Spatial variability of short-term rainfall amounts in a coastal mountain region of southern Africa

DA Hughes* and A Wright[1]
Hydrological Research Unit, Department of Geography, Rhodes University, Grahamstown 6140, South Africa.

Abstract

This paper discusses spatial variations in short-term rainfall in the southern Cape coastal mountain region of southern Africa. The analyses of storm rainfall totals and storm profiles reveal patterns of variability that are similar to those suggested by an earlier analysis of mean annual data in the same region. The patterns of spatial variation appear to be more consistent in winter when a lower diversity of weather patterns is responsible for generating rainfall. Superimposed upon a general increase in storm rainfall with altitude, is a pattern of local rain shadows in the lee of higher relief areas relative to rain bearing winds. For 9 continuously recording rainfall stations, storm profiles exhibit a high degree of similarity in timing and shape but not total rainfall depth. This feature suggests that the spatial variation of temporal intensity occurs on a relatively large scale. The data analysed did not suggest any consistent differences between station profiles that could be attributed to differences in weather patterns.

Introduction

The importance of adequately defining the spatial variation in rainfall for modelling streamflow runoff response has been identified by many authors (Dawdy and Bergmann, 1969; Wilson *et al.*, 1979; Beven and Hornberger, 1982; Bras *et al.*, 1985). If the spatial variability of rainfall input to a model is important (relative to other modelling uncertainties) it follows that the use of a distributed modelling structure is clearly justified (Beven and Hornberger, 1982). This would still be true even when catchment response characteristics are spatially homogeneous. For the purpose of this paper the spatial variability of rainfall is considered at three time-scales.

- Long-term scales, including such measures as mean annual rainfall and mean annual number of rain days.
- Medium-term scales, concentrating on monthly or seasonal totals of rainfall.
- Short-term scales, including daily or individual storm totals as well as the intensity variations within storm events.

With respect to the first two time-scales, spatial variability within a single climate region is most likely to be associated with those physiographic factors that influence the meteorological mechanisms that generate precipitation. Over the long term, relationships between individual gauge totals should be stable as long as the prevailing rainfall generating mechanisms remain the same. This should also be true for the medium term, although seasonal differences in meteorological patterns could produce seasonally variable spatial relationships. The definition of spatial variability at these time-scales should therefore be relatively straightforward. The methods that have been developed (Singh and Chowdhury, 1986) to estimate areal rainfall or to extrapolate point rainfall measurements to ungauged areas should be applicable. Such methods include simple averages, Thiessen polygons and polynomial surfaces.

While the effects of spatial variability in rainfall producing mechanisms may be stable over medium to long time-scales, this may not be generally true over short time-scales. Convective rainstorms usually cover small areas less than about 30km^2 (Waymire and Gupta, 1981) and do not necessarily occur over the same part of some catchment during a number of separate events. Similarly, in areas where orographic effects are important, the differential role of relief during different meteorological situations will influence the spatial variability of rainfall. This is especially true when the relief patterns are complex and where a specific region experiences more than one dominant rainfall producing weather pattern. For example, areas that are in localised rain shadows during some storm types may not be during storms with different characteristics.

The areal extrapolation methods reviewed in Singh and Chowdhury (1986) are difficult to apply at the shorter time-scales because the patterns of variability may not remain the same for different events. Thus a different set of Thiessen polygons or a different polynomial surface would be applicable to each event or group of events. These methods also more or less ignore the meteorological or physiographic causes of spatial variation. Other methods have concentrated on modelling the meteorological causes of spatial and temporal variation. This has been done implicitly using stochastic or mathematical representations of dynamic cells of rainfall during storms (Colton, 1976; Waymire and Gupta, 1981; Amorocho, 1982; Valdes *et al.*, 1985) or explicitly by modelling the physics of storm development and progression (Browning *et al.*, 1973; Harrold, 1973; Hill and Browning, 1979; Hoskins, 1983). The latter are probably too complex for general application to most hydrological problems. The former should have great potential for design storm definition assuming that physiographic effects can be incorporated where necessary. They also have the advantage that the effects of a moving storm and dynamic space-time rainfall relationships are included.

