INTRODUCTION

The Drakensberg range in South Africa is part of the Main Escarpment that extends as a passive margin around the African sub-continent. In KwaZulu-Natal the mountains are divided into three regions, the northern, central and southern Drakensberg (Fig. 1). Land-use within the Drakensberg area is mainly related to altitude, with the wilderness conservation areas situated in the escarpment zone (2200 m to above 3000 m a.s.l.) and farmland and small towns found below 2200 m a.s.l. in the foothills (Fig. 1). Typically, the escarpment edge lies between 2800-3000 m and defines the watershed border 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). The Drakensberg area has recently been declared a Trans-Frontier National Park and has become South Africa's most valuable source of surface runoff since population growth and industrial development has placed increasing pressure on water resources (Mason and Jury, 1997). In the Johannesburg area, South Africa's biggest city situated in the Gauteng province, water consumption has more than doubled since 1970. It is predicted that the domestic and industrial water demand in Gauteng is to increase from 980 million cubic metres to 3800 million cubic metres per annum and such a demand will exceed existing water resources (Waites, 2001). To address this resource problem and to supply water to Gauteng, two inter-basin transfer schemes that operate in the Drakensberg region, the Tugela-Vaal transfer tunnel (TUVA) and the Lesotho Highlands Water Project (LHWP) were developed to transfer water from the upper catchments in KwaZulu-Natal and Lesotho to Gauteng (see Bell, 1999; Nel and Illigner, 2001; Waites, 2001). Although the Drakensberg is hydrologically important, climatic data are only predominantly collected in the foothills and very few contemporary analyses of these data have been forthcoming for this region.

