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THE INFLUENCE OF LOCALITY FACTORS ON MEAN ANNUAL RAINFALL

J.S. WHITMORE

INTRODUCTION

When evaluating water resources available for irrigation, industrial and municipal use or for power development, flow of ungauged rivers must often be estimated from rainfall data. Rainfall is measured at over 3000 points in South Africa and by world standards this coverage is good, but unfortunately there is often a dearth of rain-gauges in the hydrologically important mountain catchments because of their remoteness and inaccessibility. Although these mountainous headwater regions may comprise only a small part of a river catchment they generally contribute a major portion of the flow since they are invariably the regions of highest rainfall. The importance of making the best possible estimate of the average rainfall along mountain watersheds where direct measurements are not feasible, is therefore self-evident.

A rain-gauge measures the precipitation occurring at that point but its record can also serve a broader purpose as it reflects the combined influence of all

locality/ ...

locality factors, such as position, altitude and aspect, which govern the incidence of rainfall. If the data from many gauges are pooled, the relative importance of each of these locality factors, and the manner in which each operates, can be identified by means of multiple regression analysis. Once these laws of nature have been revealed by analysing existing data, they can be used to estimate the average rainfall of regions devoid of rain-gauges.

The region selected for an investigation of the combined influence of locality factors upon average annual rainfall was that part of the southern Cape Province extending inland to $32^{o}00'$S and bounded by the meridians $20^{o}30'$E and $25^{o}00'$E. Within this tract the mean annual rainfall varies from less than 4 inches to more than 40 inches; clearly environmental factors must interact strongly to cause the mean annual rainfall to vary so widely within so small an area.

TOPOGRAPHY.

Dominating the topography are the parallel ranges of fold mountains which trend east - west. The southern facing slopes often form an escarpment. Where the mountains intersect the oblique coastline they form cliffs up to 500 feet high, and prominent headlands and bays.

The southernmost range comprises the Langeberge, Outeniquaberge and Tsitsikammaberge and attains a maximum height of about 5,500 feet in the Outeniquaberge within a few miles of the coast.

Some 50 miles further inland lies a more prominent range comprising the Witteberg and Groot Swartberg, whose maximum height exceeds 7,500 feet. Eastwards the range continues as the Baviaanskloofberge which bifurcates into the Groot Winterhoekberge and the Elandsberge. Slightly to the north lies yet another fold range which, however, tends to be overshadowed by the Swartberg range except in the east where it attains prominence as the Klein Winterhoekberge.

Lying in the sheltered depression between the Langeberge and the Swartberge is the arid Little Karoo, rendered broken and uneven as a result of stream rejuvenation. The large western basin is drained by tributaries of the Gouritz River but the eastern region, where the topography is rendered more complex by the interposition of the Kammanassieberge and the Kougaberge, is drained by affluents of the Gamtoos River.

Near/ ...

RAINFALL.

There is a transition eastwards from a predominance of rain in winter to a pronounced summer maximum but the result of this interaction is a more sustained distribution through the year than elsewhere in South Africa.

The winter rains are associated with the passage of depressions in the path of the westerly wind belt which at this season is located at it's most northerly position resulting from the shift northwards in winter of the high-pressure belt. The start of a spell of unsettled weather is marked by the backing of the upper winds from north-east to north-west and west, followed a few hours later by westerly winds at the surface whereupon it generally starts to rain, the intensity increasing as the wind backs to south-west.

Summer precipitation is likewise often associated with the passage of off-shore migratory pressure systems so that precipitation is again largely of the frontal type although convectional rains in the form of afternoon thunderstorms are also prone to occur in the interior.

This general pattern is profoundly modified by the topography, the windward slopes of the fold mountains and the Escarpment experiencing a much higher mean annual rainfall than the sheltered valleys and basins to the lee.

Preliminary scrutiny of existing rainfall data indicated that there are 4 main environmental factors interacting upon the mean annual rainfall at a point, namely altitude, aspect, continentality and longitude. As there could be no a priori assumption that these relationships would be linear, recourse was had to the semi-graphical method of multiple curvilinear regression analysis described by Ezekiel,[1] which demanded no assumptions as to the nature of the net relationships between mean annual rainfall and the several environmental influences but permitted each of them to be isolated by successive approximation. This method is very suitable for exploratory studies.

METHOD.

Briefly, the method assumes that the dependent variable - mean annual rainfall - is a combined function of the independent variables comprising the various environmental factors, i.e.