Before any technique can be used to model and estimate the spatial variation of rainfall amounts over a specific area it is necessary to obtain a better understanding of the local complexity of rainfall processes. This paper discusses the spatial variation in short time-scale rainfall in a coastal mountain region of southern Africa where relief has already been shown to have an influence on medium and long time-scale rainfall variables (Hughes, 1982). The analysis is based upon daily rainfall totals for a large number of events as well as intensity data for a smaller number of events. The study reported in this paper was prompted by the need to gain an improved understanding of the spatial variation of rainfall on a shorter time-scale than that used in Hughes (1982). This understanding is needed to better define spatially distributed rainfall input to single event hydrological models.

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[1]Present address: CSIR, Ground Water Division, Bellville.

*To whom all correspondence should be addressed.

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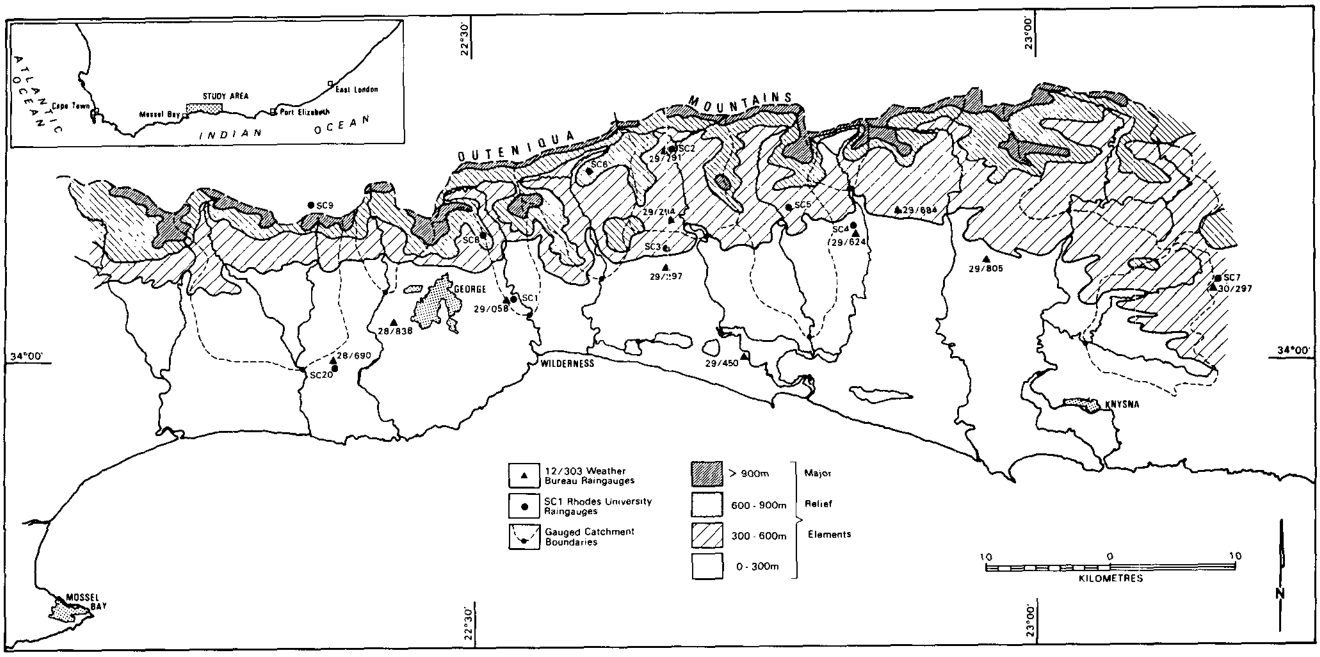

Figure 1
The southern Cape coastal region and the location of the rain gauges used in this study.

Study area

General; weather patterns and instrumentation

The study area is situated on the southern coast of the Republic of South Africa (Fig. 1) and is bounded to the north by the intensively folded Outeniqua Mountains. The physiography and general physical characteristics of the region have been described by Tyson (1971) and Hughes and Görgens (1981). The Outeniqua Mountains reach elevations of 1 600m and are separated from the narrow coastal embayment by a foothills zone and a much wider and deeply incised coastal platform. The region experiences an all-year-round rainfall regime with mean annual precipitation varying between 500mm on parts of the coastline to over 1 200mm in the mountains. Hughes and Görgens (1981) and Hughes (1982) investigated some of the rainfall characteristics of the area based on medium and long time-period rainfall totals. Specifically, a least squares multiple regression approach was used to derive relationships between mean annual and seasonal rainfall totals and physiographic variables. Altitude, longitude and an index of exposure were found to have significant effects on the dependent rainfall variables and the existence of localised but poorly quantified rain-shadow effects was identified. There was found to be a difference between the form of the equations for winter and summer average seasonal totals (Hughes, 1982).