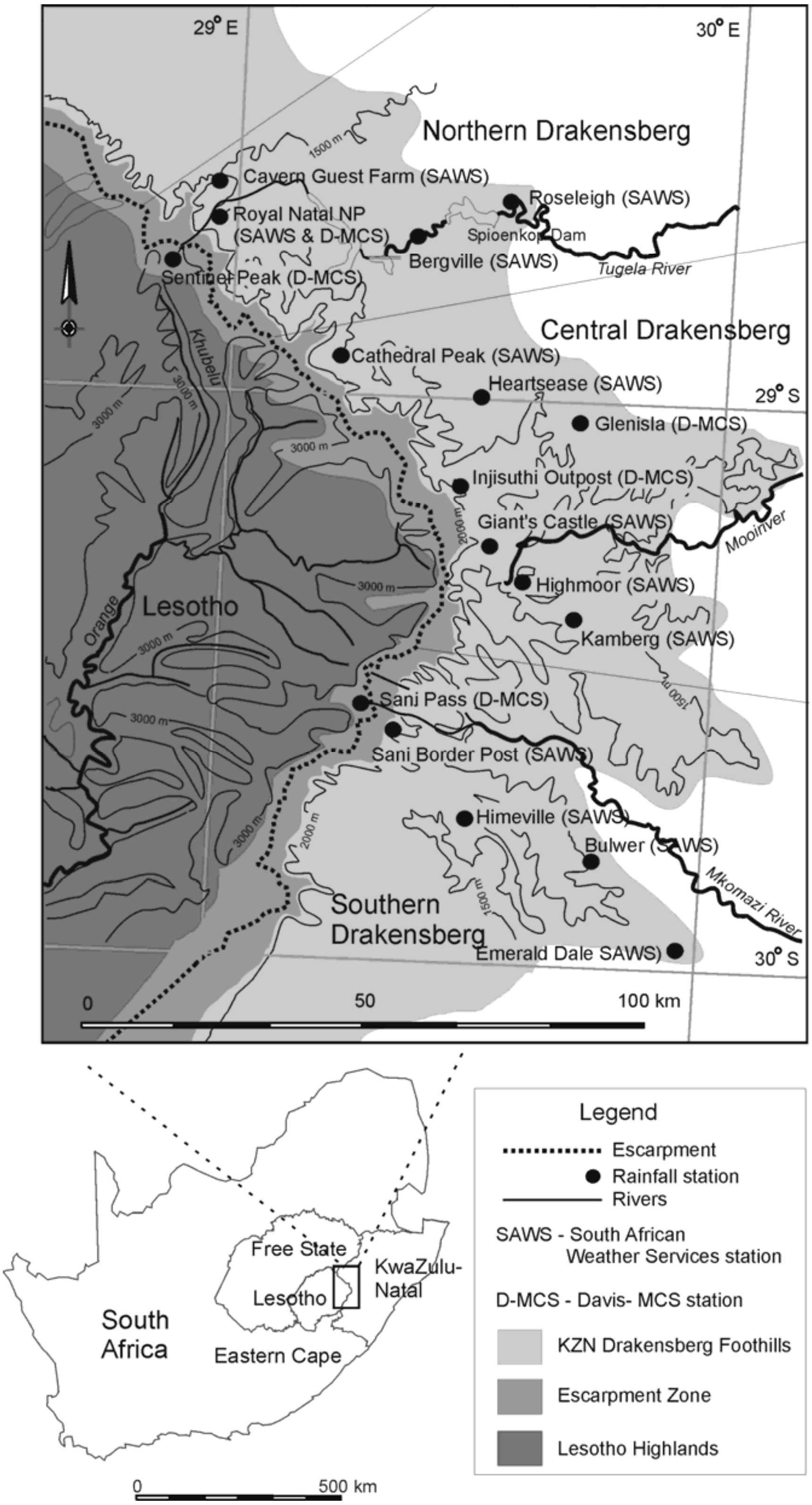

Figure 1: Location of the Drakensberg and the SAWS and D-MCS rainfall stations used for analysis in this study.

Where KwaZulu-Natal borders on eastern Lesotho, the catchments generate nearly twice as much total runoff per unit of rainfall than for the average of South Africa as a whole, and this contributes a quarter of South Africa's streamflow (Whitmore, 1970). Sources of precipitation over the Drakensberg include large-scale line and orographically induced thunderstorms, and cold fronts that 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). 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 considered (Boelhouwers and Meiklejohn, 2002).

Stations in the Drakensberg experience an average of 16 to 18 rain days in the months of December and January and the summer months November to March account for 70% of the annual rainfall, whilst May to August accounts for less than 10% (Tyson *et al.*, 1976). Even though the high altitude region of the Drakensberg is an important catchment area, little research has focussed on assessing rainfall on the escarpment. Mean annual precipitation (MAP) measured in the 1930's at Sani Pass (2865 m a.s.l.) on the southern Drakensberg escarpment edge was 995.8 mm (Killick, 1978). Three years of rainfall data are also presented from an unknown station at the summit of Organ Pipes Pass (2927 m a.s.l.) on the central Drakensberg escarpment. Mean annual precipitation measured at this site was 1609 mm (Killick, 1978) (Table 1). Carter (1967), in an assessment of the rainfall in Orange River catchment in Lesotho, published data from a station situated approximately 1,8 km west of the escarpment at an altitude of roughly 3121 m a.s.l. Based on five years of measurements in the early 1960's, MAP for this site was 1068 mm. Sene *et al.* (1998) uses rainfall data from Sani Pass to assess the flow variations in the Lesotho Highlands and 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, estimates exceeding 1800 mm per annum are given using relief-based extrapolation from lower altitude (Tyson *et al*., 1976; Schulze, 1979), possibly exceeding 2000 mm per annum (Tyson *et al*., 1976) (Table 1).

Author(s)	**Topic**	**Station Name**	**Recording period**	**Data published**	**Mean annual precipitation**
Carter (1967)	Water resources of the Upper Orange catchment.	N	6 years	Monthly	855 mm (measured)
Tyson *et al.* (1976)	Climate of the Drakensberg	Sani Pass	Unknown	No. of raindays and annual total	For station unknown For escarpment >2000 mm (estimated)
Killick (1978)	Climate of the Alpine Vegetation Belt of eastern Lesotho.	Sani Pass Organ Pipes Pass	12 years 3 years	Monthly Monthly	995.8 mm (measured) 1609 mm (measured)
Schulze (1979)	Hydrology of the Drakensberg	Sani Pass Cleft Peak	18 years Few months	Monthly Monthly	For stations unknown For escarpment >1800 mm (estimated)
Sene *et al*. (1998)	Rainfall and flow variations in the Lesotho Highlands	Sani Pass	Unknown	Annual	Unknown

Table 1: Previous published rainfall data from the Drakensberg escarpment.

