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# STUDIES ON RAINFALL-RUNOFF MODELING

## 1. Estimation of Mean Areal Rainfall

Partial Technical Completion Report

Project No. 3109-206





**New Mexico Water Resources Research Institute**

New Mexico State University • Telephone (505) 646-4337 • Box 3167, Las Cruces, New Mexico 88003

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## 1. Estimation of Mean Areal Rainfall

Vijay P. Singh, Assistant Professor of Hydrology
Yüksel K. Birsoy, Graduate Student in Hydrology

Partial Technical Completion Report
Project No. 3109-206

New Mexico Water Resources Research Institute
in cooperation with
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STUDIES ON RAINFALL-RUNOFF MODELING

1. Estimation of Mean Areal Rainfall

ABSTRACT

The current methods of estimating mean areal rainfall are presented. By applying them to five different areas of the world an objective comparative assessment is made of their performance. Advantages and disadvantages of each method are enumerated. It is shown that for many hydrologic problems simpler methods are as good as more sophisticated ones - an observation contrary to what is generally believed.

INTRODUCTION

Determination of the average amount of rain which falls on a watershed during a given storm is a fundamental requirement for many hydrologic studies. Of prectical necessity rainfall is measured at a number of sample points, and the amounts recorded at these points are utilized to form an estimate of mean areal rainfall for the storm of interest. This estimate, however, will deffer from the true mean areal rainfall for three reasons:

(1) The sample points may be unrepresentative of the watershed in that no gauge may lie in the sector of watershed having extreme rainfall (Rodda, 1970).

(2) The record may be constantly higher or lower than the true rainfall at that sample point (Rodda, 1967).

(3) The factors may combine to cause the rainfall amounts recorded at gauges to differ from their true values in an unsystematic manner (Sutcliffe, 1966; Herbst and Shaw, 1969).

It is, therefore, not surprising that little is known about the accuracy of the mean areal rainfall estimates (McGuiness, 1963). Nevertheless, a number of techniques for estimating mean areal rainfall have evolved. Some (Thiessen, 1911; Reed and Kincer, 1917; Horton, 1923; Wilm et al, 1939) of these techniques are simple and well-tried and old, as old as modern hydrology, and normally adequate but they they tend to be employed without sufficient appreciation of their limitations; while others (Myers, 1959; Dawdy and Langbein, 1960; Rodda, 1962; McGuiness and Harold, 1965; Sutcliffe and Carpenter, 1967; Solomon et al, 1968; Unwin, 1969; Chidley and Keys, 1970; Mandeville and Rodda, 1970; Pentland and Cuthbert, 1971; Clarke and Edwards, 1972; Hutchinson and Walley, 1972; Shaw and Lynn, 1972; Wei and McGuiness, 1973; Lee et al, 1974) are complex and demand a great deal of skill, and even judgement in some cases, on the part of the user. There are several questions that naturally arise:

(1) How do these methods compare?

(2) Can a guideline or an objective criterion be specified to determine which method to use when and where?

(3) Are these methods simply different alternative tools to estimate mean areal rainfall, or have they evolved as a result of our increased understanding of space-time distributional characteristics of rainfall?

The user must resolve these questions before using a particular method. The present study attempts to answer these questions. In order to arrive at definitive conclusion, the various methods are applied to 5 different areas of the world; two of them are in New Mexico, U.S.A., one in South Africa, and two in Great Britain. First, we examine inconsistencies normally present in rainfall records.

# ADJUSTMENT OF LONG-TERM RECORDS

Inconsistencies in rainfall records may arise for the following reasons:

(1) The records cover different periods of time.

(2) The locations of stations have changed.

(3) The observational procedures have changed.

(4) The instrument exposure has changed.

These inconsistencies render the rainfall records incomparable, and hence the records must be adjusted before use. We must, therefore, quantitatively detect and establish, if there is any, heterogeneity in the records.

## Detection of Heterogeneity in Rainfall Records.

Heterogeneity in a rainfall record may be identified by graphical and statistical methods.

### 1. Double Mass Analysis.

This is a graphical method for identifying inconsistencies in a station record by comparing it with the records of other stations. Accumulated annual, seasonal, or monthly values at a station in question are plotted against those of a nearby reliable station or group of stations. This plotting results in what is called as the double mass curve, which is then examined for trends and changes in slope (Bruce and Clark, 1966). An example of double mass analysis for detecting change in exposure at a rainfall station is shown in Fig. 1, where the record of this hypothetical station is compared with the relatively stable record of an average of several nearby stations.

Plotted points in a double mass analysis usually deviate about the straight line drawn through the points. The points can be fitted most

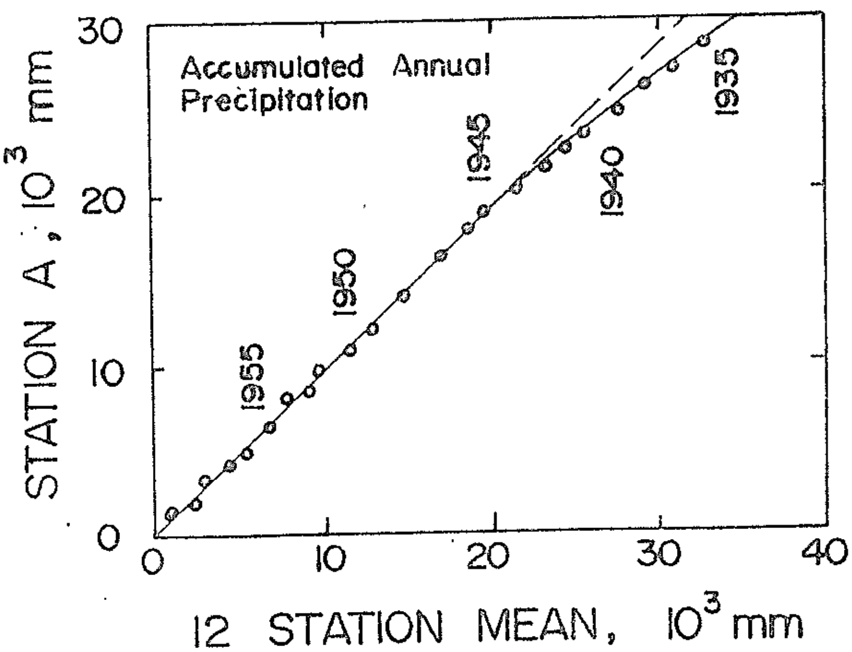



Fig. 1. Double-mass analysis example.

closely by changes in slope at intervals of only a few years. However, it must be recognized that such small changes in slope could arise by chance, and no segment of less than about 5 points should be accepted as indicating a valid change. In general, a change in slope is accepted as real only if substantiated by other evidence, or is well defined over a long period of time.

From examination of the curve in Fig. 1, it is seen that the relationship of annual rainfall at station A to the 12-station mean changed rather abruptly in 1945, with a slope change from 0.75 prior to 1945 to 0.95 after 1945. This change in slope is less likely due to chance, and is due to change in the instrumental exposure.

2. Run Test.

This is a statistical test to detect heterogeneity in a rainfall record. This test is conducted by counting the number of runs above and below the median or middle in a naturally ordered data (for example, annual rainfall totals arranged chronologically), and then determining the probability that this observed number of runs would occur in a homogeneous data series.

Adjustment of Means of Rainfall Records

The record for each station should be tested for homogeneity. If possible, station histories should be investigated to verify any changes in rainfall regimen that are suggested by breaks in the double mass curve, or by the run test. Heterogeneity in the rainfall record can be removed by the following methods:

1. Double Mass Curve.

As seen from Fig. 1, the slope of the double mass curve changed abruptly from 0.75 prior to 1945 to 0.95 after 1945. The older records can then be adjusted by the ratio of 0.95 to 0.75 to compensate for a change which must have taken place at station A.