A number of different weather patterns are responsible for generating rainfall over this region. While some have well-defined characteristics in terms of direction of storm movement, storm size, rainfall intensities and wind direction, others are less clear. Tyson (1971), Heydorn and Tinley (1980), and Hurry and Van Heerden (1981) refer to the following rain producing weather systems:

(i) Shallow coastal lows in advance of cold fronts often resulting in low intensity, intermittent rainfall. Rain bearing winds are generally from the south-west.

(ii) Cold fronts resulting in variable intensity and duration (few hours to several days) rainfall. Rain bearing winds from the west to south-west. This system is the dominant rain generating system during the winter months.

(iii) Advection of cool moist air from the south Indian or Atlantic high pressure system. Rain bearing winds can be from the east to south-east.

(iv) Summer convectional storms often enhanced by (iii) with highly variable intensities but usually short durations. Wind directions are locally variable and these storm types are less common than others in this region.

(v) Particularly heavy and often long duration rains are associated with stagnated or slowed down depressions referred to as cut-off lows. Wind directions can be from the south-east or south-west depending upon the positioning of the low pressure system.

Within the study area, there are 26 daily rainfall stations with reasonably long and consistent records, some dating back to the 1880's. Of these, 19 are operated today by the South African Weather Bureau. The average distance separating these gauges is 5,6km and the overall gauge density is approximately 1 gauge per 83km^2. Unfortunately few of the gauges are situated in the relatively inaccessible mountain areas. The Weather Bureau operates an autographic rain gauge at George in the western part of the region and a further 9 continuously recording rain gauges have been established by Rhodes University since 1981. The positions of all gauges are shown in Fig. 1. The only readily available information on the weather systems prevailing during previous storm events is published by the South African Weather Bureau (SAWB, 1980 to 1986) in the form of daily maps of the situation at 14h00 SAST (12h00 GMT).

Available data and methods of analysis

The analysis of short time-scale spatial variations in rainfall amount is initially based upon a data set of 'event totals'. 'Event totals' are defined as the amount of rain over a period of days where rain was recorded on all days. Thus, the 'events' represent continuous rainfall on a daily basis but do not imply truly continuous rainfall. This method of extracting rainfall totals was used, as many of the gauging stations only record daily rainfall. Had individual daily rainfall totals been used, problems would have arisen when short time differences in rain falling at different stations occurred close to the time boundary between days. The distribution of durations of the 218 events used in the analysis is positively skewed with a modal value of 2 d and a mean of 2,9 d. The event totals cover a wide range of rainfall depths from about 1mm to over 200mm. The main area of interest is the western two thirds of the region and consequently 9 daily and 9 continuously recording rain gauges are used in the analysis. Not all stations have records coincident in time and interstation comparisons are based upon different sub-sets of the complete data set. Conventional correlation and least squares regression analyses are used to investigate the patterns of spatial variability for storms occurring during different seasons of the year. The regression relationships between gauge pairs are used to rank the gauges on the basis of the relative amounts of rainfall they receive. This ranking is then assessed in terms of the physiographic position of the gauge locations (mountain top, plateau, ridge, valley, etc.).

Only those nine stations where continuous rainfall data are available (Fig. 1) can be used to examine spatial variations in intensity during events. Their positions vary from the mountain tops (SC9), through different locations in the foothills zone, to the coastal platform area (SC20). The objective of examining a series of individual storm profiles is to identify differences in storm profile shape or timing between differently located gauges and to note whether the weather pattern and particularly the wind direction during rainfall has a consistent effect upon such differences. If there is little consistency, then extrapolation from the available observed rainfall data will be difficult. As timing and gross rainfall depths are important in comparing stations, the storm profiles are plotted using absolute and not relative axes scales. A total of 20 storms are examined but not every gauge is represented for all events. Emphasis is placed on the larger rainfall events that occurred during the period over which continuous rainfall data have been collected (1981 to 1986).

