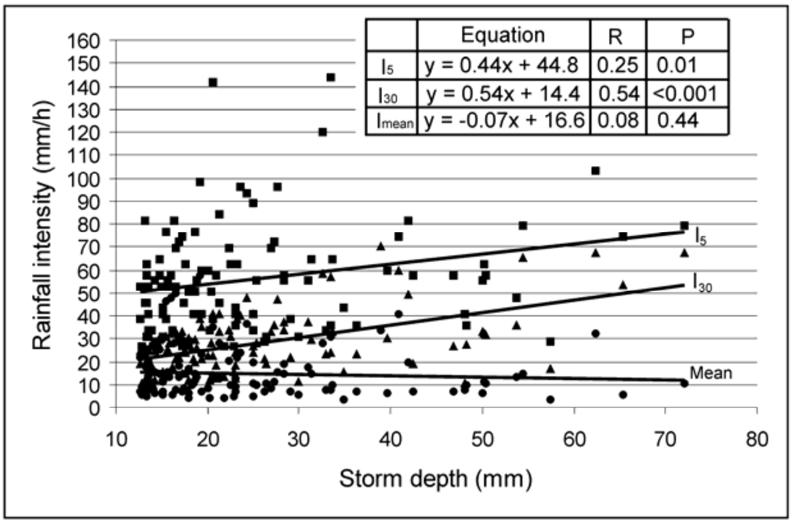


Figure 4: Maximum rainfall intensity recorded for each storm event at stations in the Drakensberg.



	Equation	R	P
I_5	y = 0.44x + 44.8	0.25	0.01
I_{30}	y = 0.54x + 14.4	0.54	<0.001
I_{mean}	y = -0.07x + 16.6	0.08	0.44

Figure 5: Correlation between storm rainfall intensity and storm depth.

Even though erosive events have, by the definition of Stocking and Elwell (1976), a maximum 5-minute intensity exceeding 25 mm/hour, the occurrence of high intensity storm events also needs to be considered. A high intensity event is defined as one with maximum I_5 greater than 50 mm/h (Schulze, 1978) and the number of high intensity events that occurred at each station is given in Table 1. RNNP has the highest number of high intensity rainfall events during the recording period (27) with the high altitude stations (Sani Pass and Sentinel Peak) having the least (5 and 6 respectively).

Storm kinetic energies

Wischmeier and Smith (1958) used measurements of drop size characteristics and terminal velocity to derive a relationship between rainfall intensity and kinetic energy. The proposed relationship is a logarithmic function in the form:

$$E = 11.87 + 8.73\mathrm{Log}_{10}R \qquad (1)$$

where the intensity R is in mm/h. Van Dijk *et al*. (2002) did a critical appraisal of the literature on the rainfall intensity–kinetic energy (R–E_K) relationship and, based on the average parameter values that were derived from the best data-sets, the following general equation to predict storm kinetic energy content from rainfall intensity data is given:

$$E_K = 28.3\,[1-0.52\,\exp(-0.042R)] \qquad (2)$$

where the intensity R is in mm/h. However, earlier work by Elwell and Stoking (1973) in Zimbabwe suggest that for subtropical climates the kinetic energy of rainfall can be predicted by the equation:

$$E_k = (29.82 - 127.51/\,I) \text{ in J m}^{-2}\text{ mm}^{-1} \qquad (3)$$

where the intensity I is in mm/h. This equation has also been adopted for use in the SLEMSA (Soil Loss Estimation Model for Southern Africa) and was used by Schulze (1980) in a first assessment of the kinetic energy of rainfall in South Africa. As such, for the purpose of a spatial study any of the three equations would suffice in estimating kinetic energy contents. In order to allow for consistency with previous studies in southern Africa, the equation by Elwell and Stoking (1973) (eq. 3) is used here to assess the 5-min incremental kinetic energy content derived from rainfall intensity. Total storm kinetic energy (E) generated during each individual erosive storm event (in J. m^{-2}) is calculated through the 5-min kinetic energy content, multiplied by the quantity of rain (in mm) falling in that specific 5 minutes to give the 5-min kinetic energy. Each of the 5-min kinetic energy values generated during the storm is then summed to give the total storm kinetic energy generated during each individual event.

Maximum energy produced during any individual storm was 1639.7 J m^{-2} recorded at Royal Natal National Park, and the storm with the lowest kinetic energy was also measured at this station (142.0 J m^{-2}). Mean kinetic energy of all erosive events measured during the recording period was 490.1 J m^{-2}, and no significant differences exist between mean kinetic energy of individual events at the different stations (Table 2). For the 17-month period between December 2001 and April 2003, an altitudinal difference exists when the cumulative energies are calculated. (Table 2). The kinetic energies measured at the low altitudinal stations (Glenisla and Royal Natal) are 10 212.3 J m^{-2} and 11 542 J m^{-2} respectively. Lower kinetic energies were measured at the higher altitude stations of Injisuthi Outpost (4409 J m^{-2}) and much lower at the escarpment station at Sani Pass (3556 J m^{-2}). Similarly, during 2003 at Royal Natal National Park the annual kinetic energy generated by erosive events was 5021.3 J m^{-2} but at the Injisuthi Outpost for the same period 1656.1 J m^{-2} was generated by erosive events and on the escarpment at the Sentinel Peak only 705 J m^{-2} was measured (Table 2).

The relationship between storm kinetic energy and storm depth and storm duration was examined for all events at all stations (Fig. 6), and as expected a strong correlation, that is statistically significant, exist between storm kinetic energy and storm depth (R= 0.83; P< 0.001). However, no correlation exists between storm kinetic energy and the duration of the storm (Fig. 6).

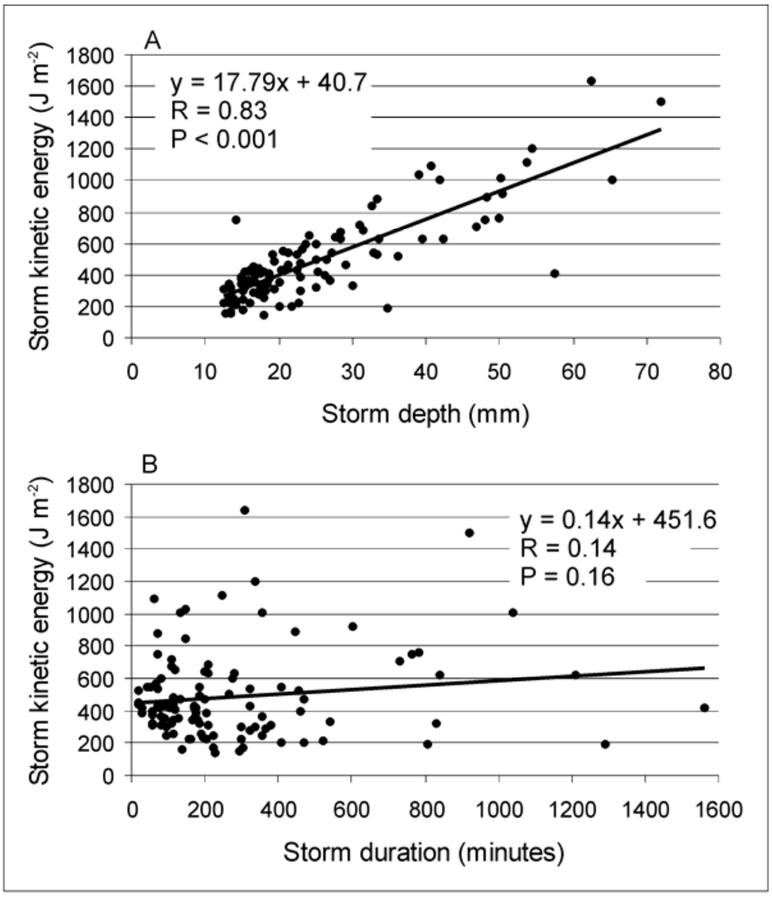


Figure 6: Correlation between storm kinetic energy and (a) storm depth and (b) storm duration.

Storm erosivity

Seuffert *et al*. (1999) developed an integrated rainfall erosivity index (REI) for assessing rainfall structure, runoff and erosion. This index was developed from a number of rainfall elements including rainfall quantity, energy, (dis)continuity, intensity and spatial pattern. Erosivity can also be determined by the product (EI_{30}) of the total kinetic energy (E) of the storm times its maximum 30-minute intensity (I_{30}) developed by Wischmeier and Smith, (1978). This equation has been used globally as part of the (Revised) Universal Soil Loss Equation (R)USLE and in southern Africa to asses the spatial distribution of erosivity (Stoking and Elwell, 1976; Smithen, 1981; Smith *et al*., 2000) and reflects the combined potential of raindrop impact and turbulence created in overland flow. To be consistent with erosivity studies elsewhere the spatial distribution of erosivity in this study was determined by the product (EI_{30}) of each individual storm (in J mm m^{-2} h^{-1}).

The erosivity of each individual storm (EI_{30}) varies in the Drakensberg with maximum erosive power generated by a storm being 110 186.7 J mm m^{-2} h^{-1} at the RNNP station and minimum erosivity was 1135.7 J mm m^{-2} h^{-1} also measured at RNNP. Mean erosivity of storm events measured during the recorded period for all stations is 7107.3 J mm m^{-2} h^{-1}. and slight differences exist between stations regarding the mean storm erosivity generated during individual events (Table 3). As with kinetic energies, a difference in cumulative erosivity exists between stations. Erosivity measured at Glenisla and Royal Natal during December 2001 to April 2003 (Table 3) is 360 460.6 J mm m^{-2} h^{-1} and 351 370.7 J mm m^{-2} h^{-1} respectively. Erosivities measured at the higher altitude stations of Injisuthi Outpost (124 985.9 J mm m^{-2} h^{-1}) and at the escarpment station at Sani Pass (155 256.7 J mm m^{-2} h^{-1}) were lower than at the low altitude stations. Also during 2003 at Royal Natal National Park the annual erosivity generated by erosive events was 152 451.3 J mm m^{-2} h^{-1} but at the Injisuthi Outpost (34 572.9 J mm m^{-2} h^{-1}) and on the escarpment at the Sentinel Peak annual erosivity measured for the same period was of an order of magnitude lower (11 976.2 J mm m^{-2} h^{-1}).

Storm erosivity was also investigated in relation to storm depth and storm duration (Fig. 7). A strong significant correlation (R= 0.72; P< 0.001) exists between storm erosivity and storm depth but no correlation exists between storm erosivity and the duration of the storm.

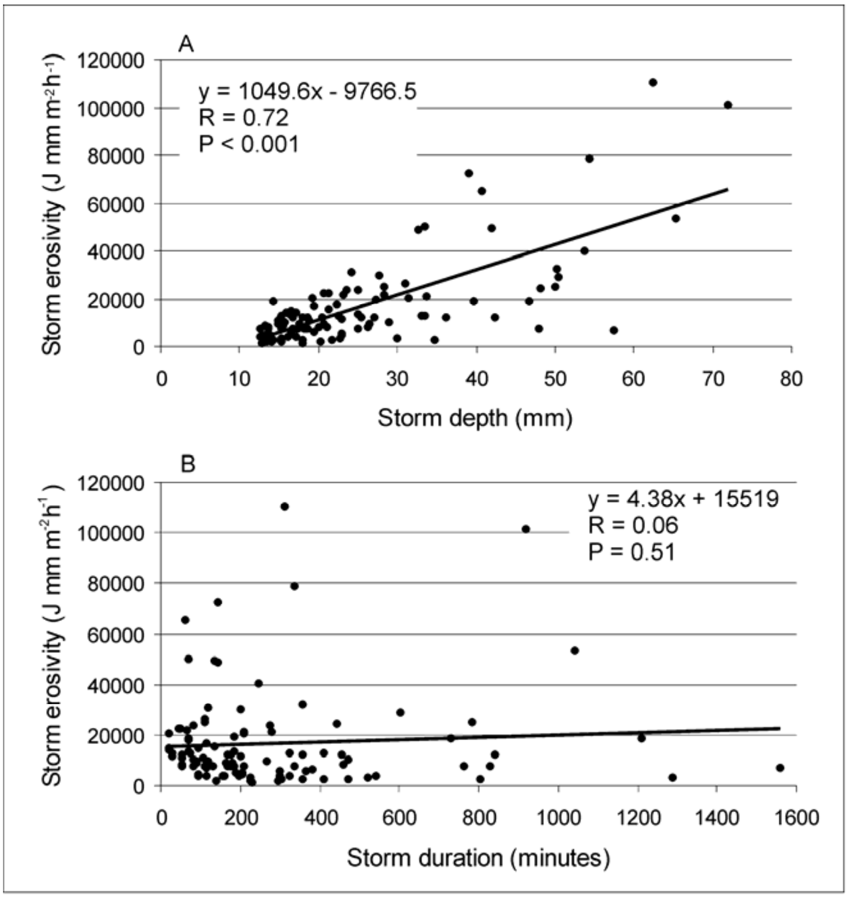


Figure 7: Correlation between storm erosivity and (a) storm depth and (b) storm duration.

DISCUSSION

Erosive storm events across the KwaZulu-Natal Drakensberg vary considerably in duration as well as depth of rainfall generated. The distribution of events is also skewed with a bias towards shorter shallower storms. Rainfall in the Drakensberg is highly seasonal (Nel and Sumner, 2006) and this seasonality is also observed in the monthly occurrences of erosive storm events. No erosive storms occurred at the recording sites during the winter months of May, June, July and only two erosive events were recorded during August. There appears to be a clear contrast in the kinetic energy contents associated with orographic storms and those associated with drizzle (Van Dijk *et al*., 2002). In South Africa a strong correlation exists between high intensity rainfall and thunderstorm activity, and that low intensity rainfall are normally associated with frontal systems (Schulze, 1980). In KwaZulu-Natal rainfall in the winter season displays much lower kinetic energy than rainfall during mid summer (Schulze, 1978). In the Drakensberg, the seasonality of erosive events is associated with the source of precipitation. During winter, frontal rainfall is linked mostly to low intensity drizzle, while thunderstorms develop over the summer period that gives rise to erosive storm events being primarily a summer phenomena.