Y = / ...

$$Y = a + f_1 (X_1) + f_2 (X_2) + f_3 (X_3) + f_4 (X_4)$$

where Y = mean annual rainfall, in mm.,

X_1 = altitude above sea level, in metres,

X_2 = continentality, being the distance inland (in minutes of latitude) from the coast, measured along the meridian,

X_3 = longitude, measured in minutes east of the boundary meridian $20^{\circ}30'$E.,

X_4 = aspect relative to the main axis of the nearest mountain range, measured in directional units of 10° clockwise from north,

a = a constant whose value depends mainly on the units selected for the independent variables, and

f is a general term denoting a non-specific functional relationship.

The choice of the X variables was limited by the requirement that they should be independent of each other.

Regarding the index of continentality, the slight variation in the length of a minute of latitude was ignored as the span is not more than 2°.

The/ ...

The study was based on data pertaining to 288 rainfall stations whose period of record covered at least 20 years. The values of mean annual rainfall (Y) pertained specifically to the period 1920-1960[2], the values for stations with a shorter or longer record being suitably adjusted by reference to stations with the correct 40-year record.

The first step towards isolating the several partial (or 'net') regression curves was to derive the linear multiple regression from the 288 sets of data, and then to calculate estimated values of Y for each of the 288 observations by substituting the corresponding values of X_1, X_2, X_3 and X_4 in the equation. These estimates of Y were then subtracted from the actual values of Y, giving positive or negative residuals.

The net regression of Y on X_1 was plotted, showing the change in mean annual rainfall with change in altitude while the remaining variables were held constant at their average values. The residuals were grouped for suitable class intervals of X_1 and averaged within each group. These group mean residuals were then plotted as deviations from the net regression line, whereupon a smooth curve of best fit was drawn through the points, the course of the curve being dictated by logic rather than by idiosyncracies in the scatter

diagram/...

diagram. Similar first approximations to the net regression curves for Y against each of the remaining three independent variables were then compiled.

As in each case the net linear effects of the remaining variables had been eliminated, the process was repeated to determine more exactly the true relation of Y to each independent variable in turn by eliminating the curvilinear effects (so far as they were manifested by the first approximations) of the remaining independent variables. To do this, revised estimates of Y were calculated from the set of first approximation curves and the differences between these new estimates and the actual values of Y were calculated; as before these residuals were grouped into suitable classes based on values of X_1 and the group averages plotted as deviations from the first approximation regression curve of Y on X_1, whereupon the curve was modified where required. Similar adjustments were effected to the net regression curves of all the other variables.

This process of successive correction was repeated until stability - represented by the minimum standard error of estimate of Y - was attained. In all, five successive approximations were drawn, the standard error of estimate of Y for the final version being 32% less than that for the initial linear

relationship./...

relationship.

RESULTS.

The four net regression curves are shown in the accompanying figures. As the main interest lay in the relationship between mean annual rainfall(Y) and altitude (X_1) this is portrayed directly in the first curve, the contributory rôle of each of the three other factors being shown in the form of adjustments to be made to the estimate of Y based on X_1.

The following features merit comment:-

The initial fairly sudden increase in rainfall with altitude (X_1) is probably due both to the fact that the mere passage of moist air from the sea to the land (shear) is conducive to convergence, uplift and hence precipitation, as well as to the fact that cliffs several hundred feet high overlook the sea along much of the coastline. There is a marked steepening in the rate of precipitation increase above 800 metres but this is not maintained indefinitely. However, no attempt has been made to extrapolate to altitudes higher than those covered by the data.

It should also be noted that in this instance altitude above sea level is not a true reflection of relief due to the rising base level (that is, of the valleys and basin floors) northwards. This effect might have been eliminated by including it as yet another independent variable, but it was omitted as it is confounded with continentality.

Referring next to the net regression curve for continentality (X_2), the most noteworthy features are the increase in mean annual rainfall occasioned by forced uplift against the first mountain barrier range (irrespective of considerations of height) and the very rapid diminution in mean annual rainfall beyond the barrier. Of all the net regression relationships this was the most dominant and the least subject to change during successive approximations. As already mentioned, this curve represents the combined effect of increasing distance from the sea and the general rise in base-altitude inland; it was not possible to separate the two as they are correlated.

The net regression curve for longitude (X_3) reveals a slight tendency towards increasing rainfall from west to east in the direction of increasing predominance of rain in summer. The dip in the curve towards it's western extremity represents a rain-shadow in the region of winter rainfall.

The / ...

The final net regression curve, that for aspect (X_4), is the one exhibiting the greatest scatter of the group averages. This is doubtless due to the fact that the criterion for aspect is somewhat subjective; aspect was taken to be the direction of slope normal to the main axis of the most prominent topographic feature in the vicinity (in order to eliminate the effect of minor topographic variations too small to affect the incidence of rainfall) but there was sometimes doubt as to which of several alternatives was the dominant mountain range in a region of complex topography, and also sometimes uncertainty as to the main direction of the axis. Nevertheless the curve clearly illustrates the marked difference in precipitation on windward and leeward slopes.