Results and discussion

Of the 153 pairwise correlations (the maximum possible using 18 rain gauge stations), 102 are based upon more than 10 values in both winter and summer seasons and have correlation coefficients significant at the 1% level or better. Table 1 lists the number of pairs having coefficients of determination (R^2) values within 10 groups of range 0,1. The greater number of higher correlations and fewer low correlations suggest that the pattern of spatial variation in rainfall during winter is generally more consistent than during summer. The average distance separating gauge pairs having R^2 values of 0,9 or greater is 2,7km for the summer data and 5,5km for winter.

The results in Table 1 might be expected if the relief plays a differential role during different rainfall producing weather types. The differential role may be due to differences in wind direction affecting local rain-shadow effects. It may also be due to differences in the larger scale orographic effect on uplift during different meteorological conditions. During winter the predominant rainfall generating weather system is an east-moving cold front trough with associated west to south-westerly winds during the rain period. In summer a greater diversity of weather system types are responsible for rainfall. These can be small or large area storms and also have a wider variety of associated rain bearing wind directions than winter storms. There are, unfortunately, insufficient readily available meteorological data to allow a more thorough analysis based upon individual weather types.

TABLE 1
COMPARISON OF COEFFICIENT OF DETERMINATION VALUES FOR THE SUMMER AND WINTER SEASON ANALYSES.

Coefficient of determination (range of R^2)	Number of pairs (total 102) Summer	Winter
1,0 to 0,9	11	46
0,9 to 0,8	32	19
0,8 to 0,7	25	21
0,7 to 0,6	14	6
0,6 to 0,5	10	6
0,5 to 0,4	5	2
0,4 to 0,3	4	1
0,3 to 0,2	1	0
0,2 to 0,1	0	0
0,1 to 0,0	0	1

Summer: months 10 to 3; Winter: months 4 to 9

To estimate which gauges receive more rainfall during storm events, each individual gauge is selected to be the dependent variable and regression equations calculated using all other gauges in turn as independent variables. Scattergram plots (Fig. 2) of all relationships indicate that the linear regression model is applicable and no noticeable curvilinear relationships between gauge pairs are evident. The analyses are based on all the data as well as separated summer and winter season data. Figures for the average equivalent rainfall expected at other stations given 50mm at the dependent variable station are calculated (Table 2) from the following equation.

$$\text{Average equivalent rain} = \frac{1}{n}\sum_{i=1}^{n} (50-\text{Int}_i)/\text{Sl}_i$$

where n = number of other stations

Int_i and Sl_i = intercept and slope in the regression equation with station i as the independent variable.

The stations are ranked in Table 2 using the figures for the average equivalent rainfall (AER) based on all the data. The figures for AER based on summer and winter data are also given where a sufficient number of data points allow their calculation. A different pattern would only be produced if a much lower constant rainfall value had been chosen as most of the intercepts are small (less than 5mm). Those stations that emerge as having

TABLE 2
RANKING OF STATIONS BASED ON REGRESSION ANALYSIS.

Station name of dependent variable rain = 50mm		Average equivalent rain at other stations All data (mm)	Summer data (mm)	Winter data (mm)	MAP (mm)
SC9	Mtn.top	28,0	25,5	??	
SC8	F.hill ridge	35,2	34,4	??	
28/838	Plateau	45,8	45,1	47,2	885
29/297	Plateau	46,7	53,9	43,3	800
SC5	F.hill ridge	47,1	49,5	45,4	
SC1	Plateau	50,7	44,7	47,8	
29/058	Plateau	51,8	51,1	50,7	848
29/294	F.hill val.	55,7	57,1	49,5	837
29/291	Mtn.val.	56,4	67,6	53,9	613
SC3	F.hill ridge	58,7	58,9	59,0	
29/805	Plateau	59,0	62,6	54,4	810
SC6	Mtn. ridge	62,7	64,7	62,9	
29/624	Plateau	62,9	68,1	54,5	827
29/690	Plateau	63,1	62,9	56,5	
SC20	Plateau	64,6	63,1	73,0	
29/450	Coast	66,3	73,9	54,4	652
SC2	Mtn.val	76,0	79,6	76,9	
SC4	Plateau	84,4	90,4	95,1	