2. Ratio Method.

To apply the method, an adjustment constant is estimated by the equation:

$$c = \frac{\sum_{i=1}^{n} r_A(i)}{\sum_{i=1}^{n} r_B(i)} \qquad (1)$$

where $c$ = adjustment constant, $r_A(i)$ = rainfall for $i$ th period for station A which needs adjustment, $r_B(i)$ = rainfall for $i$ th period for station B which is a supplementary station, and $n$ = length of homogeneous period. If we define:

$$R_B' = \sum_{j=1}^{m} r_B(j) \qquad (2)$$

where $m$ = length of the heterogeneous period, and $R_B'$ = the sum of rainfall at station B (supplementary) during the heterogeneous period. Then the estimated total rainfall $R_A'$ for the same period at the station to be adjusted is:

$$R_A' = c\ R_B' \qquad (3)$$

Adjustment of Means of Rainfall Records to Standard Base Period.

A problem frequently encountered in determining long-term means of areal rainfall is the varying periods of record at individual gauging stations. One station might have operated during a period of high rainfall, and another during a spell of particularly dry years. A base period should be chosen for calculating long-term means. A bar graph, such as shown in Fig. 2, which shows the period of record of several stations on the same time-scale, can assist in selecting an optimum period of record. Missing data must be estimated for stations whose records are incomplete in order to utilize partial records, especially in data sparse areas. The base period chosen should not be so long as to require too much synthesis of record, nor so short as to be unduly influenced by unusually wet or dry periods. The extension of records shorter than the selected base period may be accomplished by the following methods:

1. Ratio Method

Extension of records shorter than the selected base period may be accomplished by the ratio method, using one or more long-period stations as reference for the adjustment. The reference stations should be as close as possible to the station to be adjusted, as the effectiveness of the adjustment depends on the correlation between the stations, and in the same climatic regime. The ratio method employs the ratio of rainfall totals or means of two concurrent homogeneous series as a multiplying factor on the series total or mean which is to be extended.

The ratios of mean rainfall for the relevant time intervals (month, season, year) may be established for the period common to a station A (having a short record only) and the long-record stations B selected as reference. If the ratio between mean rainfall values at A and B for an N-year period of simultaneous record is:

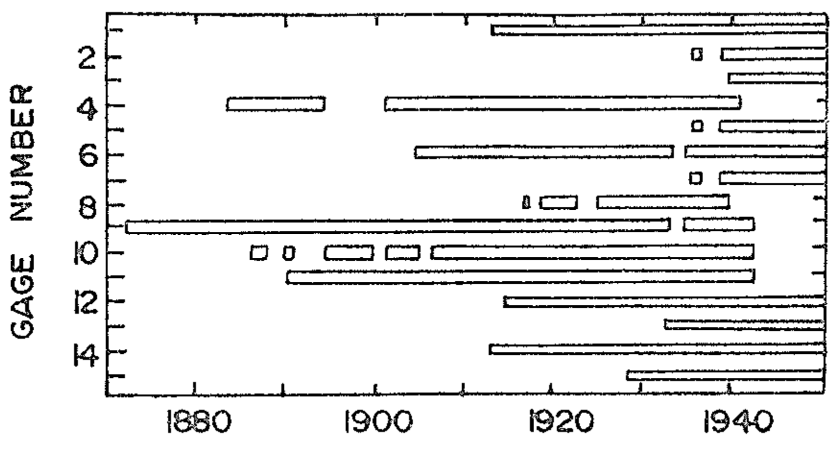



Fig. 2. Bar graph showing period of record.

$$c = \frac{\sum_{i=1}^{N} r_A(i)}{\sum_{i=1}^{N} r_B(i)} \tag{4}$$

Then N-year mean value at A may be adjusted to the selected base period by:

$$\bar{r}_A(T) = c\ \bar{r}_B(T)$$

$$= \sum_{i=1}^{N} r_A(i) \frac{\sum_{i=1}^{T} r_B(i)/T}{\sum_{i=1}^{N} r_B(i)} \tag{5}$$

where T = base period.

This method is based on the premise that the variability of the ratios is much less than the variability of rainfall at station A, and that in a region of homogeneous climate, ratios between rainfall values of stations tend to remain constant from one time period to another, although this is more true for longer time periods, say a year or so. If the quantity

$$\frac{\sum(r_A(i) - c\ r_B(i))^2}{\sum(r_A(i) - \bar{r}_A)}\ ,\ \bar{r}_A = \sum_{i=1}^{N} r_A(i)/N \tag{6}$$

does not exceed the following critical values (Brooks and Carruthers, 1953):

| N = 5 | N = 10 | N = 20 | N = 30 |
|---|---|---|---|
| 0.5 | 0.64 | 0.74 | 0.77 |

the mean rainfall at B for the whole period can be multiplied by c to get the rainfall normal at A .

2. Double Mass Curve.

Cumulative rainfall for the complete period of record at the short-term station is plotted against the group average rainfall for the same period of years, and the slope of the double mass curve is determined. If there were no change in conditions of observation, the slope would be constant for the period. The product of this slope and the group mean rainfall for the base period T gives an estimate of mean rainfall during the base period at the short-term station.

## Estimation of Data for Gauged Locations

Many rainfall stations have incomplete records. Breaks may vary in length from one or two days to several years. It is often necessary to estimate the missing data in order to exploit partial records, especially in data sparse areas. The following methods can be used to estimate missing data:

1. Normal Ratio Method.

This method is used to fill short breaks in records (Paulhus and Kohler, 1952). Rainfall is estimated from that observed at three stations as close to and as evenly spaced as possible around the station with the missing record. The amounts at the index stations are weighted by the ratios of the normal rainfall values. Rainfall at station x , $r_x$ is given by:

$$r_x = \frac{1}{3}\left\{\frac{\bar{r}_x}{\bar{r}_A} r_A + \frac{\bar{r}_x}{\bar{r}_B} r_B + \frac{\bar{r}_x}{\bar{r}_C} r_C\right\} \qquad (7)$$

where $\bar{r}$ = normal rainfall, and A , B , C are index stations.

2. Ratio Method.

When rainfall values for station pairs are compared, their ratio may tend to be constant. This may be more pronounced for monthly and annual sums than for short-period observations. Where a more or less constant ratio exists between simultaneous sums or mean values (or simultaneous observations, as the case may be) at station pairs, it provides a convenient procedure for filling gaps in records. The procedure to be followed is essentially the one explained previously.

3. Isohyetal Method.

Missing data may also be estimated by drawing isohyets and interpolating values at locations where data are missing. This procedure is graphical and consumes more time than the procedures described above, but may yield more accurate results, especially in hilly areas where it is most appropriate.

Judgement must be exercised, however, in deciding how far to go in estimating missing data. If too few gaps are estimated, large quantities of nearly completed records may be neglected. If too many data are estimated, spurious conclusions may be drawn. Rarely should more than 5 to 10 per cent of a record be estimated.

Procedures are now available to estimate rainfall data for ungauged locations, but we will not go over them in this report. We will now present various methods of estimating mean areal rainfall.

## METHODS OF ESTIMATING MEAN AREAL RAINFALL

The following methods were considered:

1. Unweighted mean (UM)

2. Grouped area aspect weighted mean (GAAM).

3. Individual area weighted mean, Thiessen polygon (TP).

4. Individual area altitude weighted mean (AAM).

5. Triangular area weighted mean (TAM).

6. Myers method, grouped mean weighted for distance and altitude (MYER).

7. Isohyetal method (ISO).

8. Trend surface analysis (TREN)

   (a) Linear function (LIN), a simple TREN.

   (b) Quadratic function (QUAD), a complex TREN.

   (c) Cubic function (CUB), a more complex TREN.

9. Reciprocal distance squared method (RDS).

Before discussing the methods we summarize the sources of information on them in Table 1. Henceforth, these methods will be referred to by their corresponding abbreviations.