Tyson *et al*. (1976) indicate that mean annual rainfall increases with altitude, and that the top of the escarpment should receive over 2000 mm of rain annually. Schulze (1979) also defined a clear relationship between altitude and rainfall, and predicted mean annual rainfall at over 1800 mm and January rainfall at 250 mm along the High Berg, but these estimations have been challenged (Nel and Sumner, 2005). A significant linear relationship in the KwaZulu-Natal Drakensberg foothills between mean annual rainfall and altitude below 2100 m a.s.l does exist (Nel and Sumner, 2006), but whether or not the increase in rainfall with altitude extends up to the escarpment (above 2100 m a.s.l.) is uncertain. In this study, when comparing rainfall totals measured at the different stations for the same periods, as well as mean kinetic energies and erosivities from individual storm events, no real spatial difference with regards to these attributes can be discerned. However, altitudinal differences exist when comparing depths of erosive storms as well as cumulative kinetic energy and erosivity. A high proportion of rain falls as erosive events at the lower altitude stations and only a small percentage of monthly rainfall falls as erosive events at the escarpment edge. The lower altitude stations record higher cumulative kinetic energies and erosivities than those at higher altitude. If the monthly distribution of erosive events is considered, it seems that the main differences between stations is that the higher altitude stations recorded no erosive events during the early and late summer months while the lower altitude stations did record significant erosive rains during this period.

In the KwaZulu-Natal Drakensberg an increase in altitude shows a decrease in maximum rainfall intensity of erosive events. The high altitude stations recorded lower maximum five-minute rainfall intensities as well as fewer high intensity events than the stations at lower altitude. Mean rainfall intensities of erosive events show no spatial differences, but storms with a higher total, tend to have higher maximum rainfall intensities, kinetic energies and erosivity.

Raindrop size distribution at a given intensity also decreases with altitude (Van Dijk *et al*., 2002), although greater fall velocities associated with higher elevations could offset the effect on kinetic energy (Beard, 1977). Earlier findings from Schulze (1979) in the Central Drakensberg indicate that a higher frequency of high intensity storms was measured at Ntabamhlope (1457 m a.s.l) than at the higher altitude station at Cathedral Peak (1854 m a.s.l). Ntambamhlope also measured higher annual kinetic energy of rainfall than Cathedral Peak per unit of rainfall (Schulze, 1979). Seuffert *et al*. (1999) from their Figure 8 suggests that their Rainfall Erosivity Index decreases from east to west from the foothills to the escarpment. Our study found that in the Drakensberg mean kinetic energy produced during individual storms are similar throughout the area. Therefore, rainfall has the potential to detach soil through the combined potential of raindrop impact and turbulence created in overland flow from individual storm events at all altitudes in the Drakensberg, but at high altitude a lower percentage of rain falls as erosive storms, and the cumulative kinetic energy produced as well as total erosivity of rainfall is less on the escarpment than at stations lower down.

CONCLUSION

Erosive storm events across the KwaZulu-Natal Drakensberg vary in duration as well as in depth, but events tend to be short and shallow. Erosive rainfall is associated with thunderstorms and highly seasonal with limited erosive storms occurring at the recording sites during the winter months. Storms with a higher total tend to have higher maximum rainfall intensities, kinetic energies and erosivity. The suggested increase in rainfall with altitude in the Drakensberg (Tyson *et al*. 1976; Schulze, 1979) is not apparent in the data when comparing rainfall totals measured at the different stations for the same periods.

This study found that in the KwaZulu-Natal Drakensberg an increase in altitude gives a decrease in maximum rainfall intensity of erosive events. The high altitude stations recorded lower maximum five-minute rainfall intensities as well as fewer high intensity events than the stations at lower altitude but mean kinetic energy produced during individual storms are similar throughout the area. Therefore, individual storm events at all altitudes in the Drakensberg has the potential to detach soil, but at high altitude a lower percentage of rain falls as erosive storms, and the cumulative kinetic energy produced as well as total erosivity of rainfall is less on the escarpment than at stations lower down. This altitudinal differences in erosivity attributes compares well with earlier findings from Schulze (1979) and Seuffert *et al*. (1999). Analysis of the monthly distribution of erosive events suggest that the differences in cumulative kinetic energy and cumulative erosivity can be explained by the lack of erosive events during early and late summer at the escarpment, and significant erosive rains during this period at lower altitudes in the foothills.

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INTRA-STORM ATTRIBUTES OF EXTREME STORM EVENTS IN THE DRAKENSBERG, SOUTH AFRICA

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Submitted: Research paper to *Physical Geography*

ABSTRACT

Intra-storm rainfall attributes were analysed for 49 extreme storm events at five locations in the KwaZulu-Natal Drakensberg in the east of South Africa. Three stations located in the mountain range foothills and two stations sited on the escarpment edge above 2800 m a.s.l. provide the first detailed intra-storm data for the Drakensberg escarpment area. Extreme rainfall events were found to vary in duration and in depth, but all stations measure a clear exponential distribution of cumulative kinetic energy content of storm rainfall over time. The first 300 minutes of storm duration generate more than 90% of the total energy content available as well as 80% of the total rainfall. When rainfall generation and high rainfall intensity (exceeding 25 mm/h) is plotted as a function of storm duration, most storms at the stations indicate a high proportion of rainfall being generated within the first and second quartile of the storm duration. More than half the storms generate their maximum peak intensity within the first quartile of the duration of the storm and 84% of the storms show maximum intensity within the first half of the storm duration. Even though these common tendencies are evident, the data show that the structure of erosive rain is site specific, and that the within-storm distribution of rainfall should be incorporated into soil loss modelling in the region. It is suggested that further research is needed to ascertain the actual effect within-storm distribution of rainfall has on runoff and soil detachment in the KwaZulu-Natal Drakensberg.

INTRODUCTION

South Africa is predominantly a semi-arid country; and it is only primarily areas in the east that record rainfall above 600 mm (Schulze, 1979). In the east of South Africa, the KwaZulu-Natal Drakensberg is part of the Main Escarpment that reaches above 2800 m and defines the watershed between the interior catchments of the Kingdom of Lesotho, and the shorter and steeper catchments of the rivers in the South African province of KwaZulu-Natal. Annual rainfall totals in the high mountains have been estimated to exceed 1500 mm although recent records show this could be an overestimate (Nel and Sumner, 2005). Notwithstanding this, the Drakensberg is considered South Africa’s most important source of runoff and was recently declared a World Heritage site. The province of KwaZulu-Natal contributes nearly twice as much total runoff per unit of rainfall than in South Africa as a whole and a quarter of South Africa’s streamflow (Whitmore, 1970). The major source of precipitation over the Drakensberg is large-scale line and orographically induced thunderstorms that occur mostly during summer (Tyson *et al*., 1976). During winter, just over 40 cold fronts affect KwaZulu-Natal annually (Grab and Simpson, 2000). These develop as closed low-pressure cells in the western Atlantic and move across southern Africa in a west-northwest to east-southeast direction (Tyson *et al*., 1976) bringing widespread rainfall to the region.

Rainfall in the Drakensberg is a major driving force of many hydrological and erosional processes through the detachment of soil particles and creation of surface runoff (Moore, 1979). The amount of erosion caused by the rainfall from a certain storm is a function of the rain's physical characteristics, including the total rainfall as well as the intensity at which it falls (Obi and Salako, 1995). During summer in the Drakensberg some thunderstorms can generate erosive rainfall, and the attributes of these storms namely rainfall intensity, kinetic energy and erosivity are positively correlated with the amount of rainfall produced (Nel and Sumner, submitted). However, natural rainfall is long known to be highly variable both spatially and temporally (Schiff, 1943; Huff, 1967) and storm patterns can be complex with the peak rainfall intensity early in the storm, in the middle or at the end (Flanagan *et al*., 1987; Nyssen *et al*., 2005). This intra-storm variation in peak rainfall intensity has been shown to effect peak runoff rates, infiltration and soil loss (Flanagan *et al*., 1987) and significant differences in eroded material exist across different soil types for different storm patterns (Parsons and Stone, 2006). Although studies have investigated storm kinetic energy and erosivity in South Africa (Schulze, 1980; Smithen, 1981; Seuffert *et al.*, 1999) and in the Drakensberg (Schulze, 1979, Nel and Sumner, submitted) no studies have investigated the intra-storm distribution of rainfall parameters in this hydrological area. The aim of this study is to investigate the within-storm distribution of rainfall depth, extreme rainfall intensity and cumulative kinetic energies. The need for further research to supplement the understanding of the relationship between rainfall and the subsequent soil loss dynamics from rainfall events in the KwaZulu-Natal Drakensberg is highlighted.

STUDY SITES AND METHODS

Davis-MC Systems (D-MCS) automated tipping-bucket rain gauges logged rainfall at five locations within the Drakensberg from the end of 2001. The D-MCS rainfall gauges have a 163 mm collection diameter and log total rainfall every 5 minutes on a tipping resolution of 0.2 mm rainfall. The locations were as follows: on the escarpment edge at the top of Sani Pass (29.57° S, 29.27° E, 2850 m a.s.l.) in the southern Drakensberg, on the escarpment edge at the Sentinel Peak (28.74° S, 28.89° E, 3165 m) in the northern Drakensberg, in the Royal Natal National Park (RNNP) (28.68° S, 28.95° E, 1392 m) in the northern Drakensberg, on the farm Glenisla (29.02° S, 29.49° E, 1060 m) and at the Injisuthi Outpost (29.13° S, 29.45° E, 1920 m) in the central Drakensberg. The two high altitude stations are the first that attempt to record detailed and long-term rainfall data from the upper reaches of the catchments and the freestanding Sentinel Peak is the highest point where rainfall is currently measured in southern Africa (3165 m).

Rainfall at the top of Sani Pass was collected over 1425 days, commencing during September 2001 to mid April 2003 and again in early September 2003 to early January 2006. Recording of rainfall on the top of the Sentinel Peak commenced in late November 2002 and data presented here are for 1201 days from the 28th of November 2002 to the 12th of March 2006. At the RNNP rainfall recording started on the 21st of November 2001 and ended on the 10th of January 2005 (1147 days). Data presented here for the Injisuthi Outpost are from the 29th of October 2001 to the 12th of January 2004 (828 days) and at Glenisla from the 29th of October 2001 to the 30th of April 2003 (528 days).

For a rainfall event to qualify as a distinct erosive event, Stocking and Elwell (1976) state that each storm should have a total amount of rainfall exceeding 12.5 mm and a maximum 5-minute intensity exceeding 25 mm/hour. Each event should be separated by at least two hours of no rain. Applying this definition, the data series collected from the five different locations in the Drakensberg contain 106 individual erosive storm events.

A number of equations have been developed to calculate kinetic energy from rainfall intensity (see Van Dijk *et al*., 2002), but Elwell and Stoking (1973) show that for subtropical climates the kinetic energy of rainfall can be predicted by the equation:

$$E_k = (29.82 - 127.51/ I) \text{ in J m}^{-2} \text{ mm}^{-1} \qquad (1)$$

where the intensity I is in mm/h. This equation is used to assess the 5-min incremental kinetic energy content of the rainfall derived from the measured 5-min rainfall intensity. To investigate the intra-storm changes in rainfall attributes received from an extreme rainfall event, the 10 storms with the highest total kinetic energy content at each station were chosen for analyses. However, it must be noted that the Sani Pass station only recorded 9 erosive storms in total and therefore all available storms were used for analyses from that station. A total of 49 events is thus analysed in detail of the 109 storms that meets the criteria of an erosive event.

INTRA-STORM DISTRIBUTION OF RAINFALL DEPTH

The 49 extreme storm events analysed in this study had an average duration of 383 minutes (6 hours and 23 min) with the shortest storm being 55 minutes long and the longest 26 hours. Mean depth of the 49 individual storm events is 32.4 mm with the lowest totaling 12.6 mm and the highest 72.0 mm (Fig. 1). The distribution is skewed (CV = 0.85) with 25% of the storms being shorter than 120 minutes (2 hours) and 75% shorter than 450 minutes (7 hours and 30 min).

From the definition of Elwell and Stoking (1973), the 5-minute kinetic energy content (E_k) for each individual event at each station was calculated and the cumulative kinetic energy as a percentage of total energy plotted (Fig. 2). All stations show a clear distribution of cumulative kinetic energy of rainfall received over time, with the rainfall events at Sani Pass generating 90% of the total kinetic energy in the first 60 minutes of the onset of the storms and 90% generated in 250 minutes at Royal Natal National Park.

Since the stations receive more than 90% of all the potential kinetic energy content generated by the storms within the first 300 minutes of the onset of the storms, for analysis of the intra-event temporal distribution of rainfall, the 5-minute increment rainfall depth of each individual storm measured at each station was plotted over the first 300 minutes (Fig. 3). All the storms show clear variations in rainfall depth over time, but all stations receive above 80% of the rainfall generated by extreme storm events in the first 300 minutes. At Sani Pass 50% of the cumulative rainfall received are within the first 38 minutes from the onset of the storm, and at Glenisla half the rainfall received from extreme rainfall events are within the first 40 minutes. At Sentinel Peak and Injisuthi Outpost half the rainfall received is within 90 minutes and at RNNP it is within 135 minutes.

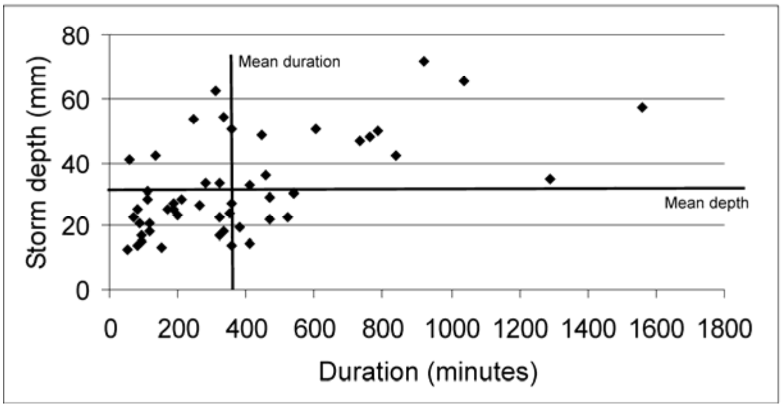

Figure 1: Total rainfall depth and duration of extreme storm events in the Drakensberg.