According to the values available in the literature, precipitation on the escarpment thus has a notably large range from 1000 mm per annum to in excess of 2000 mm per annum. Many contemporary authors cite MAP exceeding 1000 mm per annum especially when extrapolating for palaeoclimates above the escarpment zone using departures from current values (Boelhouwers, 1988; Grab, 1994; 1996), In particular the high values (MAP exceeding 1500 mm per annum) are cited in favour of former glaciation during the Last Glacial Maximum (Grab, 2002). Precipitation for this period is believed to be 70% of current values (Partridge, 1997), but if current rainfall estimates are above 1500 mm this supports snow accumulation during the LGM. Alternatively, contemporary dryer conditions would favour periglaciation at high altitude during the LGM (see Boelhouwers and Meiklejohn, 2002).

Collection and analysis of current data could to a large extent resolve the situation by giving researchers a platform from which to base extrapolations for palaeoclimates.

Few studies have investigated contemporary rainfall erosivity and no studies have assessed rainfall structure and characteristics 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 (Giant's Castle) as representative of the mountainous area and mapped findings suggest that their Rainfall Erosivity Index decreases from east to west from the foothills to the escarpment.

The South African Weather Services (SAWS) operate a number of weather stations in the Drakensberg, but they are mostly confined in the foothills at altitudes below 1800 m. At the stations, daily rainfall is measured manually from a rain-gauge at 08h00 by SAWS volunteers; for example police officers (e.g. Sani Border Post), conservation personnel (eg. Royal Natal National Park (Fig. 2a); Giant's Castle Game Reserve) and farmers (eg. Heartsease) (Fig. 1). In earlier reports, 95-98% accuracy was noted for station data (Schulze, 1979; Dent *et al*., 1987) but presently, the SAWS do not claim such accuracy from stations (Swart, pers. com). Consequently, in assessing the spatial and temporal trends of rainfall and rainfall variability in the foothills, this thesis only used data from well-established SAWS weather stations with long-term unbroken rainfall measurements (Fig. 1). On the escarpment, where no SAWS stations and consequently no contemporary climatic data exist, measurement is difficult due to equipment theft and inaccessibility. In this thesis rainfall recordings on the escarpment took place at temporary field stations on the Sentinel Peak (Fig. 1, Fig. 2c) in the northern Drakensberg, which can only be accessed through climbing the steep cliffs, and at the Sani Pass chalet complex in the southern Drakensberg, which has established tourist related infrastructure and people guarding the recording equipment (Fig.

1, Fig. 2d). In assessing the structure and characteristics of rainfall in this thesis, automated tipping-bucket rain-gauges (Davis-MC Systems) were installed at these two escarpment sites as well as three sites in the foothills namely: Injisuthi Outpost, Royal Natal National Park and Glenisla (Fig. 1).