1. Unweighted Mean.

The simplest expression of mean areal rainfall is the simple average of rainfall recorded at all stations for the time period under consideration. This method is satisfactory if:

(1) The area is equipped with a large number of rainfall stations that are fairly evenly distributed or in some way may adequately sample the rainfall distribution and physiographic factors over the basin.

(2) The catchment is fairly flat.

(3) Rainfall does not vary greatly over the area.

If the distribution of stations is irregular, the estimated mean areal rainfall may be biased in favor of those that are most closely grouped. The adequacy of the method in a given situation may be tested

Table 1. Sources of information on methods of estimating mean areal rainfall.

| Method | Source of information |
|---|---|
| UM | Wilm, Nelson and Storey (1939); Butler (1957); Linsley, Kohler and Paulhus (1958); Whitmore, et al (1961); Rainbird (1967). |
| GAAM | Whitmore, et al (1961). |
| TP | Thiessen (1911); Butler (1957); Linsley, Kohler and Paulhus (1958); Whitmore, et al (1961); Gilman (1964); Bruce and Clark (1966); Rainbird (1967); Hutchinson (1969); Diskin (1969, 1970). |
| AAM | Whitmore, et al (1961). |
| TAM | Whitmore, et al (1961). |
| MYER | Myers (1959); Whitmore, et al (1961). |
| ISO | Reed and Kincer (1917); Butler (1957); Linsley, Kohler and Paulhus (1958); Whitmore, et al (1961); Gilman (1964); Bruce and Clark (1966); Rainbird (1967); Diskin and Davis (1970). |
| TREN | Dawdy and Longbein (1960); Rodda (1962); Sutcliffe and Carpenter (1967); Unwin (1969); Chidley and Keys (1970); Shaw and Lynn (1972); Lee et al (1974). |
| RDS | McGuiness and Harold (1965); Solomon, et al (1968); Pentland and Cuthbert (1971); Wei and McGuiness (1973). |

by comparing it with other methods. Because of its extreme simplicity, this method is frequently utilized in rainfall-runoff modeling.

2. Grouped Area-Aspect Weighted Mean

This method assumes that altitude and aspect are two main factors controlling incidence of rainfall. The method consists of the following steps:

(1) Divide the area into a convenient number of primary altitudinal zones as shown in Fig. 3.

(2) If necessary, subdivide the area along the main axis into secondary zones based on aspect.

(3) Measure the area (a) of each zone.

(4) Compute mean rainfall of stations situated in a zone. Carry out the computation of mean rainfall (r) for each zone.

(5) Compute the mean areal rainfall ($\bar{R}$) by

$$\bar{R} = \frac{\sum_{i=1}^{N} a_i r_i}{\sum_{i=1}^{N} a_i} \tag{8}$$

where N = number of zones. This method is an improvement over an unweighted mean. Because of its graphical nature, it is time-consuming.

3. Thiessen Polygon Method

(1) Divide the area into a number of triangles by lines joining adjacent stations.

(2) Form polygons around the stations by drawing perpendicular bisectors of the sides of the triangles as shown in Fig. 4. These polygons represent their respective areas of influence.

(3) Compute the area (a) of each polygon.

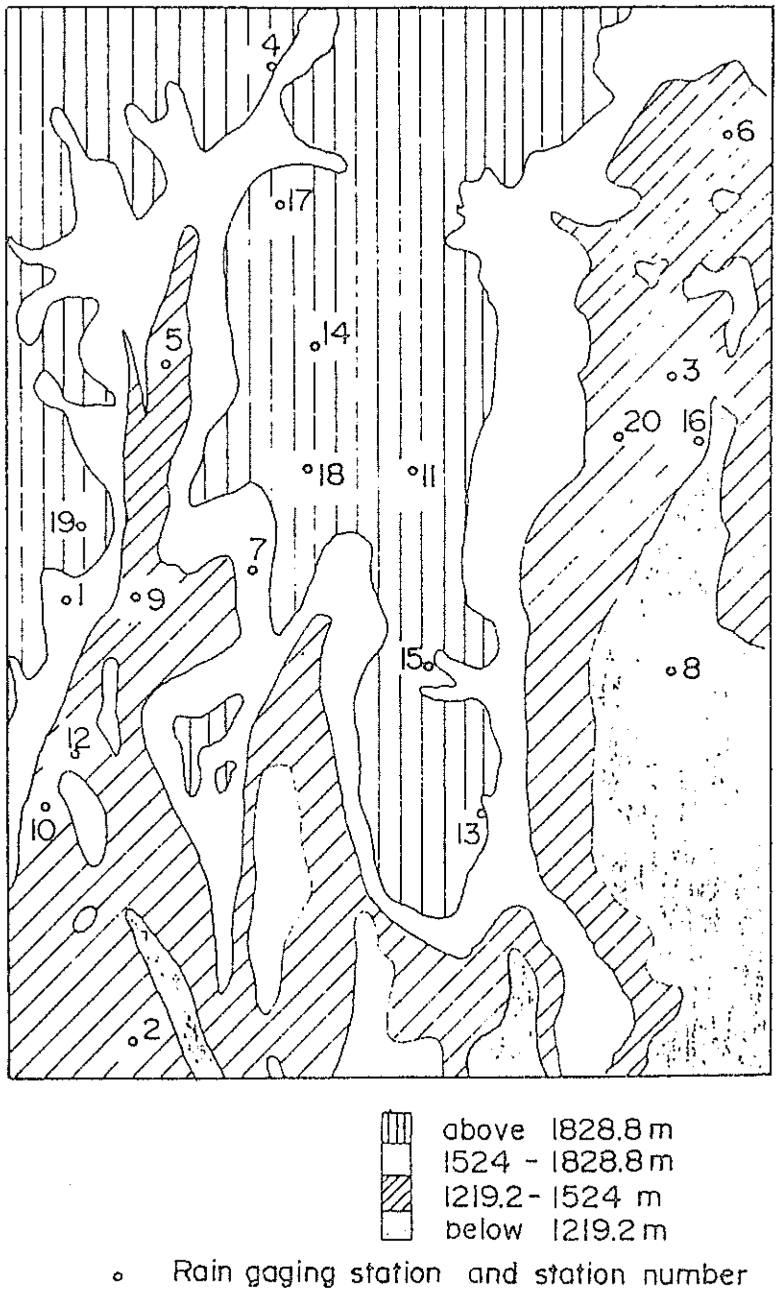
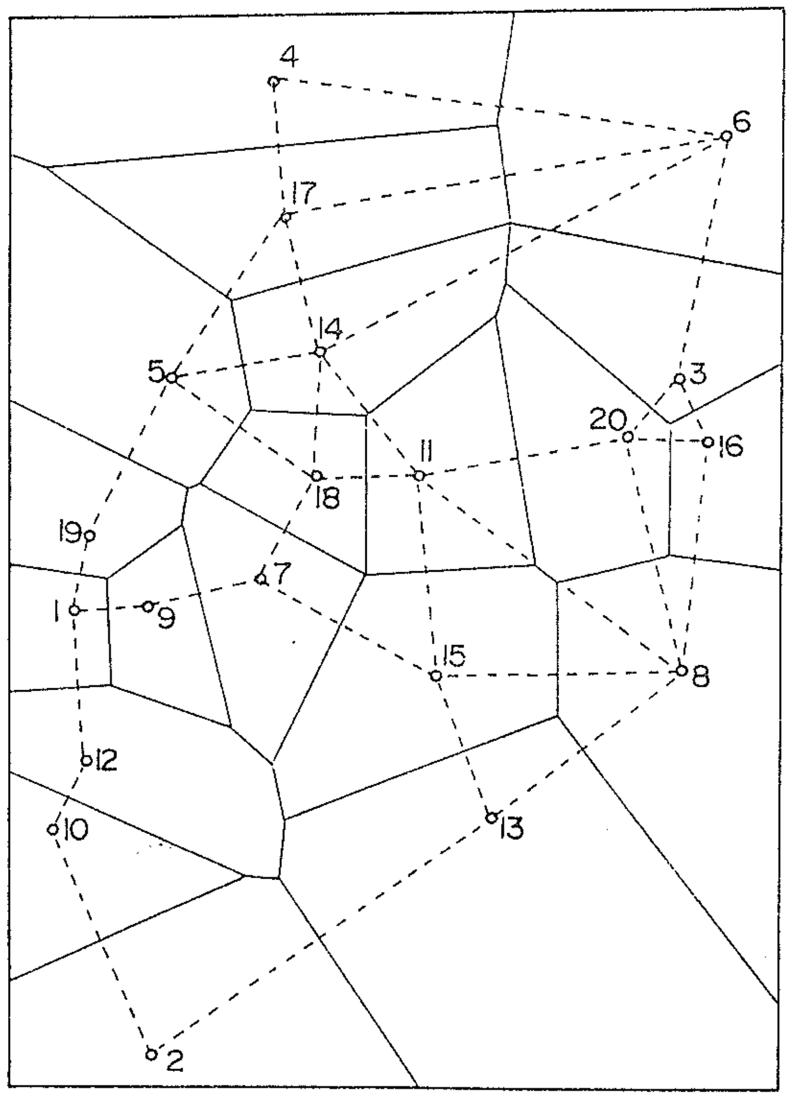