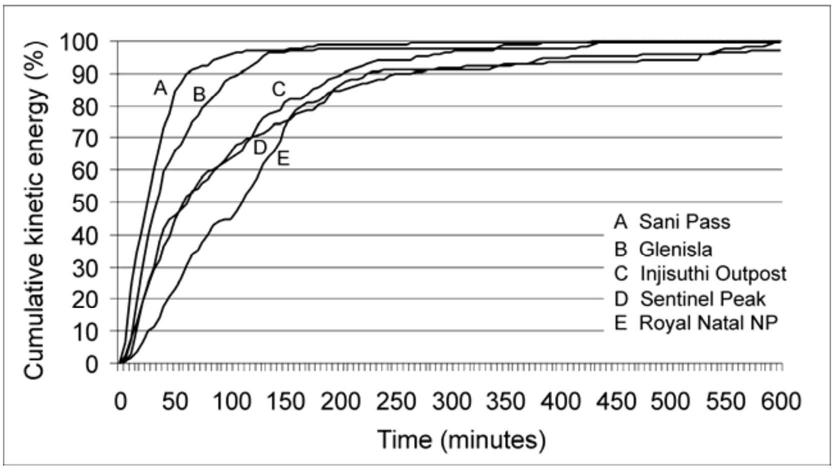

Figure 2: Cumulative kinetic energy generated over time by extreme storm events at the respective stations in the Drakensberg.

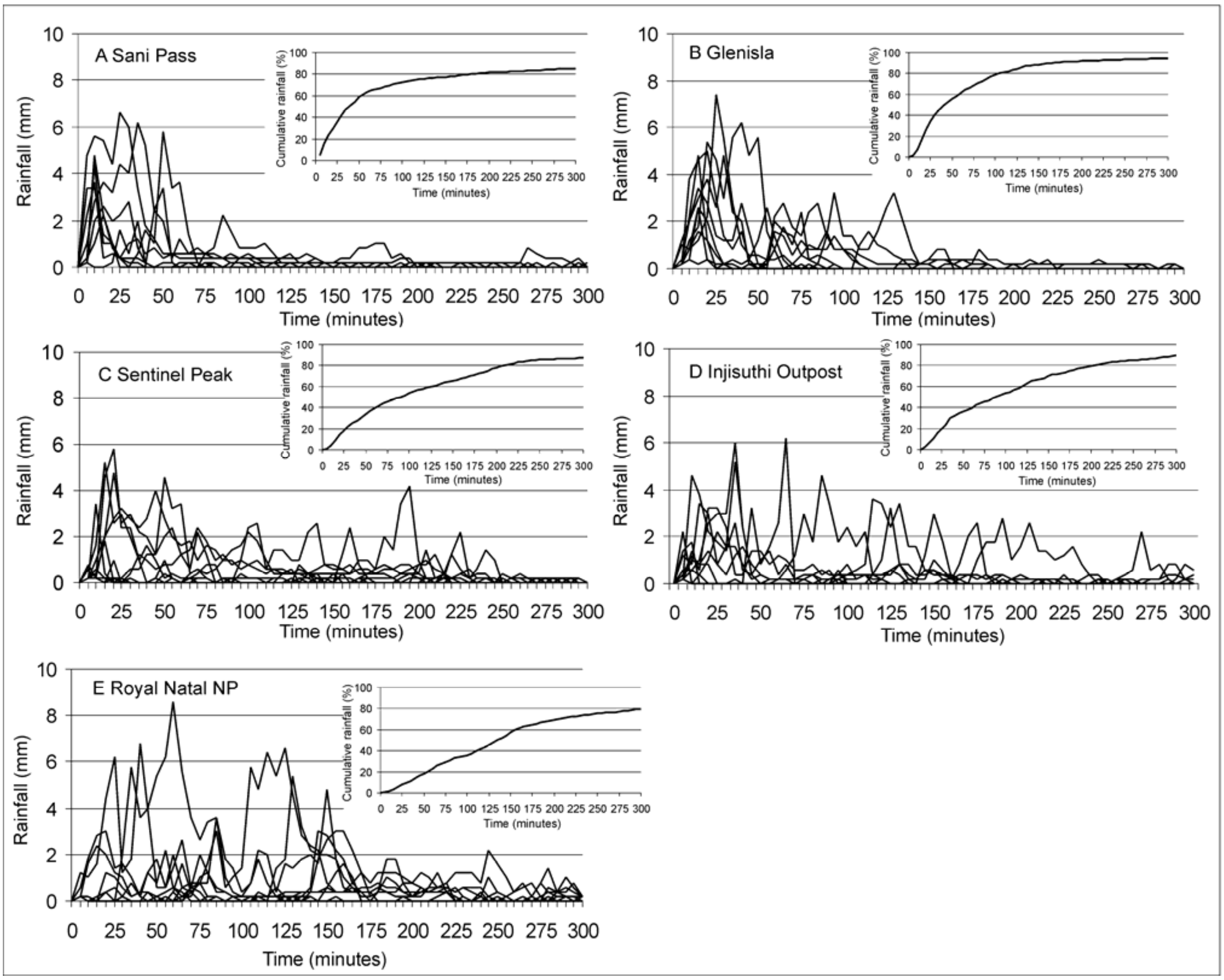

Figure 3: Rainfall depth and cumulative rainfall generated over time by extreme storm events measured at the respective stations in the Drakensberg.

To test for rainfall generation as a function of storm duration, the 5-min rainfall depth of each individual storm measured at each station was plotted as a percentage of the storm duration (Fig. 4). Each storm is divided into 4 quartiles namely: First Quartile (Q1), Second Quartile (Q2), Third Quartile (Q3) and Fourth Quartile (Q4). The extreme rainstorms measured at the stations show variability of rainfall over time, but a high proportion of storms generate peak rainfall within the first and second quartile of the storm duration. At RNNP, 76% of the total rainfall received from extreme rainfall events fall in the first half (Q1 and Q2) of the storm duration (Fig. 4F). Sani Pass, Injisuthi Outpost, Sentinel Peak and Glenisla receive 73%, 73%, 72% and 65% respectively within the first half of the individual storm duration. Only a small number of storms generate peak rainfall in the third and fourth quartile. Glenisla and Sani Pass only receive 16% and 15% of all rainfall from extreme events in the last quartile (Q4). At the Injisuthi Outpost, RNNP and Sentinel Peak stations it is 13%, 9% and 8% respectively.

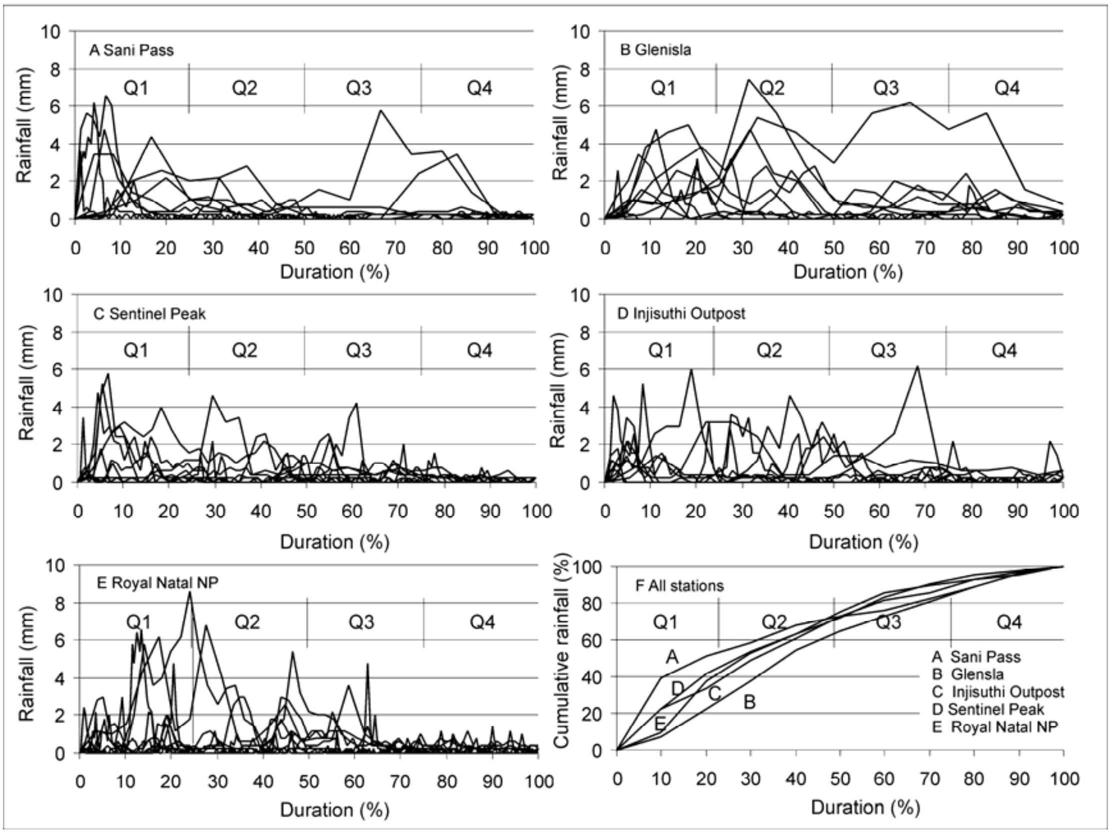

Figure 4: Storm rainfall depth and cumulative rainfall as a function of storm duration at the respective stations in the Drakensberg.

INTRA-STORM DISTRIBUTION OF EXTREME AND PEAK RAINFALL INTENSITY

All the 49 extreme erosive events analysed have, by the definition of Stocking and Elwell (1976), a maximum 5-minute intensity exceeding 25 mm/hour. To test at what stage within a storm the rainfall intensity has the potential to possibly exceed infiltration rates the intra-storm variations of 5-minute intensity exceeding 25 mm/hour were considered. Most storms (70%) measured at the stations have intensities above this threshold during the first 100 minutes of the storm duration (Fig. 5). At Sani Pass and Glenisla all high rainfall intensities received from the storms are within the first 140 minutes, but at Injisuthi Outpost and RNNP intensities above 25 mm/h have been received from storm events as late as 345 minutes and 535 minutes since the onset of the individual storms. If the distribution of high intensity as a function of the storm duration is considered then most of the storms (80%) have their high intensities within the first and second quartile of the storm duration (Fig. 6). Only Sani Pass, Glenisla and Injisuthi Outpost received high intensity rainfall from a number of storms during the last quartile.

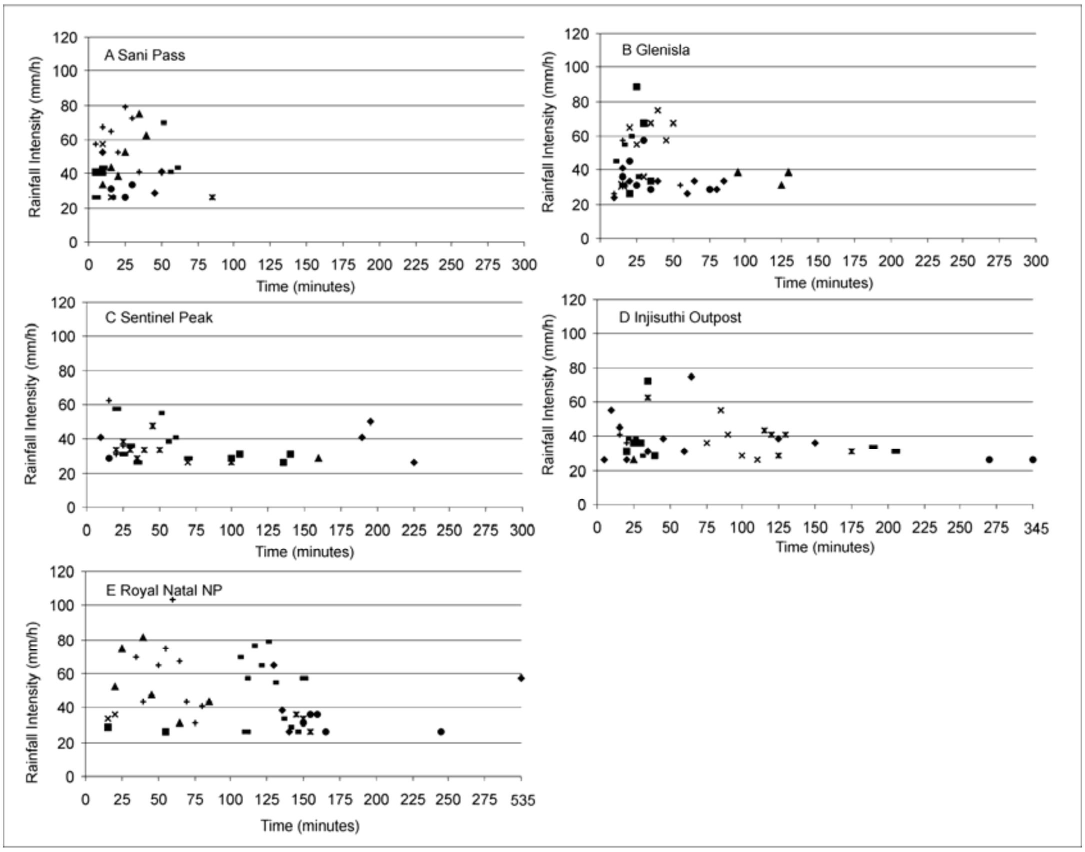

Figure 5: Timing of extreme rainfall intensity (above 25 mm/h) generated by extreme storm events at the respective stations.