CONCLUSION.

Use of a semi-graphical method of multiple curvilinear regression analysis has enabled the individual and combined influence of altitude, aspect, continentality and longitude on mean annual rainfall to be identified.

As the region to which the analysis has been applied is fairly large, it is likely that the standard error of estimate could be reduced somewhat by carrying out separate analyses for longitudinal subdivisions of the area. It is also possible that further improvement could be effected by investigating joint, as distinct from individual relationships, especially the joint relationship of aspect and altitude.

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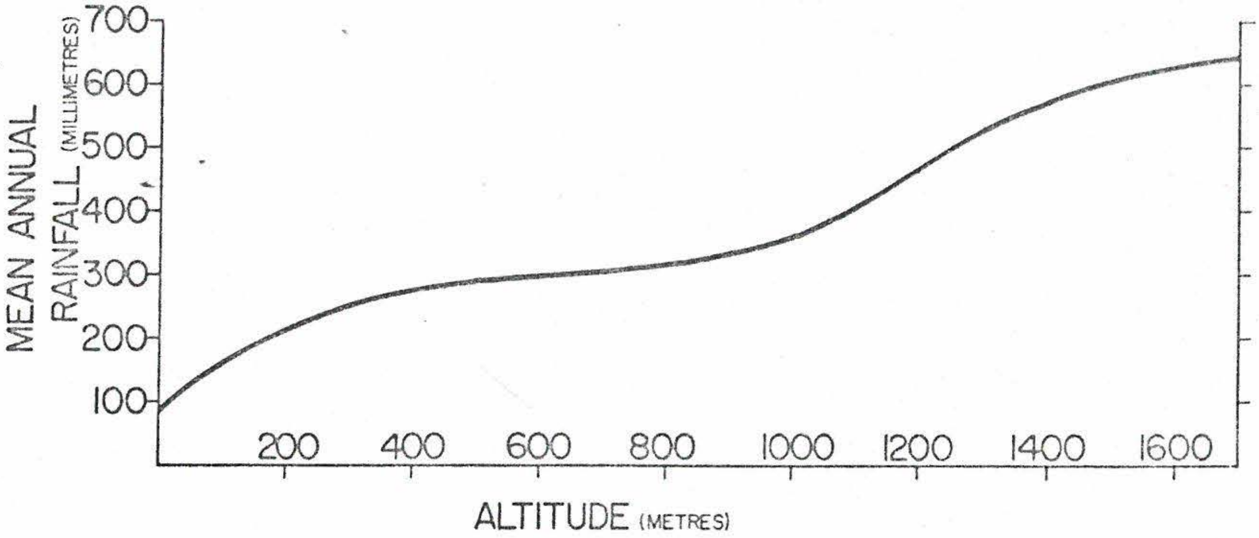
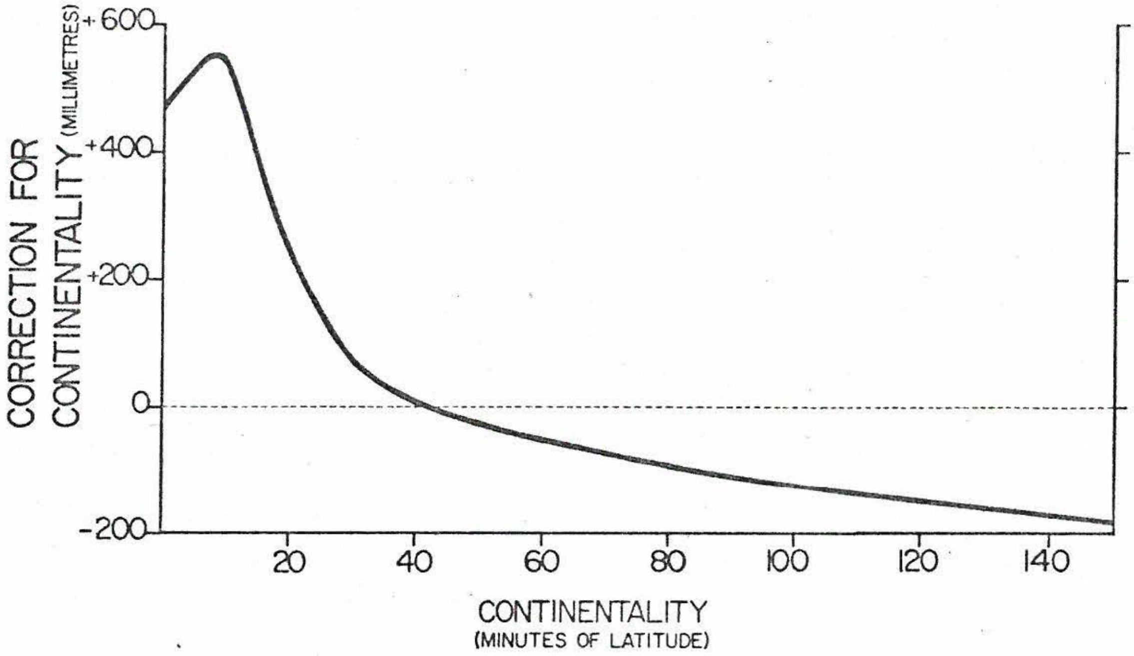
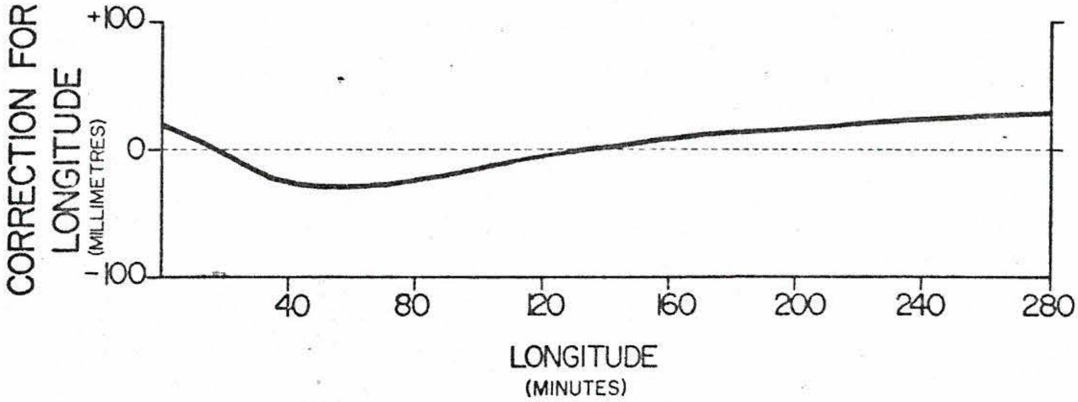
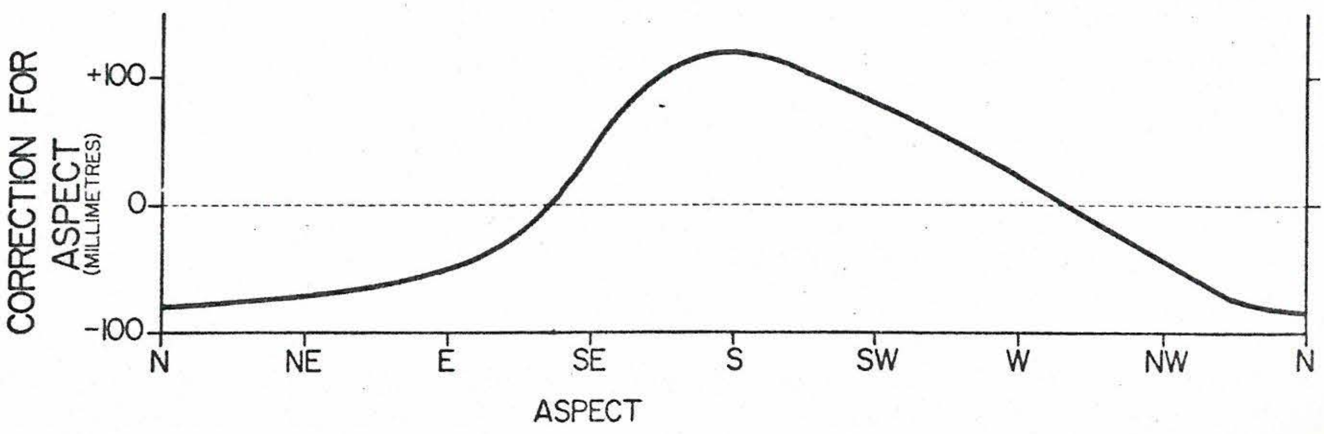
2. SOUTH AFRICA 1:250,000 RAINFALL MAP (1921-1960): Masks prepared by B.R. Schulze.


MEAN ANNUAL RAINFALL (MILLIMETRES)
700
600
500
400
300
200
100
200
400
600
800
1000
1200
1400
1600
ALTITUDE (METRES)


CORRECTION FOR CONTINENTALITY (MILLIMETRES)
+600
+400
+200
0
-200
20
40
60
80
100
120
140
CONTINENTALITY (MINUTES OF LATITUDE)


CORRECTION FOR LONGITUDE (MILLIMETRES)
+100
0
-100
40
80
120
160
200
240
280
LONGITUDE (MINUTES)


CORRECTION FOR ASPECT (MILLIMETRES)
+100
0
-100
N
NE
E
SE
S
SW
W
NW
N
ASPECT