Fig. 3. Altitudinal zones for grouped area-aspect weighted mean method.




° Raingage station and station number

Fig. 4. Thiessen polygon method.

(4) Determine rainfall (r) of each station or polygon.

(5) Compute the mean areal rainfall ($\bar{R}$) by

$$\bar{R} = \frac{\sum_{i=1}^{N} a_i r_i}{\sum_{i=1}^{N} a_i} \tag{9}$$

where N = number of polygons or stations. An advantage of this method is that the influence of stations outside the area can be included. However, good results will be obtained only if the station network is fairly dense and even, or if average rainfall does not vary greatly over the area, for no account is taken of altitude. Another advantage of this method is that it is mechanical; that is, once the station weights are assigned, computations can be performed with machine methods. But a change in the rainfall network by removal or addition of a station requires recomputation of the weighting coefficients. This is one of the most frequently used methods in hydrology. For mountainous areas its use is, however, not recommended.

4. Individual Area-Altitude Weighted Mean

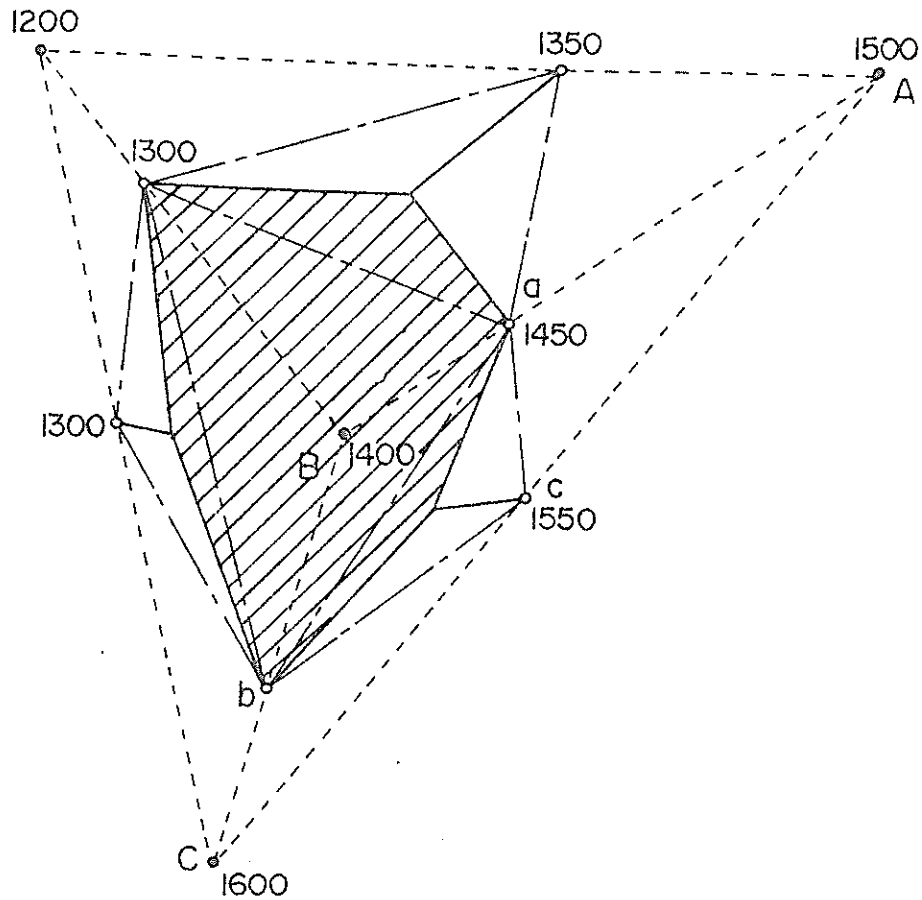
The following steps are involved in the method:

(1) Draw the contour map of the area.

(2) Divide the area into triangles by joining adjacent stations.

(3) Project the mid-point in altitude between two stations (not in distance as in the Thiessen method) on the line joining them. See Fig. 5.

(4) When the mid-altitudinal points (a, b, and c) between three stations forming a basic triangle (ABC) are joined, they




- Rain gaging station and corresponding altitude
- Mid-altitudinal points of adjacent stations and corresponding altitudes
- Basic triangles
- Residual triangles
- Bisections of Residual triangles
- Effective area of station B

Fig. 5. Construction of effective areas of raingage stations for individual area-altitude weighted mean method.

form a small residual triangle whose area is apportioned equally between the three stations (by lines drawn from the mid-point of each side of the residual triangle to the opposite vertex).

(5) Form a polygon around each station, which is representative of its altitudinal location.

(6) Measure the area (a) of each polygon and the rainfall (r) of the station representing it.

(7) Compute the mean areal rainfall ($\bar{R}$) as:

$$\bar{R} = \frac{\sum_{i=1}^{N} a_i r_i}{\sum_{i=1}^{N} a_i} \qquad (10)$$

where N = number of polygons.

When the topography is complicated and there is not a simple graduation in altitude between two stations, the mid-altitudinal value may be encountered at more than one point along the line joining them. Should it occur an odd number of times, the middle position should be used; whereas should it occur an even number of times, the mid-point in distance between the two central recurrences should be the best compromise.

Stations outside the area may be used with advantage to fix the extent of the marginal polygons, but where this guidance does not exist the margin of the catchment not covered by basic triangles can be subdivided by perpendiculars drawn from the outermost mid-altitudinal points to the areal boundary.

An important advantage of this method is that by combining horizontal and vertical distances it can reproduce influence of different land forms. This method is an improvement of the traditional method of Thiessen polygon. This method is also mechanical in that once the weighting coefficients are specified, computations can be carried out with machine methods, unless a change in the network takes place.

5. Triangular Area Weighted Mean

This method includes the following steps:

(1) Join the nearby stations to form triangles. Let $p$ , $q$ , $r$ be the rainfall at 3 stations forming the vertices of the triangle PQR.

(2) Measure the length of the line joining two stations (say PQ) and the vertical distance $(h)$ from that base to the remaining vertex.

(3) Compute the mean depth over the triangle (PQR) by

$$r = PQ \frac{(p + q + r)h}{6} ; \qquad (11)$$

thus for most part the calculation can be based on measurements of length, instead of time-consuming planimetry of areas.