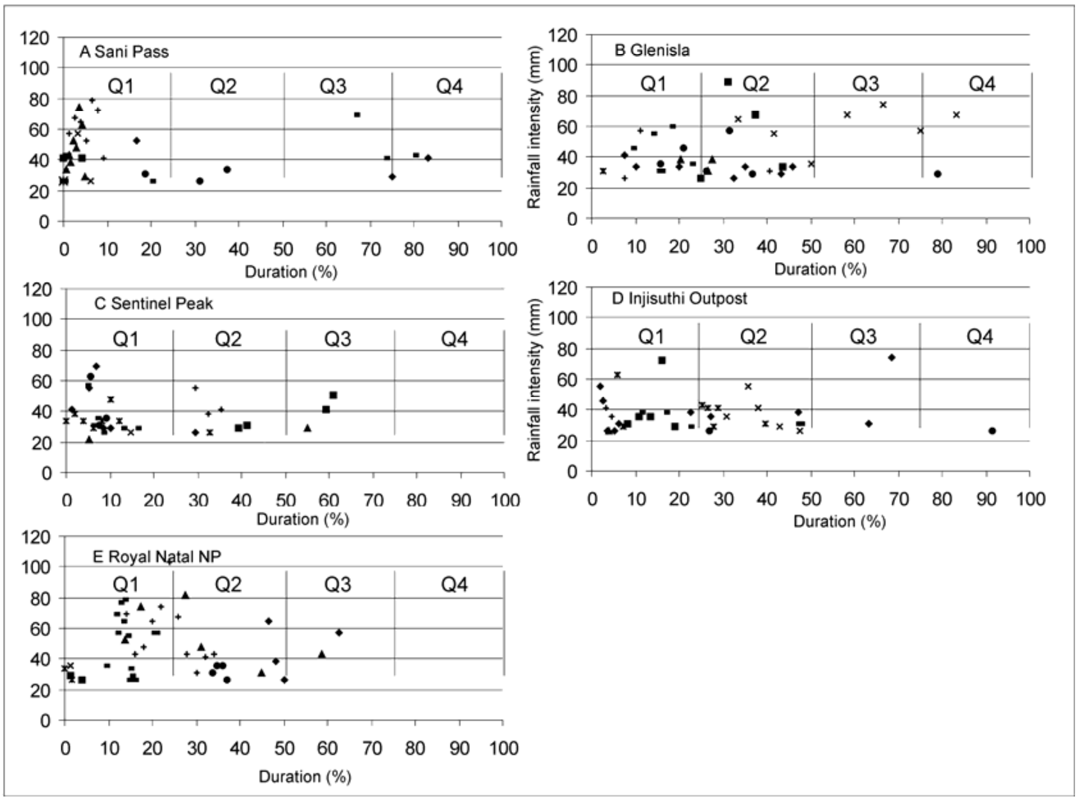

Figure 6: Timing of extreme rainfall intensity (above 25 mm/h) as a function of storm duration at the respective stations.

Peak rainfall intensity received within 5 minutes of each storm was plotted as a function of the storm duration (Fig. 7) and 57% of all storms that were analysed generate peak intensity within the first quartile. Of the storms, 84% show maximum rainfall generation in 5-minutes during the first half of the storm (50%). No storms generate peak intensity after 80% of the storm has passed.

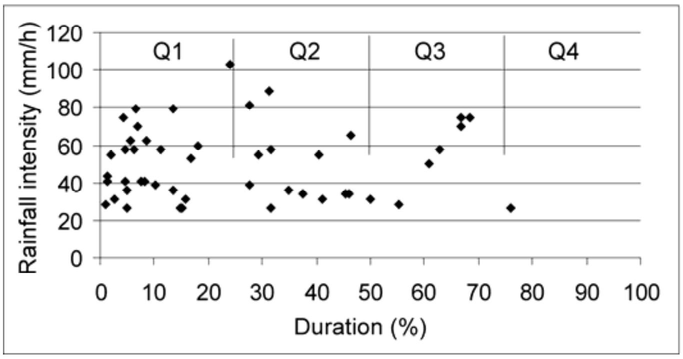

Figure 7: Timing of extreme rainfall intensity (above 25 mm/h) generated by storm events as a function of storm duration.

DISCUSSION

In the Drakensberg extreme rainstorms exhibit temporal variability in rainfall depth, but a common trait is that more than 80% of the rainfall generated by extreme storm events is within the first 300 minutes of the onset of the storms. If rainfall generation as a function of storm duration is examined, then between 65% and 76% of rainfall is received within the first half of the storm duration at the respective stations. The intensity of rainfall received from extreme rainfall also exhibits intra-storm temporal variability and no storm show constant intensity over time. Parsons and Stone (2006) found that a constant-intensity storm yields lower soil loss than the varying-intensity storms, and the eroded sediment from the constant-intensity storms had lower clay content than that from the varying-intensity storms.

Soil loss data in Zimbabwe has indicated that the magnitude of peak intensities is most critical to the erosion process (Stocking and Elwell, 1976) and under natural storm conditions sediment transport peak in response to intense rainfall (Smith and Olyphant, 1994). Even though the storms in the Drakensberg show variations in intensity above 25 mm/h, 70% of the storms measured at the stations have intensities above this threshold during the first 100 minutes of the storm duration. When the distribution of high intensity as a function of the storm duration is analysed then all stations receive a high proportion of peak rainfall intensity within the first half of the storm. If it is considered that storms that peak in intensity towards the end of the storm duration have the highest peak runoff rates and soil loss (Flanagan *et al*., 1987), then the erosivity of erosive rainfall in the Drakensberg could be moderated by the within-storm distribution of rainfall intensity.

It has been known that the erosivity of a rainfall event is affected by the intra-storm distribution of rainfall intensity, but only recently has such variability been incorporated into soil erosion models (Parsons and Stone, 2006). In South Africa a study of rainfall erosivity by Seuffert *et al*. (1999) did consider the timing of peak intensities within a rainfall event to establish erosivity, but only one station in the central Drakensberg foothills was used as a representation of the mountainous area. Other erosion studies in South Africa, notably by Smithen (1981) only presents the yearly averages of rainfall kinetic energies and do not take into account the structure of rainfall. The model used to establish soil loss in the Lesotho Highlands Water Project catchment areas (Smith *et al*., 2000) also uses the long-term average annual EI_{30} values and figures on the seasonal distribution of EI_{30} obtained from the iso-erodent map of South Africa by Smithen (1981). All previous erosivity models used in the Drakensberg assume that erosive rainfall falls at a constant intensity, and no rainfall erosivity models or experiments have taken into account the within-storm distribution of rainfall in this crucial area. This study shows that even though common tendencies of storm structure between storms and between stations can be distinguished in the Drakensberg, the within-storm rainfall distribution of no two storms are precisely similar and no two stations in this region show exact similar distributions of storm patterns. This implies that the structure of erosive rain is site specific and too many spatial disparities exist for intra-storm rainfall distribution measured at a small number of stations to be extrapolated for the region as a whole.

Storm rainfall in the Drakensberg tend to peak in the beginning of the storm, which could possibly decrease peak runoff rates, soil loss and overall erosivity from the storms. However, rainfall is generated at varied intensity, which could also imply that soil loss could be more and the characteristics of the wash material could be different than if the storms exhibit constant intensity. These factors make it difficult to assess total erosivity from rainfall in this region. Previous models assume rainfall at constant intensity, yet constant intensity storms do not occur in the Drakensberg, and the within-storm distribution of rainfall must be incorporated in soil loss modelling. Further research is also needed to ascertain the actual effect within-storm distribution of rainfall has on the soil surface dynamics in the KwaZulu-Natal Drakensberg.

SUMMARY

In the KwaZulu-Natal Drakensberg, extreme rainstorms exhibit temporal variability in rainfall depth, but between 65% and 76% of rainfall is received within the first half of the storm duration at the respective stations. The intensity of rainfall received from extreme rainfall also exhibits intra-storm temporal variability and no storm show constant intensity over time. All stations receive a high proportion of peak rainfall intensity within the first half of the storm.

Even though these common tendencies exist, the data suggest that the structure of erosive rain show too much of spatial difference for a small number of stations to be representative of the region, but the within-storm distribution of rainfall must be incorporated when soil loss for the region is modelled. Further research is also needed to determine the effect within-storm rainfall characteristics has on runoff and soil detachment in the KwaZulu-Natal Drakensberg

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SURFACE-CLIMATE ATTRIBUTES AT INJISUTHI OUTPOST, DRAKENSBERG, AND POSSIBLE RAMIFICATIONS FOR WEATHERING

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ABSTRACT

Aerial and sub-aerial climatic data were collected from a station at 1920 m a.s.l. in the Injisuthi region of the South African Drakensberg. Sensors monitored air temperature, soil surface and rock surface temperature, for two rock types, over the summer and winter of 2001/2002. Rainfall was measured from the summer of 2001 to January 2004. These are the first rock and soil surface-climate data to be collected for an exposed site at this altitude in the area. Rainfall over the two calendar years 2002 and 2003 was found to be below estimates for the region but patterns imply numerous rock wetting and drying cycles in summer. At the site, air, rock and soil temperatures differ considerably on a diurnal basis both with respect to absolute temperature and daily ranges. Mean rock daily ranges, as conducive to possible thermal fatigue, are found to be similar in the summer and winter periods. Of the two rock types monitored, the darker coloured basalt attained higher maximum and marginally lower minimum temperatures than the sandstone. Soil frost did not occur at 2.5cm depth, but rock did reach below –6°C in winter. Both rock types maintain relatively high rock temperatures in winter (exceeding 25°C) thus chemical weathering is probably only moisture-restricted during this dry period. Findings highlight the importance of directly monitoring rock temperature when attempting to discern the rock weathering environment.

INTRODUCTION

Given the importance of basic climate attributes to surface processes, surprisingly few data are available from southern Africa. The Ukhahlamba-Drakensberg Park, in the province of KwaZulu-Natal, is part of the southern African Great Escarpment mountain range and contains sites of historically and culturally valuable rock art painted onto sandstone exposures below 2000m a.s.l. Geomorphologically, the area has generated much interest and debate, particularly in the field of climatic or palaeo-climatic interpretation based on landforms (see Boelhouwers and Meiklejohn, 2002). Central to many ongoing issues is the absence of contemporary climatic data in this mountain range. Aerial and sub-aerial data, upon which to base process interpretations and palaeo-climatic extrapolations, are scarce (Boelhouwers and Meiklejohn, 2002). Weather stations are mostly confined to altitudes below 1800m (Nel and Sumner, 2005) thus general temperature conditions remain speculative. For example, ground frost is estimated to have a disruptive effect on soil at altitudes as low as 1800m a.s.l. (Boelhouwers, 1988) but no other data exist to further verify soil frost below the escarpment region. Some climatic data specific to rock weathering have been collected in pursuit of rock art preservation (Meiklejohn, 1994; 1997) and monitoring is ongoing (Hoerlé and Salomon, 2004; Hoerlé, 2005). However, only three studies to date have actually gathered rock temperature conditions in the sub-continent; in the Drakensberg (Meiklejohn, 1994; Sumner *et al*., 2004) and near the west coast of Namibia (Viles, 2005). Hoerlé and Salomon (2004) suggest as a compromise that regional climatic data can be extrapolated to infer rock art weathering processes in shelters but this is in contrast to findings by Meiklejohn (1994) and elsewhere (see e.g. Hall *et al*., 2002) where climatic extrapolations to rock temperatures appear tenuous at best.

As part of a broader programme to monitor surface climatic conditions in the mountain range, a station was established below the escarpment zone in what is known as the central Drakensberg where precipitation, air temperature, soil surface and rock surface temperatures were monitored. This project thus serves two interests. First, general surface-weather conditions are gathered at a site where no data are yet available and therefore adding to the very scarce database on temperatures in the Drakensberg. Second, this study presents the first data from an exposed site as opposed to rock shelter conditions previously monitored in the interest of rock art weathering (see Meiklejohn, 1994). Some temperature data from the logger station have been published in an inter-regional comparison (Sumner *et al.*, 2004) but a more detailed synopsis from the site, including additional rainfall, soil and rock temperature data, is provided here.

STATION LOCATION AND LOGGER MEASUREMENTS

Located on an interfluve at 1920 m a.s.l. at the Injisuthi Outpost in Giant's Castle Game Reserve (29° 42' S; 29° 12' E) (Figure 1), the logger station lies immediately above the contact between the Lower Jurassic Drakensberg Group basalts and the underlying Clarens Formation sandstones. Valleys are deeply incised in the area and the escarpment reaches 3450m in the west. General climatic conditions for the area, based on the nearest station at the Main Camp, are estimated at 1050 mm of rainfall p.a. and 14°C mean annual air temperature (Sumner *et al.*, 2004). Basaltic soil underlies the station to a depth of approximately 1.0 m and the site is located on the Montane-Subalpine vegetation belt transition (Boelhouwers, 1988) dominated by *Themeda triandra* grassland with scattered *Protea*.

Rainfall was measured with a Davis-MC Systems (D-MCS) automated tipping-bucket rain-gauge. The bucket has a 163 mm collection diameter and logs every 5 minutes at a 0.2 mm rainfall resolution. Calibration of the D-MCS against typical manual-recording rain-gauges at two South African Weather Service meteorological stations shows some deviation between the two device-types but results are deemed comparable (Nel and Sumner, 2005). The rain-gauge was positioned 0.6 m above the surface to avoid rainsplash into the recorder. Although manual weather stations record daily at 08h00, records from the D-MCS are totalled each day for the diurnal period from 00h00 to 24h00 to correspond with daily temperature records.