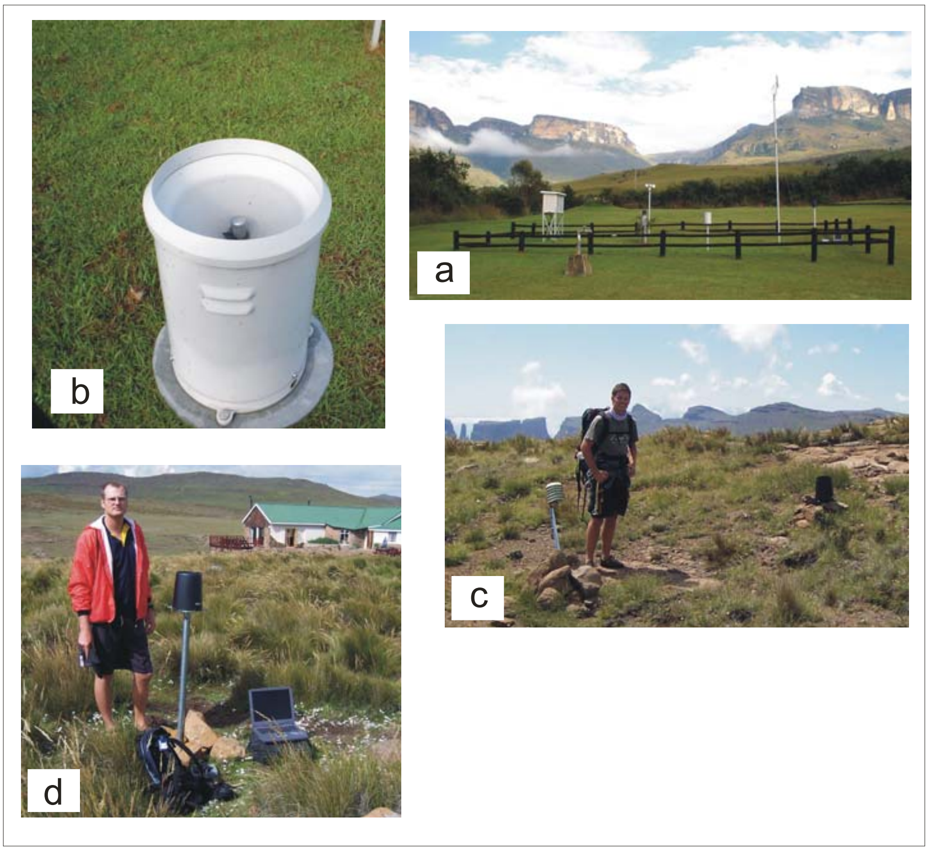

Figure 2: Photographs of a) Royal Natal National Park SAWS station b) blocked rainfall intensity meter at Royal Natal National Park SAWS station c) the D-MCS rainfall and temperature logger on Sentinel Peak and d) the D-MCS rainfall gauge at Sani Pass.

General air and soil temperature conditions in the Drakensberg escarpment zone remain uncertain, particularly since temperatures in headwater catchments on the escarpment edge or above the escarpment are formerly derived from extrapolations from lower altitude. The escarpment and adjacent summits is classified as a marginal periglacial area (Boelhouwers, 1991) but, 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). Researchers in the area concede that contemporary air and soil temperatures, from which extrapolations can be based, are scarce (Boelhouwers and Meiklejohn, 2002; Sumner, 2003). First assessments of air temperature on the escarpment estimated mean winter temperature to be 4°C and winter mean minimum air temperature be as low as -13°C (Tyson *et al*., 1976) (Table 2). Grab (1994) published data from Letseng-la- Draai station 3050 m a.s.l west of the escarpment in Lesotho and used it to extrapolate mean annual air temperature (MAAT) and winter temperatures for the escarpment zone. Mean winter temperatures is estimated to be 0.4°C and mean minimum as low as -6°C (Grab, 1994; 1997a; 1997b; 1999; 2002). 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. During winter, frost action disrupts soil on the escarpment (Boelhouwers and Meiklejohn, 2002), but the penetration and intensity of frost processes are unclear (Sumner, 2003). It appears that frost penetration is limited to the upper 15 cm of soil and given this marginal frost activity, the effect of climate warming on frost-related processes is unknown.

Geomorphological researchers estimates MAAT above 2800m to be in the region of 3°C to 7°C (Boelhouwers, 1994; Grab, 1997a; 2002) and although this estimated MAAT range appears small, departures from these current values are often cited when substantiating or refuting certain palaeoclimates, particularly the intensity of soil frost processes and the presence or absence of ground ice during the Last Glacial Maximum (see Boelhouwers and Meiklejohn, 2002). Scenarios, such as former permafrost, become controversial when estimated temperature depressions are 5 to 6°C from current MAAT values (see e.g. Grab, 2002; Sumner, 2004).