(4) Compute mean areal rainfall by

$$\bar{R} = \frac{\sum_{i=1}^{N} r_i}{\sum_{i=1}^{N} a_i} \qquad (12)$$

where $N$ = number of triangular areas, and $a$ = area of a triangle. The method is illustrated in Fig. 6. The margin of the area not covered

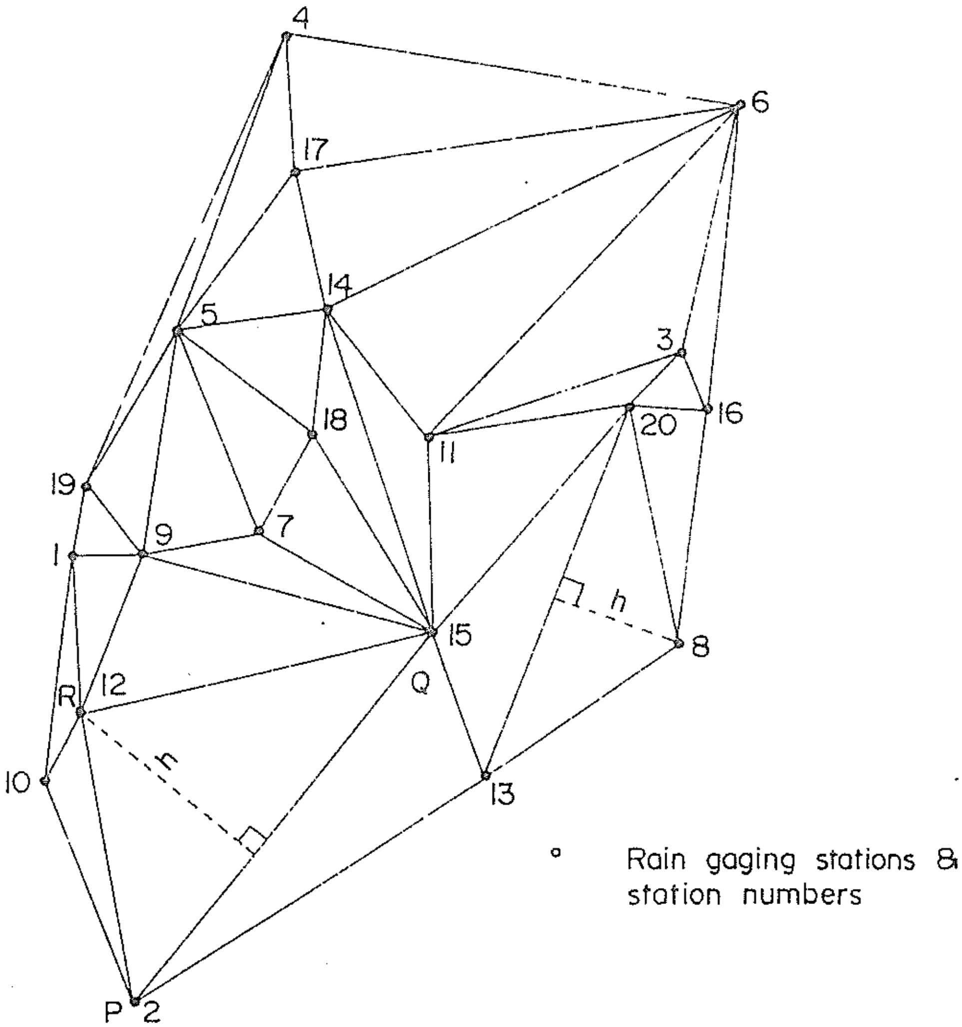



Figure 6. Basic triangles for triangular area weighted mean method.

by triangles can be partitioned by lines drawn from the outermost stations perpendicular to the areal boundary; each such area is planimetered and multiplied by the mean rainfall of the two stations at the ends of its base. Average areal rainfall is then the sum of the products of segment area and its mean rainfall, divided by the total area. This method is suitable for flat topographical areas.

6. Myers Method

This method is a grouped mean method weighted for distance and altitude. It can be described in the following steps:

(1) Locate the centroid of the watershed area.

(2) Connect rainfall stations with straight lines.

(3) Draw lines through the centroid of the area perpendicular to the lines connecting the stations.

(4) Using station values of rainfall for the period of time selected for the study, compute precipitation at the points where perpendiculars intersect the connecting lines. See Fig. 7. Let there be three stations A, C, and E. Let O be the centroid. Let the intersection points be B, D and F. Then compute precipitation at points B, D, and F using the following:

$$\text{Rain B} = \frac{\text{Rain A} \ (CB) + \text{Rain C} \ (AB)}{AC} \tag{13}$$

$$\text{Rain D} = \frac{\text{Rain C} \ (DE) + \text{Rain E} \ (CD)}{CE} \tag{14}$$

$$\text{Rain F} = \frac{\text{Rain A} \ (EF) + \text{Rain E} \ (AF)}{AE} \tag{15}$$

where CB , AB , and AC are the lengths of the respective lines.

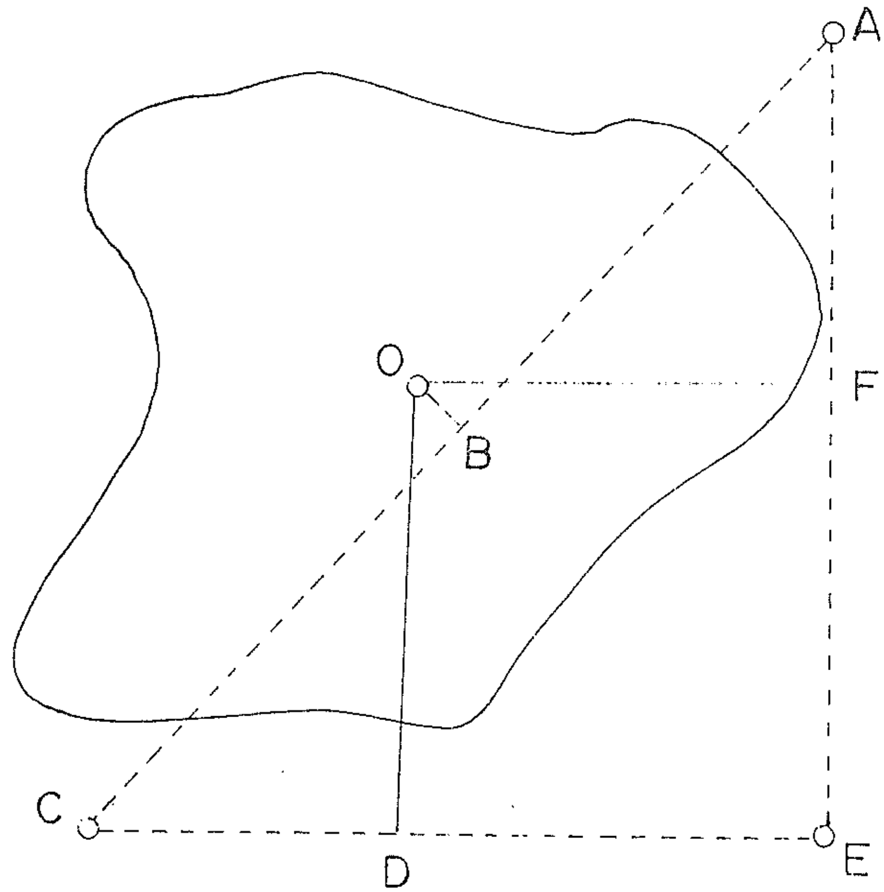



Figure 7. Myers method.

(5) Compute the mean areal rainfall $(\bar{R})$ at O by the following:

$$\bar{R} = \frac{\frac{\text{Rain B}}{OB} + \frac{\text{Rain F}}{OF} + \frac{\text{Rain D}}{OD}}{\frac{1}{OB} \quad \frac{1}{OF} \quad \frac{1}{OD}} \tag{16}$$

(6) Compute the average elevation of rainfall stations.

(7) Determine the average elevation of the watershed.

(8) Construct a curve of elevation versus 24-hr values of rainfall from a study of general storms that cover rainfall stations in the areas of various altitudes.

(9) Compute elevation factor. This is equal to the ratio of 24-hr values of rainfall for the average watershed elevation, and average elevation of the stations.