Mtn.top - Mountain top; Mtn./F.hill ridge - mountain/foothill ridge; Mtn./F.hill val - valley area in mountains/foothills; Plateau - coastal plateau; Coast - coastal plain; ?? Insufficient data

relatively high rainfall amounts are the mountain top station (SC9), foothill ridge stations (SC8 and SC5) and some of the plateau stations which are close to the edge of the foothills (SC1, 29/058, 29/297). Those emerging as lower rainfall stations are the coastal site (29/450), some enclosed valley areas in the mountains (SC2 and 29/291) and two of the plateau sites that are remote from the foothills (SC20, 29/690). Stations SC6 and SC3 are ranked relatively low and reference to Fig. 1 illustrates that they may be in a westerly rain shadow from the NW-SE trending ridge to the west. A comparison between the summer and winter AER values reveals a rather confusing pattern. In many cases the two values are similar (29/058, SC3 and SC2 for example) while others have higher summer values (29/297 and 29/450 for example) or winter values (SC20). The mean annual rainfall values for those stations common to this study and that of Hughes (1982) are included in Table 2 for comparative purposes.

The pattern of differences between the rainfall at the various stations corresponds to a certain extent with the pattern suggested by analysis of the long time period data in Hughes (1982). However, there appear to be several differences, notably stations 29/297 and 29/291. The pattern remains one of increasing rainfall with elevation but confused by local rain-shadow influences during at least some of the prevailing rainfall producing weather types. The additional data provided by the more recently established gauges have extended the information about the patterns of spatial rainfall variation. This is particularly true of gauges SC6, SC8 and SC9. The position of SC6 in an elevated location, but in the lee of hills to both the west and east, is not represented by any of the earlier established gauges. Similarly, SC9 provides more information about likely mountain top maximums and SC8 about exposed mid-elevation locations. However, the additional data are still not adequate to define the complexity of the spatial variations satisfactorily.

There are insufficient data to thoroughly analyse the influence of various weather patterns on storm totals which may otherwise provide greater insight into the suggested rain-shadow effects. If the data were grouped according to weather system type, the number of storms represented in some groups would be insufficient to satisfactorily define the inter-station relationships. In addition, definition of weather system type is based upon the weather maps produced for 14h00 SAST (12h00 GMT) each day by the South African Weather Bureau (SAWB, 1980 to 1986). Although these provide a good impression of the general synoptic situation they do not contain enough detail for satisfactory definition of the meteorological conditions prevailing over the study area during storm events. This factor places some limitations on any analysis of intensity variations within storms. It is often difficult to determine the predominant wind direction, as the synoptic charts illustrate that it can move through 180° during some storms. Despite these problems, 20 storm profiles are investigated. The storm durations vary between 5 and 70 h while total rainfall amount varies between 10 and 180mm. Data from 9 continuously recording rain gauges are used (SC1 to SC3, SC5 to SC9 and SC20) but not all gauges are represented for each storm. Although outside the main area of interest, SC7 was included to discover if any time differences between rain falling at the western and eastern edges of the region could be noted. Four of the storm profiles are illustrated in Figs. 3 to 6.

There is generally a high degree of similarity in the shapes of the profiles. High and low intensity periods during the storms occur at very similar times at all the stations for most of the events analysed. It is interesting to note that for the higher rainfall