Author(s)	**Topic**	**MAAT (Estimated/Measured)**	**Winter Temperature**
Tyson *et al*. (1976)	Climate of the Drakensberg	-	Mean minimum (-13°C) (Estimated) Mean July (4°C) (Estimated)
Boelhouwers (1994)	Periglacial landforms at Giant's Castle	7°C (Estimated)	-
Grab (1994)	Thufur in the Mohlesi Valley	5 to 6°C (Estimated)	Mean (0.4°C) Mean minimum (-6°C)
Grab (1997a)	Thermal regime for a tufa apex and depression	6°C (Estimated)	Mean minimum (-6°C) (Grab 1994)
Grab (1997b)	Analysis of high altitude air temperature	3 to 5°C (Estimated)	Mean minimum (-6°C) (Grab 1994)
Grab (1999)	Block deposits in the High Drakensberg	4°C (Estimated)	Mean July (0°C) (Estimated)
Grab (2002)	Characteristics of relict patterned ground	4°C (Estimated)	Mean July (0°C) (Estimated)

Table 2: Previous published Mean Annual Air Temperature (MAAT) and winter temperatures.

The aim of the thesis is to provide a contribution to an understanding of the contemporary and historically recent climatic characteristics in the KwaZulu-Natal Drakensberg. As geographical focus area, the thesis focuses on the Drakensberg foothills when analysing long-term climatic trends, but emphasises the attributes of rainfall and to a lesser extent air and soil temperatures measured in the Drakensberg escarpment zone and its effects on surface processes, a first for this hydrologically crucial area. Key objectives of this study include the following:

- Analysing the spatial and temporal trend of rainfall totals and variability within the Drakensberg foothills,
- investigating the characteristics, structure and erosivity of rainfall events at all altitudes,
- and analysing the surface-climate attributes measured on the escarpment and in the foothills and their possible effects on geomorphological processes.

The thesis is a compilation of articles produced by the author (some are co-authored), either already published or in various stages of submission and review for journals, and comprises two sections. Section 1 constitutes two Chapters: the first is an article on rainfall spatial variability trends in the Drakensberg foothills, and the second an article on long-term temporal rainfall trends also in the foothills. Both these Chapters use existing data collected by the SAWS.

Section 2 comprises six Chapters, each originating from articles that present and discusses new rainfall and temperature data collected over a period of five years. The first Chapter presents initial contemporary measured rainfall data from the southern and northern KwaZulu-Natal Drakensberg escarpment stations. The second chapter in this section analyses rainfall totals generated from individual rainfall events. Chapter three and Chapter four of this section discuss the first data on storm erosivity in the KwaZulu-Natal Drakensberg summit area and in the foothills east of the escarpment. Soil and rock temperature data measured at a site in the Drakensberg foothills, are discussed in Chapter five and the final Chapter of the thesis presents the longest contemporary rainfall, soil and rock temperature data recorded on the Drakensberg escarpment edge.

Both sections are introduced with a Preface. The publication status of each article is noted on the Chapter title page and where papers are co-authored the relative contributions by the authors are noted in the Preface. Some repetition does occur between Chapters, particularly in the introductions in the various documents. Unfortunately this cannot be avoided since the papers are included as the text appears in the literature or in submission for publication. Relevant acknowledgements and references are presented at the end of each Chapter. The style of graphical presentation is similar throughout the thesis although published documents may show some variations due to external editorial requirements. One article by the author that discusses specific attributes of thermal conditions in four distinct climatic zones (including the Drakensberg) is included in the Appendix. This paper is related to the thesis but not integral to the discussion.

REFERENCES

Bell, F.G. 1999. The Lesotho Highlands Water Project: A geotechnical and engineering geological review of the initial phase. *Environmental and Engineering Geoscience,* 5, 271-313.

Boelhouwers, J.C. 1988. Geomorphological mapping of a part of the Giant's Castle Game Reserve, Natal Drakensberg. Unpublished MSc dissertation, University of Natal,

Boelhouwers, J. 1991. Present-day periglacial activity in the Natal Drakensberg: a short review. *Permafrost and Periglacial Processes,* 2, 5-12.