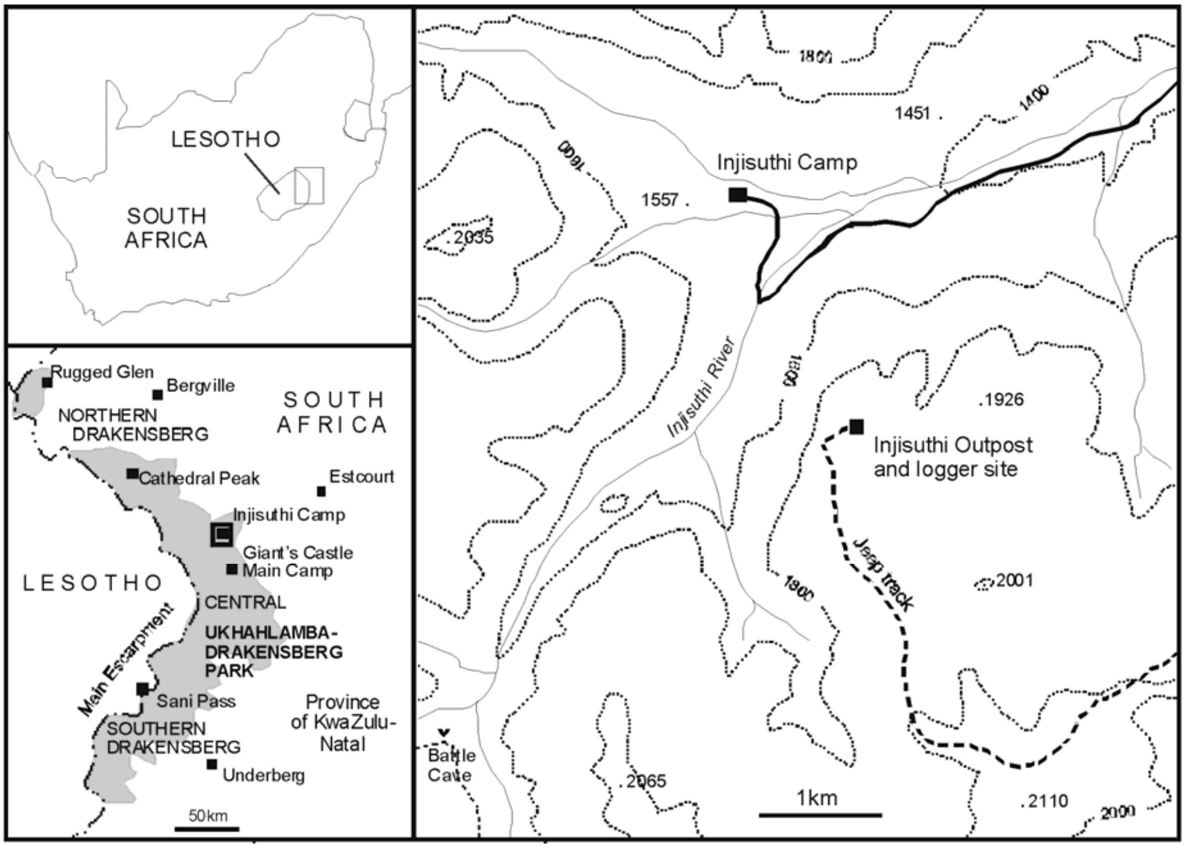

Figure 1: Location of the logger station below the escarpment in the Central Drakensberg.

A four-channel MC-Systems logger recorded temperatures at the site. Sensors comprised 5mm diameter thermocouples cased in stainless steel, the specifications of which are provided elsewhere (Sumner *et al*., 2004). Air temperature was recorded at 1.2 m height within a radiation screen. A second sensor was inserted into the soil surface at 2.5 cm depth between grass tussocks. Both the remaining sensors were placed to record rock temperature. Since the site is at the basalt-sandstone contact, two ~3 kg clasts, one light-coloured sandstone and one and darker-coloured basalt from the area were drilled to approximately 2 to 3 mm depth from the opposite clast surface. Thermistors were inserted and glued in place, and the clasts orientated with the undisturbed surface facing upwards following established practice (see Sumner *et al*., 2004). The logger recorded daily minimum and maximum temperatures in order to illustrate diurnal limits and ranges, such as relevant to frost action in soil and rock, and rock thermal fatigue. Monitoring began on 18 November 2001. A runaway grass fire damaged the temperature logger sensors on 5 August 2002 where records end, but the rainfall logger operated to January 2004 thus spanning the temperature data set and the years 2002 and 2003.

LOGGER RECORDS

For the calendar years of 2002 and 2003, rainfall totalled 873.0 mm and 752.2 mm respectively. Daily rainfall totals spanning the temperature logger record are presented in Figure 2. A total of 601 mm fell over this period on 119 days. A predominance of summer rainfall is clearly evident extending from November towards the end of March. Rainfall over winter is scarce but can occur with the passage of mid-latitude cold frontal systems. Not all fronts will bring rain but they can cause overcast conditions and a drop in temperature. Snowfalls are uncommon but light falls may occur in winter at this altitude. The water-equivalent contribution of snow is not measured by the logger but field observations are that it is unlikely to exceed an average equivalent of 20 mm (or 200 mm of snow) per year; no snow was noted during the data record period. Temperature records cover much of both the summer of 2001 and the winter of 2002. To enable a seasonal comparison the extended “summer” record is defined as running from the November start to the end of March and the “winter” period from May to the August record termination. General temperature attributes are given in Table 1 and Figure 3.

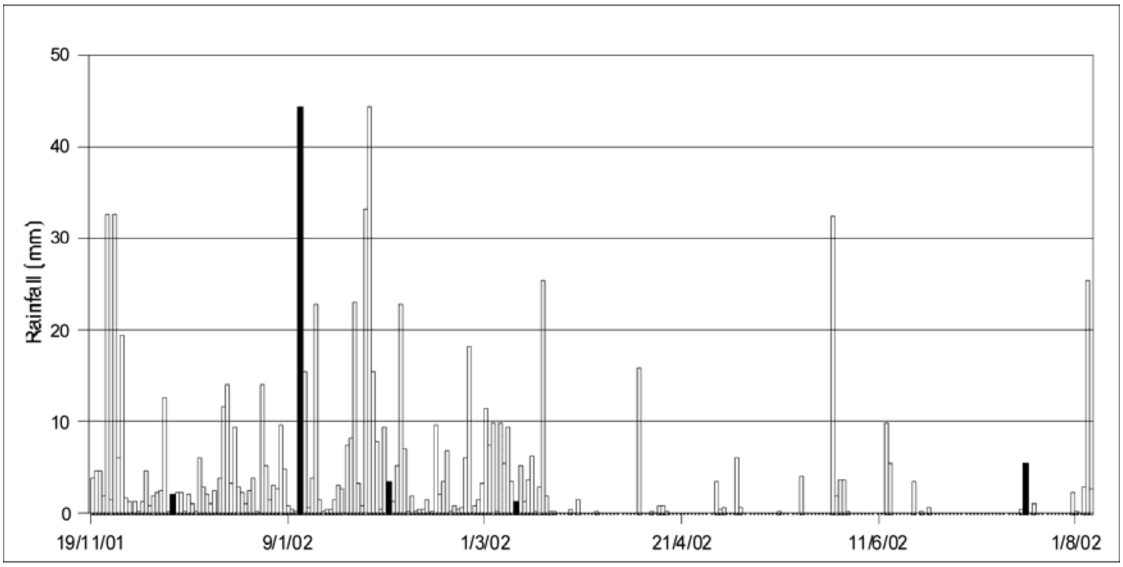

Figure 2: Daily rainfall at the logger station over the temperature monitoring period.

Sensor location	**Max. T (°C)**	**Min. T (°C)**	**Mean summer max. (°C)**	**Mean summer min. (°C)**	**Mean winter max. (°C)**	**Mean winter min. (°C)**	**Mean diurnal range (°C) [Max.]**	**Mean summer range (°C) [std dev]**	**Mean winter range (°C) [std dev]**
Air	30.6	-3.3	23.9	11.4	16.9	4.3	12.8 [25.7]	12.6 [3.4]	12.5 [3.1]
Soil	35.0	0.6	27.2	15.2	12.2	4.2	10.4 [19.4]	12.1 [4.5]	8.1 [3.0]
Basalt	56.0	-6.7	42.4	10.4	32.6	0.6	32.5 [48.7]	32.0 [10.9]	32.0 [9.0]
Sandstone	50.1	-6.1	36.0	10.6	24.8	1.0	25.1 [40.3]	25.4 [9.3]	23.7 [6.7]

Table 1: Temperatures and diurnal ranges recorded by sensors on rock (2 to 3mm depth), in soil (25 mm depth) and shaded air (1.2 m height) at Injisuthi Outpost (18 November 2001 to 5 August 2002).

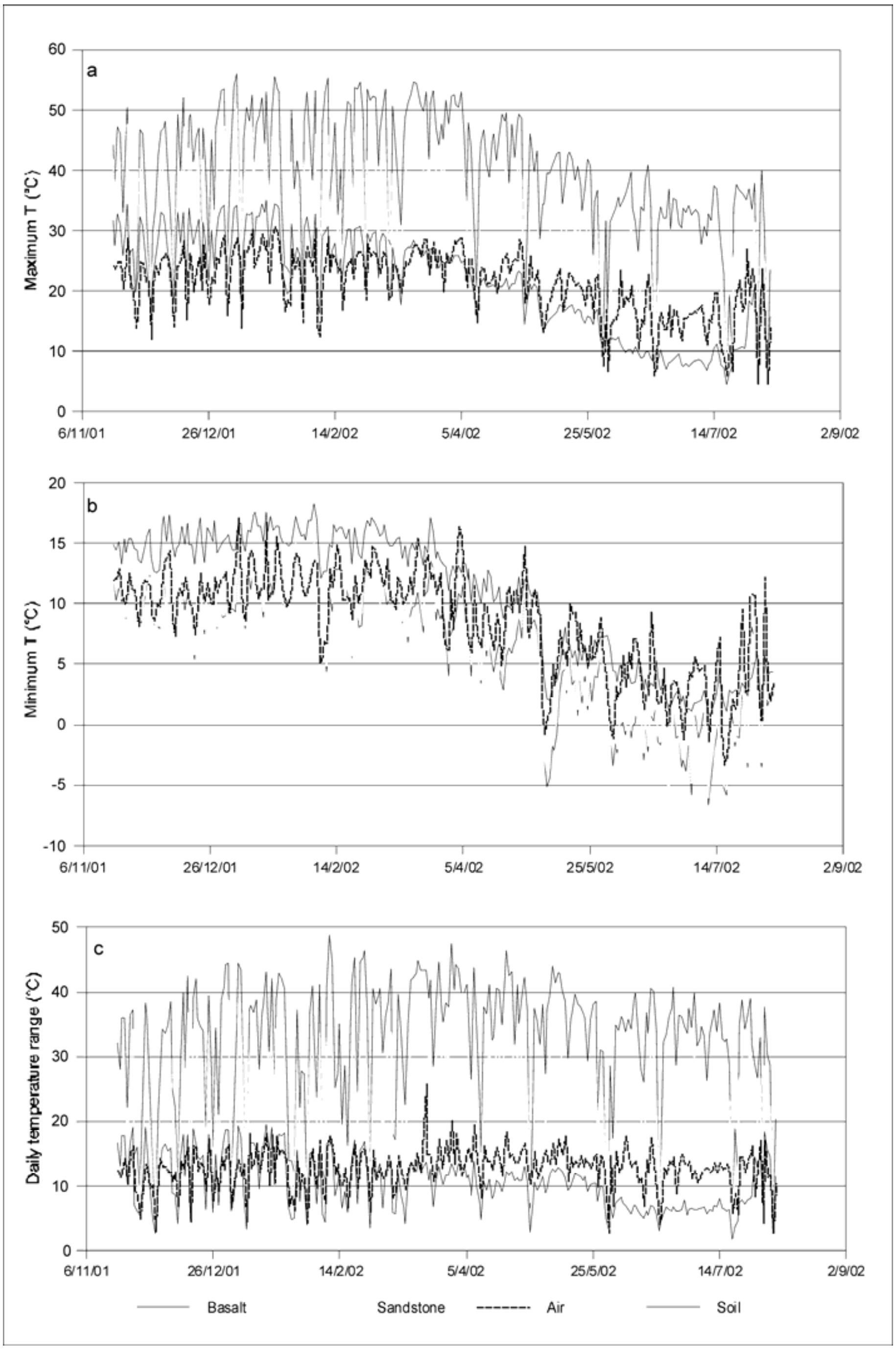

Figure 3: Daily maximum (a), minimum (b), and diurnal temperature ranges (c) recorded on air, soil and rock temperature sensors at the station.

Maximum temperature recorded over the monitoring period was 56.0°C for the basalt clast while sandstone reached 50.1°C. Both soil and air temperatures reached maximums substantially lower than those recorded on the rock clasts with soil maximum temperature (35.0°C) a few degrees warmer than that of air (30.6°C) (Table 1). There are notable differences between the summer and winter periods. In summer, maximum temperatures on rock are highly variable (Figure 3a), probably due to overcast conditions resulting from mist and convective thunderstorms that are regular features in summer. In winter, maximum temperatures are lower but are more consistent than the summer period due to less cloud cover. Several cold spells occur from the month of April onwards due to the passage of cold fronts with associated overcast conditions and influx of cold air. Soil surface maximum temperatures remain below that of rock maximum temperatures throughout the monitoring period, are higher than air temperatures in summer but are lower than air temperatures in winter.

The minimum recorded temperature for the basalt was –6.7°C (Table 1), with a minimum of –6.1°C recorded on the same day for sandstone. Air temperature dropped to a low of –3.3°C and soil temperature remained above freezing for the duration of monitoring, reaching a minimum of 0.6°C. Although basalt and sandstone differ notably in diurnal maximum temperatures, minimum temperatures are remarkably similar (Figure 3b) both in summer and winter (Table 1). Summer rock minimum temperatures are comparable to that of summer air minimum temperatures but in winter rock minimum temperatures are on average 3 to 4 degrees colder than air temperatures for the same period (Table 1). In contrast, the minimum temperature measured in soil during summer is higher than that measured by the other three sensors. In winter, however, soil minimum temperatures approximate minimum temperatures of ambient air.

Basalt records the greatest diurnal temperature range (48.7°C), somewhat higher than that for the sandstone (40.3°C) (Table 1, Figure 3c), with both maximum ranges occurring in the month of February. For air temperature, the maximum range value of 25.7°C was recorded in March but that value is anomalous in the context of the rest of the air ranges that typically do not exceed 20°C. Maximum soil temperature daily range was 19.4°C recorded in the month of January. Over the summer period the magnitude of diurnal ranges recorded on rock was highly variable but tended to stabilise in winter (Figure 3c). Comparing summer and winter, mean range values for air and both rock types are remarkably similar (Table 1) although standard deviations show increased variability in summer. In contrast, soil temperature ranges deviate from those of air in winter and overall soil has the lowest range in temperature, and hence the most isothermal conditions.

DISCUSSION AND SIGNIFICANCE

Rainfall totals for 2002 and 2003 are somewhat lower than the mean value of 1050 mm obtained from the nearest station at Giant's Castle Main Camp (see Sumner *et al*., 2004). These two years coincide with a marginally dryer spell in the Drakensberg, however, reservations have been expressed on the over-estimates for rainfall totals in the Drakensberg, particularly at high altitude (Nel and Sumner, 2005); more data are required over longer periods to verify rainfall estimates and the influence of altitude. What is apparent from the data is a high propensity for wetting and drying cycles in soil and rock, particularly in the summer period. In winter, moisture is scarcer but rainfall does occur occasionally and there is, therefore, potential for frost action if favourable temperatures coincide.