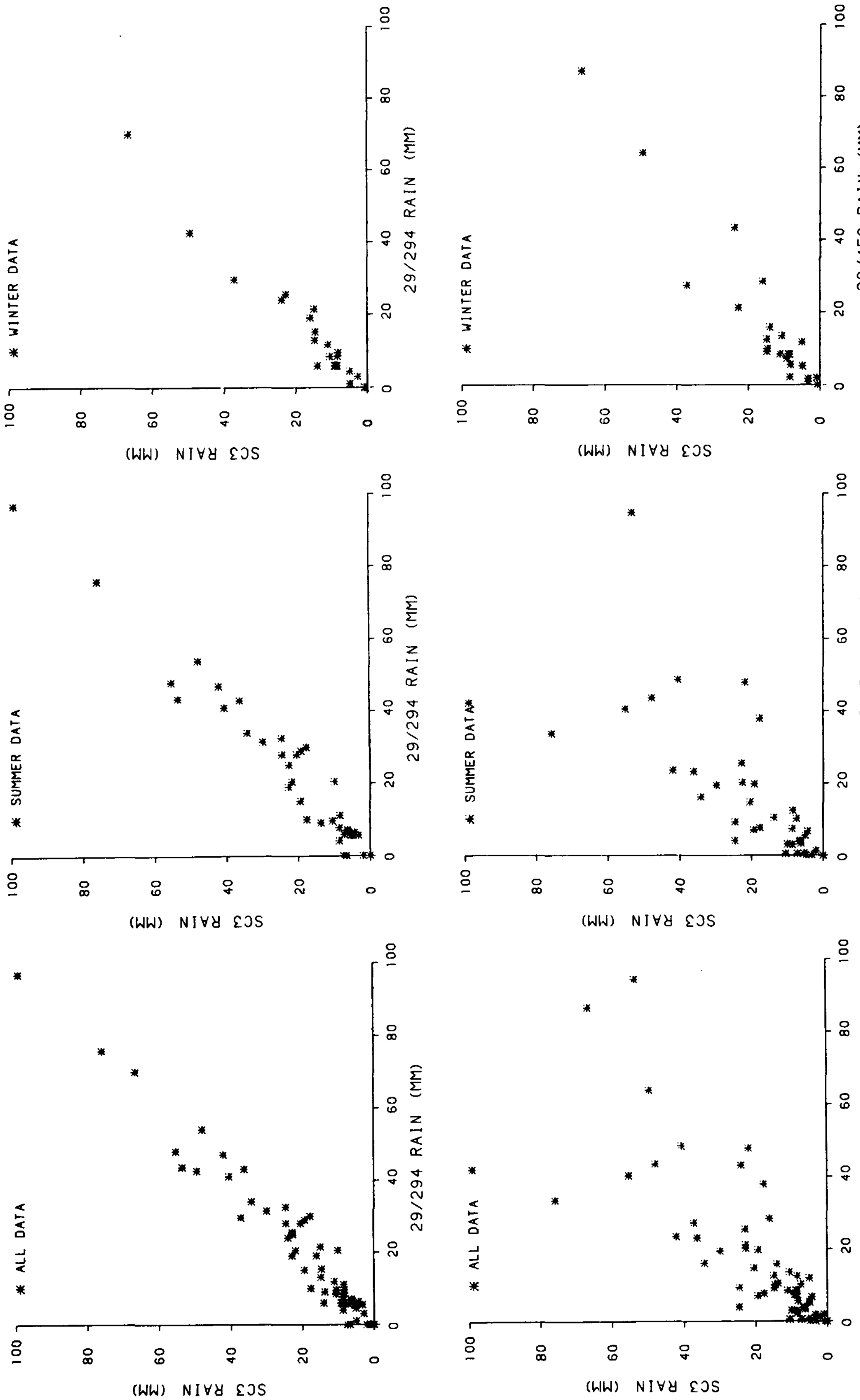

Figure 2
Scattergrams for two station pairs. In both cases all the data, summer data and winter data are plotted separately.

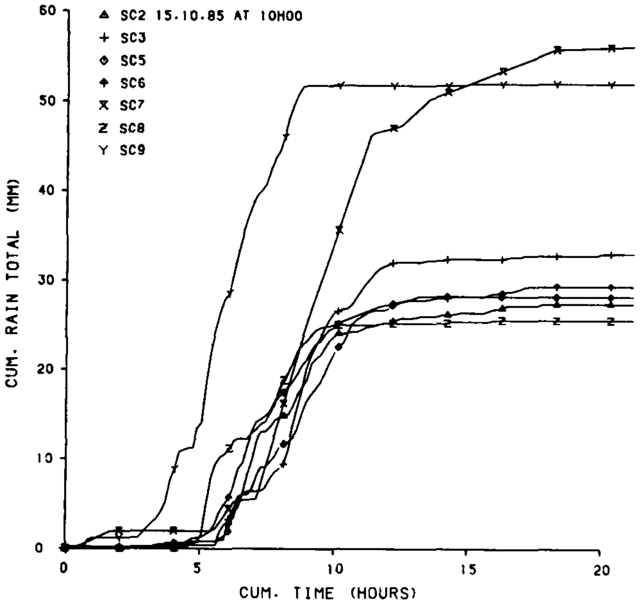

Figure 3
Storm profiles for the event of 15 October 1985: A cold front passed the southern Cape during the morning of 15 October.