Boelhouwers, J. 1994. Periglacial landforms at Giant's Castle, Natal Drakensberg, South Africa. *Permafrost and Periglacial Processes,* 5, 129-136.

Boelhouwers, J. and Meiklejohn K.I. 2002. Quaternary periglacial and glacial geomorphology of southern Africa: a review and synthesis. *South African Journal of Science,* 98, 47-55.

Carter, C.A. 1997. A survey of the surface water resources of the Upper Orange catchment. Unpublished MSc. (Eng) thesis, University of the Witwatersrand, Johannesburg.

Dent, M.C., Lynch, S.D. and Schulze, R.E. 1987. *Mapping mean annual and other rainfall statistics over southern Africa*. Water Research Commission Report, Pietermaritzburg.

Grab, S. 1994. Thufur in the Mohlesi Valley, Lesotho, southern Africa. *Permafrost and Periglacial Processes,* 5, 111-118.

Grab, S. 1996. Debris deposits in the high Drakensberg, South Africa: possible indicators for plateau, niche and cirque glaciation. *Zeitschrift für Geomorphologie,* 103, 389-403.

Grab, S. 1997a. Thermal regime for a thufa apex and its adjoinind depression, Mashai Valley, Lesotho. *Permafrost and Periglacial Processes,* 8, 437-445.

Grab, S. 1997b. Analysis and characteristics of high altitude air temperature data from northern Lesotho: Implictions for cryogeomorphic occurrences. *Geoökoplus*, 4, 109-118.

Grab, S. 1999. Block and debris deposits in the high Drakensberg, Lesotho, southern Africa: implications for high altitude slope processes. *Geografiska Annaler,* 81, 1-16.

Grab, S. 2002. Characteristics and paleaoenvironmental significance of relict sorted patterned ground, Drakensberg plateau, southern Africa. *Quaternary Science Reviews*, 21, 1729-1744.

Killick, D.J.B. 1978. Further data on the climate of the Alpine Vegetation Belt of the eastern Lesotho. *Bothalia*, 12, 567-572.

Mason, S.J. and Jury, M.R. 1997. Climatic variability and change over southern Africa: a reflection on underlying processes. *Progress in Physical Geography,* 21, 23-50.

Nel, E. and Illigner, P. 2001. Tapping Lesotho's "white gold". *Geography*, 2, 163-167.

Partridge, T.C. 1997. Cainozoic environmental change in southern Africa, with special emphasis on the last 200 000 years. *Progress in Physical Geography,* 21, 3-22.

Schulze, R.E. 1979. *Hydrology and Water Resources of the Drakensberg.* Natal Town and Regional Planning Commission, Pietermaritzburg.

Sene, K.J., Jones, D.A., Meigh, J.R. and Farquharson, F.A.K. 1998. Rainfall and flow variations in the Lesotho Highlands. *International Journal of Climatology*, 18, 329- 345.

Seuffert, O., Herrig, K., Ollesh, G., and Busche, D. 1999. REI An integrated rainfall erosivity index for assessing and correlating rainfall structure, runoff and erosion. *Geoökodynamik*, 20, 1-54.

Sumner, P.D. 2003. A contemporary winter ground thermal profile in the Lesotho Highlands and implications for active and relict soil frost phenomena. *Earth Surface Processes and Landforms,* 28, 1451-1458.

Sumner, P.D. 2004. Geomorphic and climatic implications of relict openwork block accumulations near Thabana-Ntlenyana, Lesotho. *Geografiska Annaler*, 86A , 181-194.

Swart, G. (personal communication). South African Weather Service, Pretoria, February 2005.

Tyson, P.D., Preston-Whyte, R.A. and Schulze, R.E. 1976. *The Climate of the Drakensberg*. Natal Town and Regional Planning Commission, Pietermaritzburg.

Waites, B. 2001. The Lesotho Highlands project. *Geography,* 2, 369-374.

Whitmore, J.S. 1970. *The hydrology of Natal*. Symposium Water Natal: Durban.