(10) Multiply the result of step (5) by the elevation factor to correct for the effect of differences in elevation.

The main limitation of the method is that only those stations can be used which are not too far from the centroid. This implies that the usefulness of the method is governed by the shape of the area. It works best in a roughly circular area but is not well adapted to one elongated in shape. A serious limitation of the method lies in computation of the evevation factor. First, construction of a curve of elevation versus 24-hr rainfall is quite subjective; its plot involves a lot of data scatter; and a reliable relationship cannot be established. Second, the elevation factor may be heavily biased in favor of the ungaged portion of the study area. The programming of this method on the computer is not difficult, and it can be coupled with computer-oriented rainfall-runoff simulation models without much difficulty.

7. Isohyetal Method

Isohyets are contours of equal rainfall. In constructing isohyets it is assumed that rainfall between two stations increases or decreases uniformly, unless abrupt changes in topography indicate otherwise. The following steps are involved in the method:

(1) Draw the isohyets.

(2) Compute the area enclosed within each of the isohyets.

(3) Compute the net area (a) enclosed between the two isohyets.

(4) Compute the average rainfall (r) for each net area.

(5) Compute average areal rainfall $(\bar{R})$ by

$$\bar{R} = \frac{\sum_{i=1}^{N} a_i r_i}{\sum_{i=1}^{N} a_i} \tag{17}$$

where N = number of net areas.

The method is illustrated in Fig. 8. A more accurate value of mean areal rainfall will be obtained if not only the area between the isohyets is measured but also the lengths of the isohyets; then if b is the length of the lower value isohyet B and a is the length of the higher isohyet A , and i is the isohyetal interval (A-B) , it can be proved that mean rainfall r for the segment is

$$r = B + \frac{r}{3} \frac{(2a + b)}{(a + b)} \tag{18}$$

The isohyetal method permits the use and interpretation of all available data and is well adapted to display and discussion. In constructing an isohyetal map the analyst can make full use of his knowledge

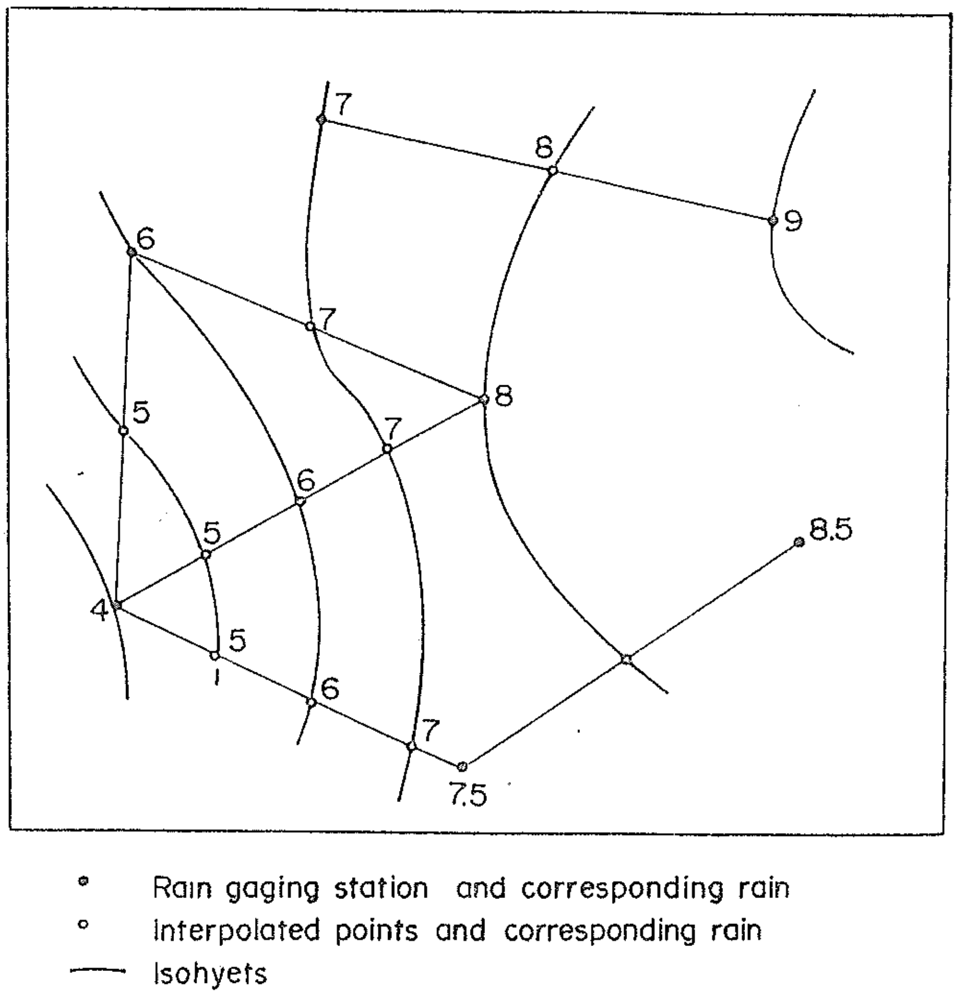



Fig. 8. Isohyetal method.

of orographic effects and storm morphology, and in this case the final map should represent a more realistic precipitation pattern than could be obtained from the gauged amounts alone. The accuracy of the isohyetal method is highly dependent upon the skill of the analyst. If linear interpolation between stations is used, the results will be essentially the same as those obtained with the Thiessen method. Moreover, an improper analysis may lead to serious errors.

A serious disadvantage of the method is its graphical nature. To carry out isohyetal computations is often tedious and time-consuming. It's not easily amenable to computer programming. Because of this shortcoming it is seldom coupled with computer models of rainfall-runoff simulation.

## 8. Trend Surface Analysis

A function of the following form is hypothesized to express the surface fitted to the observed rainfall:

$$r = \sum_{i=1}^{n} a_i f_i \quad (18)$$

where $a_i$ = the coefficients that have to be determined, $f_i$ = the values of certain functions at some point in space, and $r$ = the value of rainfall at that point. Equation (18) represents a very general function in which $f_i$ can themselves be functions of such factors as latitude, longitude, distance, etc. One form of this function that has been frequently used is of the type:

$$r = a_o + \sum_{i=1}^{n} a_i x^i + \sum_{i=1}^{n} b_i y^i + \sum_{i=1}^{n} c_i x^i y^{n-1} \quad (19)$$

where a , b , and c are weight coefficients. This obviously is a polynomial of n-th degree, and x and y represent distances as shown in Fig. 9. For presenting general formulation we will use Eq. (18).

The volume (v) of rainfall over the area(s) is:

$$v = \int^{s} r \, ds \tag{20}$$

Substituting Eq. (18) into Eq. (20),

$$v = \sum_{i=1}^{n} a_i \int^{s} f_i \, ds \tag{21}$$

Let $g_i = \int^{s} f_i \, ds$ . Then we can write:

$$v = \sum_{i=1}^{n} a_i \, g_i \tag{22}$$

Writing Eq. (22) in matrix form,

$$v = GA$$

where G is a row vector with n elements, and A is a column vector with n elements. Henceforth for this method, only upper case letters will denote vectors or matrices.