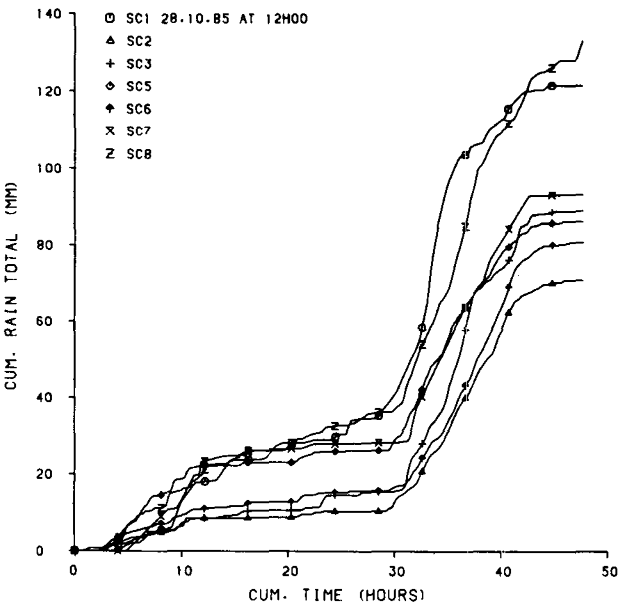

Figure 4
Storm profiles for the event of 28 October 1985: A cold front passed the southern Cape during the morning of 28 October. By 14h00 on 29 October the south Atlantic high had ridged in below the coast and a cut-off had developed over the western parts of southern Africa.

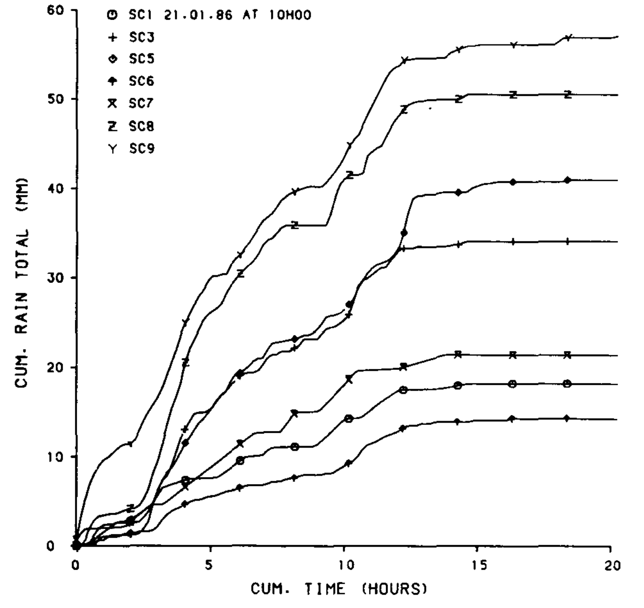

Figure 5
Storm profiles for the event of 21 January 1986: A weak front passed over the southern Cape during the morning of 21 January to be followed by advection of moist air from the south east.

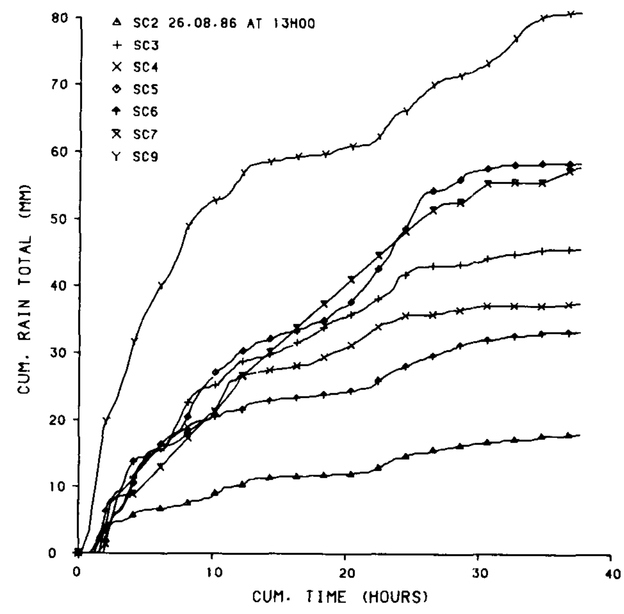

Figure 6
Storm profiles for the event of 26 August 1986: A cold front passed over the southern Cape at midday on 26 August giving rise to SW winds. On 27 August, an interior low developed and light SE winds prevailed towards the end of the event.