Over the winter period, minimum temperatures for air and both rock types frequently drop below 0°C. Rock surface temperatures reached less than –5°C on five occasions. Given the problems associated with discerning or attributing frost weathering processes in the field (Hall *et al*., 2002), frost action as an active weathering mechanism is not advocated here but conditions may be conducive at this altitude. Minimum soil temperatures were surprisingly high in relation to the temperatures measured by the other sensors and no soil frost was recorded. This is probably due to grass cover inhibiting effective radiative cooling and given the extensive vegetation cover at this altitude the widespread occurrence of soil frost appears unlikely. Frost action in soil, such as needle-ice activity (Boelhouwers, 1988), is thus likely to be predominant only at higher altitudes or restricted to exposed soil such as on stream banks or at mass movement sites.

Maximum rock temperatures are highly variable in summer and this is attributed to the frequent rainfall events, which have an obvious cooling effect. The highest temperature on record, 56.0°C for basalt, is not dissimilar to the low to mid 60°C‘s maximum temperatures reached on rock in the Namib desert (Sumner *et al.*, 2004; Viles, 2005) on the west coast of the sub-continent. The sandstone maximum of 50.1°C is also not much higher than the 45.4°C recorded outside of the Main Caves (Meiklejohn, unpublished data) at Giant’s Castle. Within the Main Cave and Battle Cave (Figure 1), both sites of prolific rock art, Meiklejohn recorded maximum sandstone temperatures of 33.4°C and 40.8°C where late-afternoon insolation reached shelter backwalls. In winter, insolation still heats rock surfaces regularly to above 30°C in the case of basalt and above 25°C on sandstone at the study site. Thus, chemical weathering of exposed rock surfaces is probably not temperature limited in winter, but available moisture may be a constraint. More data are required on rock moisture conditions for the area in combination with rock temperatures to explore this further.

A significant finding in the context of understanding surface processes is the overall poor correlation between air, soil and rock temperatures. Soil and air temperatures only correspond with respect to winter minimums, and differ with regard to maximums and summer minimums. Rock temperature maximums only correlate with air temperature maximums during rainfall periods, with both rocks being otherwise substantially hotter than ambient air. In summer, minimum rock temperatures do correspond well with minimum air temperatures, but rock temperatures fall below measured air and soil temperatures in winter.

These observations are of particular relevance to rock art conservation at sites where only air temperature is known. In the Injisuthi Valley numerous rock art sites are found on isolated sandstone boulders, and rock shelter backwalls may also receive early morning or late afternoon sun, particularly in winter. The paintings at Battle Cave receive substantial direct insolation in winter (Meiklejohn, 1994) and some art in shelters, such as at Battle Cave and Barne's Shelter at the Main Camp, has become more exposed where blocks upon which the art is painted have fallen from back walls onto shelter floors. It is argued here that rock temperatures should specifically be measured (e.g. Meiklejohn, 1994), probably using very small surface sensors (e.g. Hall and André, 2003) to ascertain rock temperatures, and that regional air temperature data as a surrogate (c.f. Hoerlé and Salomon, 2004) should only be used with caution.

Throughout the year rock experiences substantially greater diurnal temperature oscillations than air or soil. Temperature cycles can generate fatigue in rock (Hall, 1999) and result in mechanical breakdown. As with absolute temperature, the diurnal temperature range of ambient air bears no resemblance to rock temperature ranges, with mean range values of air being some 20 degrees less than that of, for example, basalt. Soil diurnal ranges in summer do approximate those of air ranges, but soil is more isothermal in winter. For both rock types, the temperature ranges are more variable in summer than winter due to the effect of rainfall, but average values for summer and winter indicate a similar physical environment for diurnal fatigue throughout the year. Air also shows similar average ranges in summer and winter, with the sensor in the soil being the only to record markedly lower mean diurnal temperature oscillations in winter than in summer.

As a final point, a comparison can be made between the temperatures of the two rock types. While darker coloured rocks are expected to achieve higher temperatures than lighter coloured rocks due to their low albedos, Hall *et al.* (2005) found that under certain conditions the reverse may apply. In this study, the data show that on all days where the rocks were heated substantially above the temperature of the air, the darker basalt achieved a higher temperature than the lighter coloured sandstone. Minimum temperatures of both rock types are virtually identical but, as noted above, both are lower than the temperature of the ambient air in winter and higher in summer. Although further study can be conducted using a finer monitoring resolution and a greater range of rock colours (see Hall *et al.*, 2005) the findings show a greater variability in diurnal temperature fluctuations of darker basalt.

SUMMARY

This paper adds a small data set to the still unclear picture on surface-climate conditions in the Drakensberg. While soil surface temperatures remained above freezing, rock temperature records and rainfall frequency suggest an environment conducive to thermal fatigue and wetting a drying with potential for frost action. Contrasting air, rock and soil surface temperatures emphasises the dissimilarity in micro-environmental conditions experienced by different natural mediums in the field. Using air temperatures as a surrogate for rock temperatures, and hence weathering processes, should thus be done with caution particularly where sites are partially exposed to sunlight. Even where sunlight is not a direct factor some degree of rock temperature departure from air has been recorded in rock art shelters (Meiklejohn, 1994) which strengthens the argument for detailed rock temperature recordings in weathering studies.

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RAINFALL AND TEMPERATURE ATTRIBUTES ON THE LESOTHO-DRAKENSBERG ESCARPMENT EDGE, SOUTHERN AFRICA

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ABSTRACT

Located near the south-eastern limit of Africa, the Lesotho-Drakensberg and associated escarpment is the highest range of African mountains south of the massifs in Tanzania. At the escarpment summit and on the adjacent high peaks, the climate is generally interpreted as marginal periglacial yet few data, specifically rainfall and temperature, exist on record at these altitudes. Climatic data from two temporary field stations on the escarpment edge, one of which is the highest rainfall station yet on record in southern Africa, provide contemporary surface-climate conditions. Although some data are missing from the records, rainfall recorded on the escarpment between 2001 and 2005 is less than that for the same period in the foothills. Even though rainfall is slightly below long-term rainfall averages for the sites due to a marginally dry spell in the area, the data show that earlier estimates for annual rainfall totals at high altitude are too high. Mean air temperature, however, falls within the range estimated for the escarpment summit. In general, soil temperatures are found to be higher than that of air. Frost cycles in air and soil surface are frequent in winter, but absent in soil for summer, and no long duration surface soil freeze was measured. Temperatures thus confirm the marginal periglacial nature as postulated by previous estimates but precipitation data indicate a dryer environment than anticipated. Palaeoenvironmental scenarios, notably arguments for former glaciation based on extrapolations from somewhat exaggerated contemporary precipitation values, thus require re-consideration.

INTRODUCTION

The Drakensberg-Lesotho range is a part of the main escarpment of southern Africa and has the highest mountains in Africa south of Tanzania's Mount Kilimanjaro. The escarpment typically summits above 2800 m on the border between the South African province of KwaZulu-Natal and the Kingdom of Lesotho. Here, frost action and associated micro-forms classify the area as marginal or sub-periglacial (Boelhouwers, 1994). Set slightly back from the escarpment within Lesotho, the highest point, Thabana Ntlenyana, measures 3482 m a.s.l. while foothills to the east in KwaZulu-Natal fall rapidly to below 1500 m a.s.l. beneath the escarpment. Recently declared a Trans-Frontier National Park, the area is a popular tourist destination and has been declared a World Heritage Site, houses unique flora and fauna and as a watershed is a vital natural water source with catchment drainage to the east coast and back into the interior via Lesotho. Given the altitudes attained, the persistence of soil frost action in winter and the palaeoenvironmental signatures found from former cold periods (see Boelhouwers and Meiklejohn, 2002), the setting is unique in Africa south of the equatorial region.

Two inter-basin transfer schemes, the Tugela-Vaal transfer tunnel (TUVA) and the international Lesotho Highlands Water Project (LHWP), have their upper catchments in the mountains and feed the dryer interior of South Africa. The major source of rainfall is from large-scale line thunderstorms and orographically induced storms (Tyson *et al*., 1976) in the summer while mid-latitude cold fronts affect KwaZulu-Natal annually, mainly during winter, bringing some precipitation. In the Drakensberg foothills, summer rainfall from November to March, accounts for 75% of the annual rainfall whilst the winter from May to August accounts for less than 10% (Nel and Sumner, 2006). Snowfalls occur on average eight times a year (Tyson *et al*., 1976), predominantly in the summit region, although the frequency could be underestimated since localised snowfalls are not taken into account (Boelhouwers and Meiklejohn, 2002). Heavy snowfalls in the high altitude areas can remain for several weeks on the ground (Hanvey and Marker, 1992) and recent observations by the authors on the escarpment suggest a water-equivalent of less than 100 mm p.a. (Nel and Sumner, 2005), but the contribution of snow to the water budget remains largely unknown.

Notwithstanding the State, public and scientific interest in the area a paucity of rainfall and temperature data, especially at high altitude, exists. Temperatures in headwater catchments at and above the escarpment are derived either as extrapolations from lower altitudes below the escarpment or from relatively short-duration field monitoring. Mean annual air temperature (MAAT) above 2800 m is estimated to be in the region of 3°C to 7°C (Boelhouwers, 1994; Grab, 1997a; 2002). Frost action disrupts soil during winter (Boelhouwers and Meiklejohn, 2002) of which the general intensity and penetration is uncertain (Sumner, 2003), but appears limited to the upper 15 cm of soil. Given the marginal frost activity, the effect of climate warming on frost-related processes is unknown. Some contemporary ground surface temperature data and observations on freezing depths on the high points of the escarpment region have been recorded but these are limited to two sites (Grab, 1997b; Sumner, 2003) over single winters. Significantly though, while the estimated MAAT range appears small, departures from these current values are often cited when substantiating palaeoclimates, particularly when debating conditions around the Last Glacial Maximum (see Boelhouwers and Meiklejohn, 2002). Scenarios such as the presence or absence of permafrost become borderline when estimated temperature depressions are 5 to 6°C from current MAAT values (see e.g. Grab, 2002; Sumner, 2003).

In addition to the paucity of temperature records there are no contemporary rainfall values published from these altitudes. This is particularly remarkable given that the central and northern Drakensberg and adjacent Lesotho upper catchments feed two major basin transfer systems. Several rainfall measurements do, however, exist from the early and mid-1900's. Killick (1978) documents the mean annual precipitation (MAP) for Sani Pass (2865 m a.s.l.) on the southern Drakensberg escarpment as 995.8 mm based on data from the 1930's and also cites a MAP of 1609 mm on the escarpment in the central Drakensberg at an unknown station at the summit of Organ Pipes Pass (2927 m a.s.l.). Carter (1967), in an assessment of the rainfall of Lesotho, published data from a station N situated approximately 1,8 km west of the escarpment at an altitude of 3121 m a.s.l. Mean annual precipitation for this site was 1068 mm based on five years in the early 1960's. Schulze (1979) published data from Sani Pass and Cleft Peak, situated on the escarpment edge at 2880 m a.s.l., where rainfall was recorded for an unspecified short duration, and the monthly data synthesised to 21 years. Mean annual precipitation from both stations are unknown but by extrapolation from lower altitude it is estimated that 250 mm of rain falls in January and annual rainfall exceeds 1800 mm (Schulze, 1979), possibly even 2000 mm p.a. (Tyson *et al*., 1976).

According to values available in the literature, precipitation on the escarpment could range from less than 1000 mm p.a. to in excess of 2000 mm p.a. Many contemporary authors cite MAP well exceeding 1000 mm p.a when considering the area above the escarpment, especially when extrapolating for palaeoclimates using departures from current values (Boelhouwers, 1988; Grab, 1994; 1996). In particular the high values (MAP exceeding 1500mm p.a.) are cited in favour of former glaciation (Grab, 2002) when precipitation for the region was considered to be 70% of current values (Partridge, 1997) but would then still support snow accumulation. Alternatively, dryer conditions would favour periglaciation at high altitude (see Boelhouwers and Meiklejohn, 2002; Sumner, 2004). The debate, highlighted by Boelhouwers and Meiklejohn (2002), remains unresolved but to a large extent could be solved by current records upon which to base extrapolations. This study provides climatic data obtained since 2001 from two temporary field stations on the escarpment edge, one of which is the highest station yet on record in southern Africa. Although some data are missing in the continuum the records provide the most recent surface-climate conditions at escarpment altitudes.

STUDY SITES AND METHODOLOGY

This study focuses on rainfall, air temperature and soil temperature measurements recorded at two field stations. Climatic measurements on the escarpment are notably difficult due in part to inaccessibility but mainly because of equipment theft. Only one vehicle route summits the escarpment in KwaZulu-Natal. Sani Pass is located in the southern Drakensberg, and a station was installed at the top of the pass on the escarpment edge adjacent to the tourist complex (29.57° S, 29.27° E, 2850 m a.s.l.). The second station was sited in the northern Drakensberg on the freestanding Sentinel Peak (28.74º S, 28.89º E) and is the highest point where climatic attributes have been measured in southern Africa (3165 m). Although some of the early rainfall data were presented from the two sites (Nel and Sumner, 2005) a longer rainfall record and temperature data from the stations are presented here.

Rainfall was measured with a Davis-MC Systems (D-MCS) automated tipping-bucket rain-gauge. The D-MCS gauge has a 163 mm collection diameter, has a tipping resolution of 0.2 mm and logs total rainfall every 5 minutes. For comparative purposes, monthly rainfall data from 1970 to 2005 were obtained from the South African Weather Service (SAWS) for stations at lower altitude, namely Sani Pass Border Post, Himeville and Emerald Dale in the southern Drakensberg, and Royal Natal National Park, Cavern Guest Farm and Roseleigh in the northern Drakensberg (Table 1). Rainfall records recorded by the D-MCS are deemed comparable against manual recording rain-gauges used by the SAWS (Nel and Sumner, 2005). Air and soil temperatures were measured at both sites using a MC Systems two-channel logger. The air temperature sensor comprises of a 5 mm diameter thermocouple cased in stainless steel, while the soil temperature sensor was on a cable extension comprises a similar thermocouple but with a resin tip. At Sani Pass the air temperature sensor was placed in a Stevenson Screen and the soil temperature sensor inserted into a loamy soil surface at 2.5 cm depth between grass tussocks. At Sentinel Peak air temperature was recorded at 1 m height in a radiation screen and the soil sensor was inserted into a coarse gravel, vegetation-free surface at 2.5 cm depth.