We wish to determine the unknown A from the observed rainfall. If there are m raingages in use and n functions, then rainfall at each gauge site can be expressed as:

$$r_j = \sum_{i=1}^{n} a_i f_{ij} \qquad i \in [1,n] \quad ; \; j \in [1,m] \tag{23}$$

where $f_{ij}$ is the value of the ith function at the jth raingage. In matrix form we can write:

$$R = FA \tag{24}$$

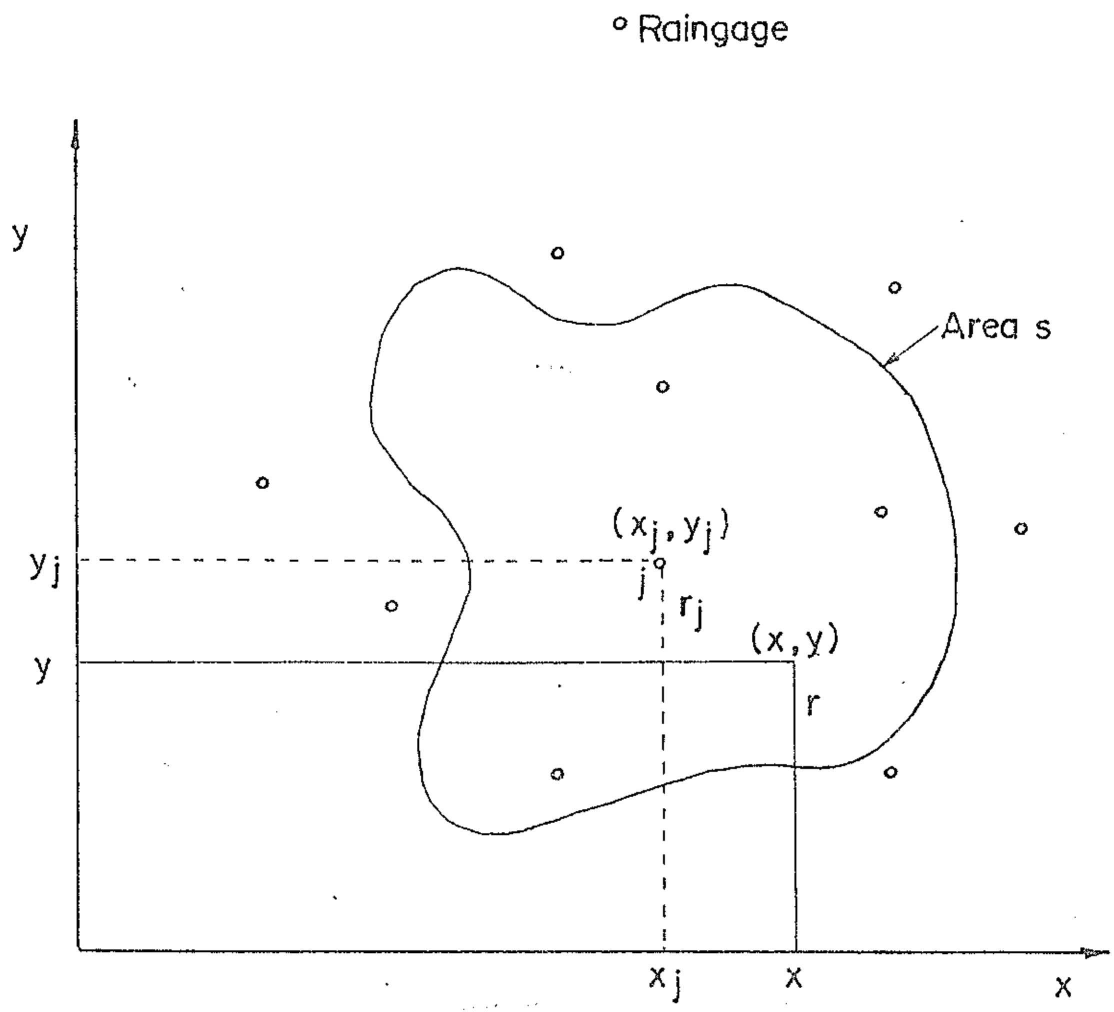



Fig. 9. A hypothetical area and raingage network.

where F is a matrix of functions with m rows and n columns, A is a column vectors with n elements, and R is a column vector with m elements, each being the observed rainfall. Generally there are more equations than unknowns; that is $m > n$. Such a situation will lead to an infinite number of solutions for A. A solution that we ordinarily desire is the one which minimizes the sum of squares of deviations between the observed and estimated values of rainfall. That is, we want to find A consistent with:

$$e = \min \sum_{j=1}^{m} \left\{ r_j - \sum_{i=1}^{n} a_i f_{ij} \right\}^2 \tag{25}$$

where e is the error criterion. We now solve for A consistent with Eq. (25). This is essentially the method of least square. Multiplying Eq. (24) by the transpose $(F')$ of F,

$$F'R = F'FA \tag{26}$$

The solution for A is

$$A = [F'F]^{-1} F'A \tag{27}$$

Multiplying Eq. (27) by G,

$$GA = G[F'F]^{-1} F'A \tag{28}$$

Writing Eq. (28) as

$$v = WR \tag{29}$$

where W is a row vector of weights with m elements, one for each raingage. That is,

$$W = G[F'F]^{-1} F'R \tag{30}$$

Having obtained W, it is a straightforward matter to compute v for each time period. Sometimes, the computation of W experiences numerical difficulties. In particular if the matrix F is large, the determination of the inverse of $[F'F]$ encounters such problems as ill-conditioning. In such circumstances the general treatment has little practical utility, although it is mathematically tractable. In order to circumvent these difficulties one must resort to simpler yet adequate forms of Eq. (18). The simplest form of Eq. (18) is a linear function. Utilizing linear function we derive expressions, in an alternative form, for computation of mean areal rainfall.

Example of linear function.

The general equation for the two-dimensional linear function is:

$$\xi = a_1 + a_2x + a_3y \tag{31}$$

Comparing Eq. (31) with Eq. (18) we notice that $f_1 = 1$, $f_2 = x$, and $f_3 = y$. Determination of A for the linear function is easier through a direct procedure. We can write Eq. (25) as:

$$e = \sum_{j=1}^{m} \left\{r_j - (a_1 + a_2x_j + a_3y_j\right\}^2 \tag{32}$$

Differentiating Eq. (32) with respect to the coefficients and equating to zero leads to:

$$\sum_{j=1}^{m} \left\{r_j - (a_1 + a_2x_j + a_3y_j)\right\} = o \tag{33}$$

$$\sum_{j=1}^{m} \left\{r_j - (a_1 + a_2x_j + a_3y_j)\right\} x_j = o \tag{34}$$

$$\sum_{j=1}^{m} \left\{r_j - (a_1 + a_2x_j + a_3y_j)\right\} y_j = o \tag{35}$$

Solving Eqs. (33) - (35) simultaneously,

$$\delta = m\,(\xi_3\xi_4 - \xi_5^2) - \xi_1(\xi_1\xi_4 - \xi_2\xi_5) + \xi_2(\xi_1\xi_5 - \xi_2\xi_3) \tag{36}$$

$$a_1 = \left\{\xi_6(\xi_3\xi_4 - \xi_5^2) - \xi_7(\xi_1\xi_4 - \xi_2\xi_5) + \xi_8(\xi_1\xi_5 - \xi_2\xi_3)\right\} / \delta \tag{37}$$

$$a_2 = \left\{m(\xi_4\xi_7 - \xi_5\xi_8) - \xi_1(\xi_4\xi_6 - \xi_2\xi_8) + \xi_2(\xi_5\xi_6 - \xi_2\xi_1)\right\} / \delta \tag{38}$$

$$a_3 = \left\{m(\xi_3\xi_8 - \xi_5\xi_7) - \xi_1(\xi_1\xi_8 - \xi_5\xi_8) + \xi_2(\xi_1\xi_7 - \xi_3\xi_6)\right\} / \delta \tag{39}$$

where $\xi_1 = \sum_{j=1}^{m} x_j$ ; $\xi_2 = \sum_{j=1}^{m} y_j$ ; $\xi_3 = \sum_{j=1}^{m} x_j^2$ ; $\xi_4 = \sum_{j=1}^{m} y_j^2$ ; $\xi_5 = \sum_{j=1}^{m} x_j y_j$ ; $\xi_6 = \sum_{j=1}^{m} r_j$ ; $\xi_7 = \sum_{j=1}^{m} r_j x_j$ ; $\xi_8 = \sum_{j=1}^{m} r_j y_j$

The trend surface analysis has several advantages. The assumptions made in traditional methods, e.g. Thiessen polygon, are much less vital here. It provides an objective means of plotting the isohyets - an extremely valuable facility in a number of circumstances. It provides a measure of the goodness of fit to the observed values, something that most traditional methods lack in. Because of its analytic nature, it can be easily coupled with any rainfall-runoff simulation model.