advection storms, very similar start times and durations occur for the gauges discussed here and a gauge situated in Grahamstown some 350 to 400km to the east. An exception to the timing similarity is that during most cold front situations (Figs. 3 and 6) rainfall begins sooner at SC9 (up to 3 h) than at the other stations. Comparison with SC20 indicates that this is related to its elevated location rather than its westerly position in the region. Similarly, during the passage of some cold fronts, SC7 can experience substantially more rainfall than most other stations. However, during advection situations with predominantly SE winds, SC7 receives relatively lower rainfalls. This feature is illustrated by the storm of 28.10.85 (Fig. 4) where a cold front (SW winds) is followed immediately by advection (SE winds) caused by the Atlantic high ridging in to the south of the Cape coast. This type of weather pattern appears to be common in the region. The 7 profiles exhibit similar shapes but have different relative intensities throughout the storm. In the early part (cold front), the more exposed stations (SC1, 5, 7 and 8) rise to between 30 and 40mm while SC2, 3 and 6 only experience between 10 and 15mm. During the advection storm SC1 and 8 receive an additional 90 to 100mm, SC3 and 6 about 70mm while the remainder receive less than 60mm. Fig. 5 illustrates a similar situation where the passage of a front is represented by only the first few hours of the profiles and resulted in less than 5mm of rain at most stations.

In general, the pattern of relative amounts of rainfall occurring at the stations is not consistent. In addition, the rainfall differences are not easily attributable to differences in weather type using the information available from the weather maps. However, some general observations can be made. Despite being in relatively elevated positions, SC2 and SC6 commonly experience some of the lowest rainfalls. The exposed mountain top and ridge stations (SC5, 8 and 9) more consistently experience the higher rainfalls. The remaining stations exhibit little consistency, sometimes having relatively high amounts and at other times low rainfalls.

Both the storm total and the profile analyses demonstrate that there is a great deal of variability in the spatial patterns of rainfall. Although some general observations can be made, quantification of the patterns at a level that might be useful for satisfactorily defining the input to distributed catchment models does not appear to be possible.

Conclusions

- The analysis of short time-scale spatial variations confirms some of the conclusions reached by Hughes (1982) based upon mean annual totals. While there appears to be a general increase in storm total rainfall with altitude, this pattern is confused by localised lower rainfall areas within the foothills or mountains. The pattern is not very consistent for the range of storms included in the analysis.
- Hughes (1982) observed some differences between the relationships of dry and wet season rainfall totals with physiographic factors. In a similar way, there is a lower degree of scatter in pairwise relationships between gauges based on winter storm data (wet season in Hughes (1982) refers to April to July) than for summer storms. The difference may be attributable to a lower diversity of rainfall generating weather types in winter than summer.
- Given the second conclusion it is unfortunate that the available information does not allow a more thorough analysis of the effects of different meteorological conditions, prevailing during storms, on relative station rainfalls. The storm profile analysis revealed some station differences that are apparently related to storm type. However, few or no reasons could be found for the differences. Perhaps the most useful observation is the degree of similarity in the timing and shape of the station profiles for individual storms. This suggests that temporal intensity variations during storm events over this region occur at a relatively large spatial scale. Cells of higher intensity rainfall due to purely atmospheric processes (as within convective storms) do not appear to occur over this area at spatial scales that are relevant to modelling hydrological processes.
- To provide adequate rainfall input to hydrological models it is necessary to extrapolate from the data observed at existing rain gauges. It was initially hoped that a detailed analysis of the few years of rainfall intensity data would reveal more consistent inter-station relationships. Such relationships might then have been used to extrapolate from the data provided by the many daily and few autographic gauges that existed before the network was expanded after 1981. The inconsistent patterns that have been demonstrated by this study preclude the likelihood of successful extrapolation. The conclusions illustrate that the application of deterministic hydrological models in this and similar mountain areas of South Africa is severely handicapped by our ability to adequately define the catchment rainfall input.

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