Rainfall Station	**Altitude (m)**	**Mean (mm) 1970-2005**	**Rainfall (mm) 2002**	**Rainfall (mm) 2003**	**Rainfall (mm) 2004**	**Rainfall (mm) 2005**	**Mean (mm) 2002-2005**
Northern Drakensberg							
Sentinel Peak	3165	----	----	764.8	417.2	741.6	641.2
Cavern Guest Farm	1980	1317.2	1151.5	759.6	1349.9	1477.3	1184.6
Royal Natal National Park	1392	1302.0	1281.2	774.1	1195.0	1260.8	1127.8
Roseleigh	1219	807.6	635.0	387.5	764.5	944.5	682.9
Southern Drakensberg							
Sani Pass	2850	----	742.0	----	702.4	859.0	767.8
Sani Pass Border Post	2055	1156.6	786.9	663.6	1051.5	928.9	857.7
Himeville	1524	919.9	798.6	792.8	1249.0	607.3	861.9
Emerald Dale	1189	852.0	902.2	526.6	945.5	797.6	793.0

Table 1: Rainfall attributes at selected rainfall stations in the Drakensberg

Sani Pass rainfall monitoring commenced from October 2001. High wind speeds caused the logger support platform to be damaged in mid-2003 and records for that year are incomplete. Rainfall data presented here for Sani Pass are from October 2001 to April 2003 and from January 2004 to the end of December 2005. Air and soil temperature were recorded at hourly intervals from 1 of November 2001 to 17 March 2002, and then two hourly from the 23 September 2002 to the 10 July 2003. Thereafter, to reduce visitation, six hourly averages were recorded from 9 January 2004 to 15 January 2005. On Sentinel Peak rainfall was recorded from 1 December 2002 to 31 December 2005. Temperature recordings on the peak were erratic due to repeated failure and replacement of the two-channel logger. The only temperature data that were available for direct comparison with Sani Pass are one hourly recordings from 23 November 2001 to 17 March 2002.

FINDINGS

Rainfall totals

Total rainfall recorded at Sani Pass during the calendar year 2002 was 742 mm. During 2004 rainfall totalled 702.4 mm and in 2005, 859 mm (Table 1). Rainfall recorded during the January months of 2002, 2003, 2004 and 2005 was 79.4 mm, 136 mm, 154 mm and 172 mm respectively (Table 2). Summer rainfall total (November to March) for 2001/2002 was 488 mm. During the summer of 2002/2003, 705 mm was recorded and rainfall during the 2004/2005 summer season was 700 mm. Winter rainfall (May to August) was considerably lower with 94.6 mm measured during 2002, 35.8 mm during 2004 and 43.6 mm measured during the winter of 2005 (Table 2).

Station	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Sani Pass	2001										100.6	141.0	101.8	
	2002	79.4	51.0	114.8	28.6	24.4	8.8	24.2	37.2	54.2	60.0	61.6	197.8	**742.0**
	2003	136.4	165.4	144.0	41.2	No Data								
	2004	154.0	92.0	12.0	15.0	4.4	7.0	17.8	6.6	46.8	96.0	132.0	118.8	**702.4**
	2005	172.4	132.8	144.2	50.2	6.6	10.8	0.2	26.0	28.0	98.8	113.8	75.2	**859.0**
Sentinel Peak	2002												187.2	
	2003	144.6	148.0	117.4	42.0	11.8	3.0	0.4	5.8	17.4	47.8	131.6	95.0	**764.8**
	2004	71.0	0.0	0.2	17.2	2.6	0.2	15.8	8.6	30.6	62.2	97.0	111.8	**(417.2)**
	2005	240.6	151.4	166.0	42.2	17.0	9.2	0.0	46.0	0.0	0.2	21.4	47.6	**741.6**

Table 2: Monthly rainfall (mm) measured at Sani Pass and Sentinel Peak.

Total rainfall on Sentinel Peak for the calendar year 2003 was 764.8 mm, in 2004, 417.2 mm and during 2005 741.6 mm was measured (Table 1). No rainfall was recorded at the Sentinel during February 2004, which is anomalous and could be due to equipment malfunction, but this could not be verified. January rainfall recorded during 2003 was 145 mm, in 2004 it was 71 mm and in January 2005 totalled 241 mm (Table 2). Summer rainfall totals (November to March) for 2002/2003 were 298 mm and for 2004/2005 were 767 mm. Winter rainfall (May to August) measured at Sentinel Peak was 21.0 mm measured during 2003, 27.2 mm in 2004 and 72.2mm measured during the winter of 2005 (Table 2).

Rainfall intensity and rain days

A rain day is defined as one on which at least 0.5 mm of rainfall is measured (Schulze, 1979). At Sani Pass the number of rain days in 2002 totalled 141 while the number of rain days in 2004 and 2005 was 136 and 141 respectively (Table 3). At the Sentinel fewer were recorded, with 112 days measured during 2003, 75 in 2004 and 93 during 2005 (Table 3). Monthly rain days also vary considerably, with the summer months (January, February, March, November and December) comprising between 58 and 73 percent of the annual total measured at Sani Pass. At the Sentinel the number of rain days measured during summer comprises between 60 and 76 percent of the annual total.

Station	**Year**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Total**
Sani Pass	2001										14	18	17	
	2002	21	9	15	6	7	5	6	10	13	12	14	23	**141**
	2003	19	16	12	9	No Data								
	2004	17	23	7	7	2	2	5	3	9	18	21	22	**136**
	2005	26	21	21	9	2	3	0	5	3	16	18	17	**141**
Sentinel Peak	2002												21	
	2003	13	18	11	9	4	2	0	2	11	12	17	13	**112**
	2004	9	0	0	2	1	0	5	4	5	13	15	21	**75**
	2005	24	15	18	9	3	3	0	7	0	0	2	12	**93**

Table 3: Number of rain days measured at Sani Pass and Sentinel Peak.

Rainfall is the key process in water erosion through the detachment of soil particles and creation of surface runoff (Moore, 1979) and in turn is related to the intensity at which this rain falls (Van Dijk *et al.,* 2002). At both escarpment sites the five-minute intensities (I_5) where analysed, and the number of occurrences of I_5 more than the thresholds of 15 mm/h, 30 mm/h and 50 mm/h were compared. Sani Pass recorded 142 occurrences of I_5 more than 15mm/h, 39 occurrences of I_5 more than 30 mm/h and 13 occurrences of I_5 more than 50 mm/h. In comparison, Sentinel Peak recorded 100 occurrences of I_5 more than 15 mm/h, 19 of more than 30 mm/h and only 2 occurrences of I_5 more than 50 mm/h. The monthly distribution of high intensity events was also analysed (Fig. 1) and the highest number of occurrences of 5-min rainfall intensity above 15 mm/h and 30 mm/h were measured in January at Sentinel Peak. At Sani Pass the most occurrences of I_5 above 15mm/h and 30mm/h were measured in December and March.

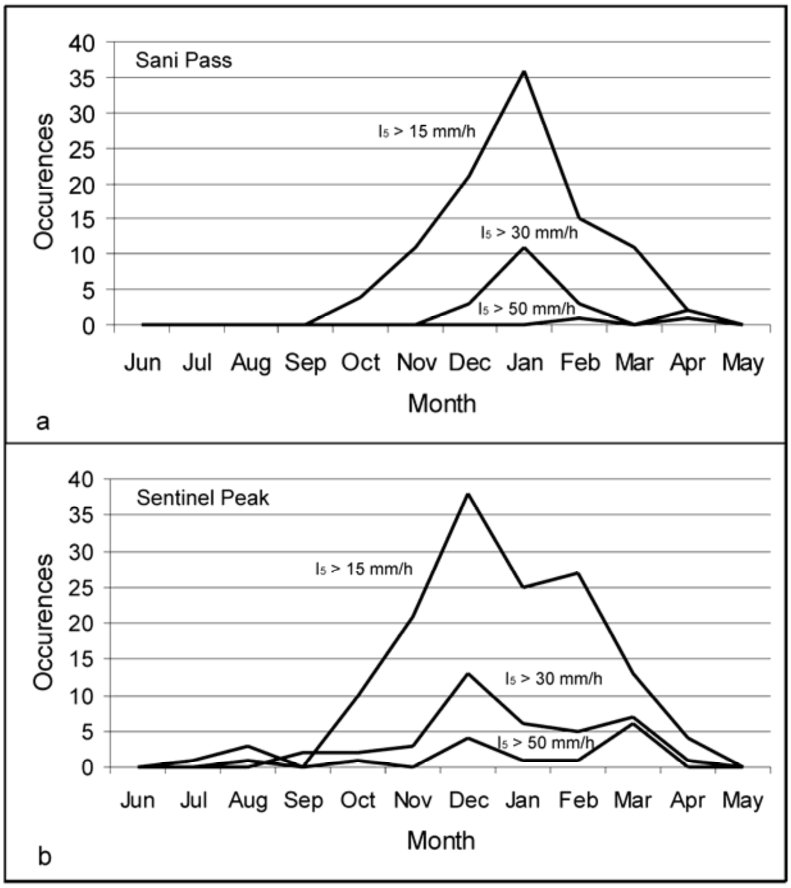


Figure 1: Monthly occurrences of high intensity rainfall events at (a) Sani Pass and (b) Sentinel Peak.

Total hourly rainfall as a percentage of total rainfall was considered and at Sani Pass nearly 10% of the total rainfall measured falls between 19h00 and 20h00 and 60% of all rainfall is measured between 13h00 and 21h00 (Fig. 2). At Sentinel Peak approximately 7% of total rainfall was measured during 16h00 and 17h00 and 21h00 and 22h00 respectively and approximately 61% between 13h00 and 23h00 (Fig. 2).

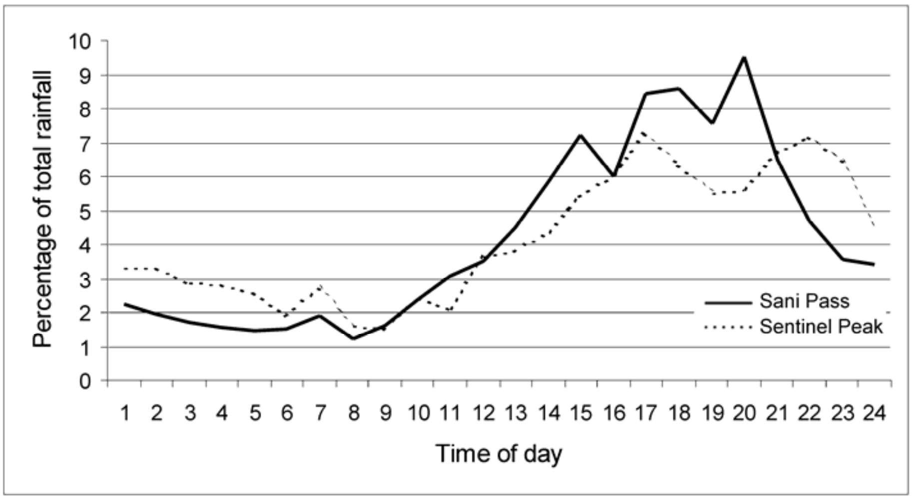


Figure 2: Timing of daily rainfall on the Drakensberg escarpment edge.

Air and soil temperatures

A continuous record of soil and air temperatures was not possible due to regular failure coupled with tampering and theft of the sensors and loggers; which highlights the difficulty in monitoring in this setting. Sani Pass provided the most complete data on record spanning the summer of 2001 to the summer of 2005 (Table 4). Only one uninterrupted year-cycle of temperatures was recorded, from 10 January 2004 to 9 January 2005. Screened mean air temperature over this period was 5.8°C and mean soil surface temperature 8.5°C. As expected, the number of freezing cycles and freezing days, where mean temperatures remain below zero, are dominant in the winter periods.

Minimum and maximum soil temperatures were consistently higher than that of the corresponding air temperatures in both winter and summer (Table 4). The minimum air temperature was –11.3°C recorded on 29 July 2004. In 2003, the winter minimum was similar at –11.0° on both mornings of 5 and 6 August. In contrast, soil surface temperatures only reached –3.0°C and –2.1°C minimums in the respective winters. Diurnal freezing cycles were, however, frequent in winter, and the longest period of continuous soil freeze recorded was only 4 days.

Temperatures (°C):	**Summer 2001/2 (1 Nov to 17Mar)**	**Summer 2002/3 (1 Nov to 31 Mar)**	**Winter 2003 (1 May to 10 Jul)**	**Winter 2004 (1 May to 31 Aug)**
Mean air T	6.7	6.6	-2.9	-2.1
Mean soil T	11.9	10.6	1.5	0.7
Min Air T	-1.6	-5.6	-11.0	-11.3
Max Air T	20.8	21.0	13.2	12.2
Min Soil T	4.0	1.4	-2.1	-3.0
Max Soil T Soil	24.3	23.8	13.5	12.5
No. of freezing cycles in air	4	6	65	76
No. of freezing cycles in soil	0	0	40	48
No. of frost days in air	0	1	6	17
No. of frost days in soil	0	0	5	0

Table 4: Air and soil temperatures measured at Sani Pass

Air and soil temperatures recorded hourly at Sani Pass and Sentinel Peak for the summer of 2001/2002 are compared in Table 5. At Sani Pass, mean air and soil temperature for this period was 9.7°C and 14.1°C, and at Sentinel Peak 9.3°C and 13.2°C respectively. Daily minimums and maximums were also considered (Table 5, Fig. 3); the mean daily minimum air temperature recorded at Sani Pass for this period was 4.8°C, mean daily maximum air temperature was 14.6°C, and absolute minimum and maximum were -1.6°C and 20.8°C. Mean daily minimum and maximum air temperature recorded at Sentinel Peak for the same period was 5.9°C and 13.5°C and absolute minimum and maximum were 2°C and 18.8°C. Mean daily minimum soil temperature for this period recorded at Sani Pass was 10.1°C and mean daily maximum air temperature was 18.9°C. Absolute minimum and maximum soil temperatures measured at Sani were 6.9°C and 24.3°C. Mean daily minimum and maximum soil temperature during the same period at Sentinel Peak was 6.1°C and 24.3°C and absolute minimum and maximum soil temperatures were 1.3°C and 38.5°C respectively (Table 5).

Station	**Statistic**	**Daily Air T**	**Daily Soil T**	**Rate of change air T (°C/hour)**	**Rate of change soil T (°C/hour)**
Sani Pass	Mean	9.7	14.1	0.9	0.7
	Mean min	4.8	10.1		
	Mean max	14.6	18.9		
	Absolute min	-1.6	6.9		
	Absolute max	20.8	24.3	6.4	4.9
Sentinel Peak	Mean	9.3	13.2	0.8	1.6
	Mean min	5.9	6.1		
	Mean max	13.5	24.3		
	Absolute min	2	1.3		
	Absolute max	18.8	38.5	4.9	11.1

Table 5: Air and soil temperatures measured at Sani Pass and Sentinel Peak (21/11/2001- 17/3/2002)

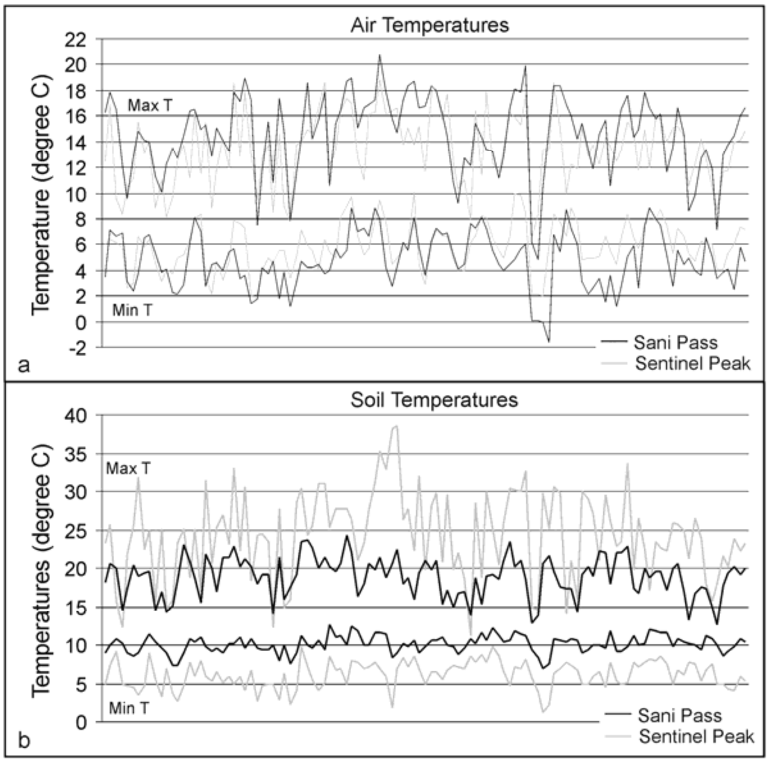


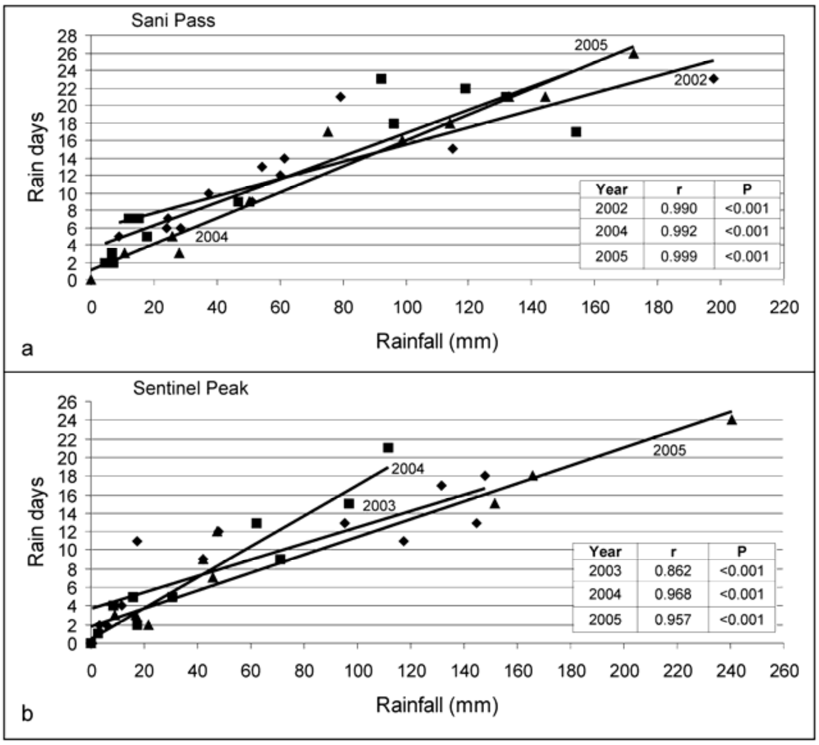
Figure 3: Daily minimum and maximum temperatures measured at Sani Pass and Sentinel Peak for (a) air and (b) soil.

DISCUSSION

Rainfall totals from the two stations were considerably less than expected in comparison to earlier literature. Although the measured totals from the 1930's show a MAP slightly below 1000 mm (Killick, 1978) all previous measurements and extrapolations far exceed the totals measured here. The monitoring period was, however, marginally dryer than long-term averages. In comparison to mean annual rainfall totals since 1970 (36 years) at six established stations, the period 2002 to 2005 had 85 to 90% of the mean annual rainfall in the northern Drakensberg and between 74 to 93% of the mean annual rainfall in the southern Drakensberg. The mean rainfall for January (135.5 mm) for the top of Sani (4 years) and 152 mm for Sentinel Peak (3 years) as well as the annual rainfall measured at the top of Sani

Pass in 2002, 2004 and 2005 (767.8 mm) and on Sentinel Peak in 2003 and 2005 (753.2 mm) are thus probably slightly below long-term rainfall averages for the sites. Nonetheless, averages remain substantially less than anticipated. Either rainfall has severely been overestimated in the past or the sensitivity to dry and wet periods is far greater at higher altitudes. It is worth noting that the 1970's, a period where several of the estimates for rainfall were made (Tyson *et al*., 1976; Schulze, 1979), was a wetter period in southern Africa (Tyson and Preston-Whyte, 2000). Longer-term records may provide a solution but, given the data provided here, it is apparent that rainfall on the escarpment area may have been overestimated in the past. Extrapolation towards palaeo-precipitation scenarios using values exceeding 1000mm p.a. should thus be made with caution.

With respect to rain days, in the southern and northern Drakensberg, the number of rain days increased slightly with altitude (Nel and Sumner, 2005; Nel, submitted) and the number of rain days measured each month at the two stations is strongly correlated with the respective monthly rainfall and the linear relationship is statistically significant at $P < 0.001$ (Fig. 4). As expected, an increase in measured monthly rainfall signifies an increase in the number of rain days for that particular month. Schulze (1979, Fig. 4.11, p.66) estimates that the Drakensberg escarpment receives approximately 125 rain days a year. Rain days measured here indicate that the southern Drakensberg receives more than the estimate, and the north fewer rain days, but as a regional figure for the whole escarpment edge 125 appears to be a good approximation. Differences in the amount of rainfall and the number of rain days that exist between the two stations can also be considered further. At Sani Pass the amount of rainfall measured in 2002 is 742 mm and it was recorded in 141 days, representing a mean of 5.3 mm per rain day. At Sentinel Peak in 2005 the same amount of rainfall (741.6 mm) only fell in 93 days, which gives 7.8 mm per rain day. For the same year (2005) Sani Pass received 6.1 mm per rain day in 141 days. Based on these data it seems that on the northern Drakensberg escarpment fewer rain days are recorded than in the southern Drakensberg, but the number of rain days recorded increases with altitude (Nel, submitted).



Year	r	P
2002	0.990	<0.001
2004	0.992	<0.001
2005	0.999	<0.001

Year	r	P
2003	0.862	<0.001
2004	0.968	<0.001
2005	0.957	<0.001

Figure 4: Correlation between monthly rainfall and rain days for (a) Sani Pass and (b) Sentinel Peak.

Nel and Sumner (submitted) indicate that erosive events in the Drakensberg are almost exclusively a summer phenomena and the distribution of high intensity rainfall events on the escarpment is also seasonal with most occurrences measured during summer. However, in the southern Drakensberg the monthly distribution of high intensity 5-min rainfall is more complex than in the north with the most occurrences measured during December and March. Most rainfall events in the high Drakensberg occur in the late afternoon/early evening with both Sani Pass and the Sentinel showing 40.1% and 30.8% of total rainfall measured between the hours of 15h00 and 20h00 respectively when sufficient cooling has occurred for condensation and cloud formation. This correlates well with the findings from Nel (submitted) for the Drakensberg foothills and Schulze (1965), which indicate that thunderstorms in the Drakensberg occur in mid- to late- afternoon.

Temperature records from Sani Pass proved to be intermittent and highlight the problems associated with attempts at monitoring along the escarpment edge. Only one complete annual cycle of records was made but several summer and winter periods are on record. The mean air temperature of 5.8°C falls within the range estimated for above the escarpment (see Boelhouwers, 1994), but is somewhat higher than the 3° to 4° MAAT postulated by, for example, Grab (1994; 1997a) on the plateau peaks immediately behind the escarpment. As expected, frost cycles in air and soil surface are frequent in winter, but absent in soil for summer although a few are recorded in air in summer. In general the soil temperatures are higher than that of air and thus air temperature cannot be realistically used as a surrogate to analyse soil frost phenomena. Even though the minimum soil temperatures measured at Sani Pass were –2.1°C and -3°C for the winters of 2003 and 2004 respectively, no long-duration, or seasonal, freeze was found for the soil surface in either of the winters on record. In contrast, a seasonal freeze of 56 days was found at 2 cm depth at 3200 m, some 300 m higher in altitude near Thabana Ntlenyana to the north of Sani Pass, with a winter minimum of –4.5°C reached (Sumner, 2003). Although the records represent separate winters the difference may highlight the role of increasing altitude above the escarpment in depressing soil temperatures. At lower altitudes, few recent soil-air temperature data sets exist for comparison with the data provided here. In the Central Drakensberg at 1920 m a.s.l. Sumner and Nel (2006) recorded air and soil surface minimum temperatures of –3.3°C and 0.6°C and mean air and soil temperatures of 4.3°C and 4.2°C respectively over the winter of 2001. During the winter of 2003 and 2004 mean air and soil temperatures recorded at Sani Pass were –2.9°C and 1.5°C, and –2.1°C and 0.7°C respectively. Based somewhat speculatively on these data, it seems that air temperature decreases more rapidly with regards to altitude than soil temperatures, thus highlighting the difficulty in extrapolating soil conditions through air temperatures.

Comparing air and soil temperature data at the two escarpment sites it is clear that differences exist with regards to minimum and maximum soil temperatures. As noted above, the soil temperature sensor at Sani Pass was inserted into a loamy soil surface between grass tussocks and at Sentinel Peak the sensor was inserted into a dark coarse gravel surface with no vegetation cover. Even though mean daily soil temperatures for the period are similar, differences in absolute minimum and maximum soil temperatures as well as the temperature range between Sentinel Peak and Sani Pass appear related to the type or texture of soil and differences in vegetation cover. At Sani Pass where the sensor was in soil with vegetation cover the range between minimum and maximum temperature and the rate of temperature change is less than the coarse Sentinel material, which has a larger temperature range, has faster rate of change in temperature and reaches higher and lower maximum and minimum temperatures (Table 5). Sumner and Nel (2006) also highlight the role of vegetation cover as an inhibitor to soil frost. Given the changes speculated for under climatic change or associated with intensified land use, the role of vegetation may be even more significant in inhibiting soil movement or degradation associated with frost action (see Boelhouwers and Meiklejohn, 2002) than previously considered.

SUMMARY

Weather station data from two sites on the Drakensberg-Lesotho escarpment provide new contemporary surface-climatic data from this unique setting in Africa. Rainfall, collected over a four-year period, shows lower totals than equivalent sites below the escarpment. Comparing mean annual rainfall totals from established stations in the foothills since 1970, 2002 to 2005 were slightly dryer than normal. Even though wind catch deficiency may exist to some extent (Nel and Sumner, 2005) and the rainfall measured at the top of Sani Pass and Sentinel Peak are probably slightly below long-term rainfall averages for the sites, the data suggest that earlier estimates for total annual rainfall between 1800 mm and 2000 mm at the escarpment appears to be too high. Linked to this, the data thus also signify that it is unlikely an increase in rainfall with altitude all the way up to the escarpment exists (e.g. Tyson *et al.*, 1976; Schulze, 1979).

The mean air temperature measured at Sani Pass falls within the range estimated for the escarpment, but is somewhat higher than the 3° to 4° MAAT postulated for the plateau peaks immediately behind the escarpment (Grab, 1994; 1997a). Frost cycles in air and soil surface are frequent in winter, but absent in soil for summer although a few are recorded in air in summer. No long-duration, or seasonal freeze was found for the soil surface and in general the soil temperatures are higher than that of air and thus air temperature cannot be realistically used as a surrogate to study soil frost. Comparing across the escarpment, no difference exist with regards to mean air and soil temperatures at the two stations although temperature range differences appear related to the soil characteristics and vegetation cover. Rainfall totals are similar, but the amount of rainfall measured in each rain day is found to be proportionately more in the north than in the south. When comparing temperature data with those at slightly higher (Sumner, 2003) and lower altitudes (Sumner and Nel, 2006) it appears that air temperature decreases more rapidly with altitude than soil does. A strong decline in soil temperatures may exist behind the escarpment onto the highest peaks but more field data are required to verify this.

Temperature findings, although limited in duration, support the classification of the Drakensberg-Lesotho summit area as currently marginal periglacial. Effects of global warming and land use change, such as increased grazing, on frost action and land degradation (Boelhowers and Meiklejohn, 2002) still require further exploration but indications are that soil frost would be enhanced under a declining grass cover (see also Sumner and Nel, 2006). The dryer then anticipated current environment above the escarpment questions the accuracy of relief-based models from which former rainfall totals were generated. In addition, palaeoenvironmental extrapolation based on inflated current values, such as used in support of former glaciation, requires re-consideration.

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