9. Reciprocal Distance Squared Method.

This method involves the following steps:

(1) Impose a cartesian coordinate system on the area so that the entire area lies in the first quadrant. See Fig. 10.

(2) Assume that rainfall at any ungaged point (x,y) in the area can be determined by N number of nearby gauges around the point where N is less than the number of raingages M

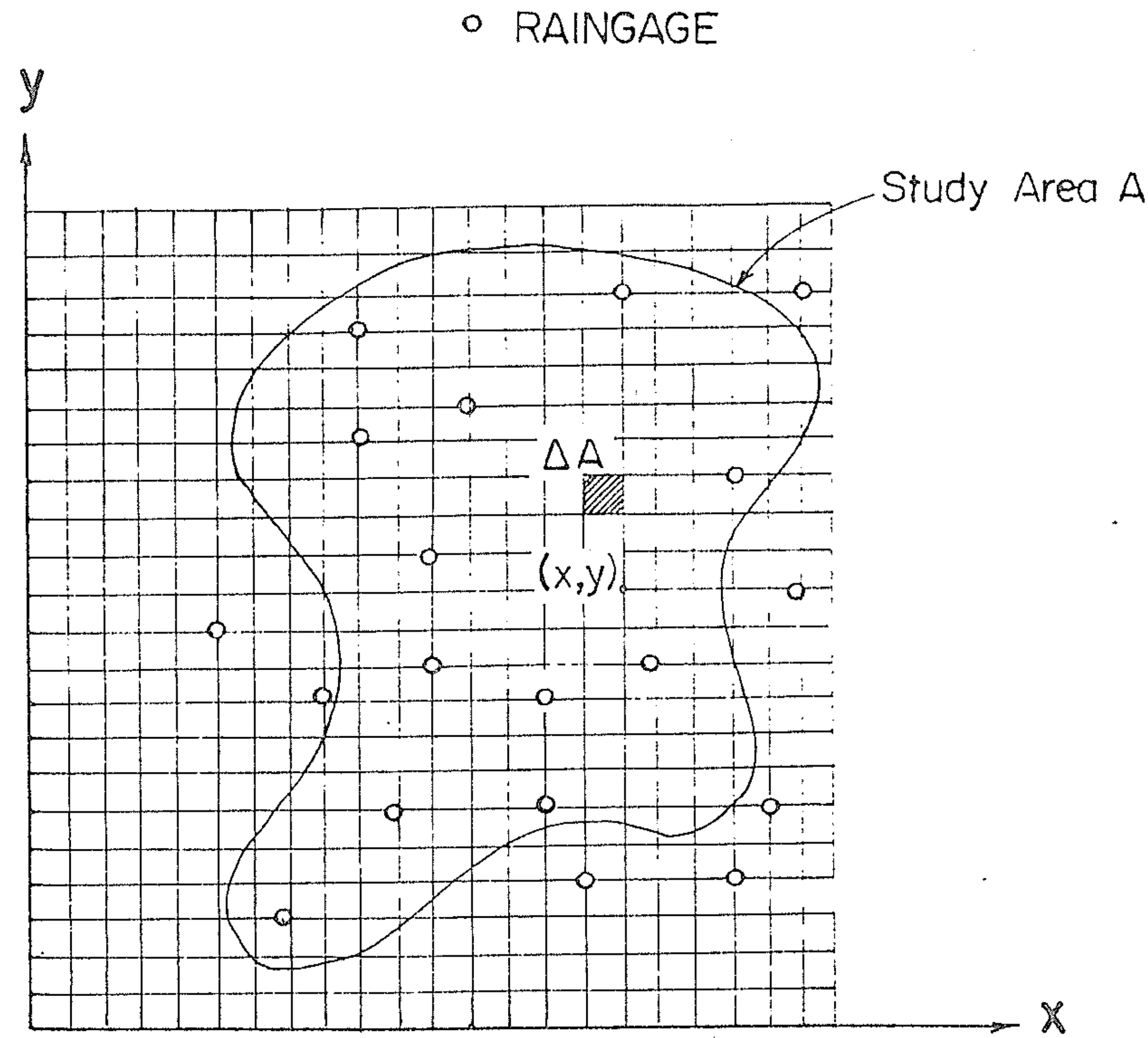



Figure 10. Raingage location and grid system for reciprocal distance squared method.

available in the area.

(3) Rainfall at the designated point $(x,y)$ is proportional to the rainfall measured at the $N$ raingages and inversely proportional to the distances between the point and the raingages. Thus the amount of rainfall $R$ at any point $(x,y)$ can be expressed by

$$R = \frac{\sum_{i=1}^{N} (P_i/D_i^2)}{\sum_{i=1}^{N} \frac{1}{D_i^2}} \qquad (40)$$

where $P_i$ = measured rainfall at gauge $i$ , $D_i$ = distance between the point $(x,y)$ and gauge $i$ , and $N$ = number of raingages used in determining rainfall at the point $(x,y)$ .

(4) Consider the area boundary as a series of straight line segments. Then the area can be calculated by summing up numerous small polygons of area $\Delta A$. If the apexes of successive angles in a polygon are assigned numbers from 1 to $n$ , the coordinates of the apexes $(x_1, y_1)$ , $(x_2,y_2)$ ..... $(x_n,y_n)$ can be read from the grid system. The polygon area $\Delta A$ can be calculated from:

$$\Delta y = (x_1y_n - x_ny_1) + \sum_{i=1}^{n-1} (x_{i+1}y_i - x_iy_{i+1}) \qquad (41)$$

where $x$ and $y$ are the $x$ and $y$ coordinates of the apexes, and the subscripts denote the corresponding numbers assigned to each apex.

(5) Compute the depth of rainfall at all points of each polygon. If $\Delta A$ is chosen to be small enough, it can be assumed that

the average rainfall in the area $\Delta A$ is a simple arithmetic mean of the rainfall amounts at the apexes of the polygon. That is,

$$\Delta P = \frac{\sum_{j=1}^{m} R_j}{m} \tag{42}$$

where $\Delta P$ = depth of rainfall in an area $\Delta P$ , $R_j$ = calculated depth of rainfall at the apex $j$ , and $m$ = number of apexes that compose the polygon. Then the volume of rainfall $\Delta V$ in the area $\Delta A$ is given by

$$\Delta V = \Delta P \; \Delta A = \left\{ \sum_{j=1}^{m} R_j/m \right\} \Delta A \tag{43}$$

(6) The mean areal rainfall $\bar{R}$ will be given by

$$\bar{R} = \frac{V}{A} \tag{44}$$

where $V$ = volume of areal rainfall, and $A$ = area. If there are $K$ number of polygons, we can write:

$$\bar{R} = \frac{\sum_{l=1}^{K} \Delta V_l}{A} \tag{45}$$

$$= \left[ \sum_{l=1}^{K} \left\{ \left( \sum_{j=1}^{m} R_{lj} \right) \Delta A_l / m_l \right\} \right] / A \tag{46}$$

The quantity $R_{lj}$ is calculated by Eq. (40). Substituting Eq. (40) in Eq. (46).

$$\bar{R} = \left[ \sum_{l=1}^{K} \left\{ \left( \sum_{j=1}^{m} \left( \sum_{i=1}^{N} P_{lji}/D_{lji}^2 \right) \left( \sum_{i=1}^{N} \frac{1}{D_{lji}^2} \right) \right) \Delta A/m_l \right\} \right] / \sum_{l=1}^{K} \Delta A_l \tag{47}$$

Equation (47) can be simply written as:

$$\bar{R} = \sum_{i=1}^{M} w_i \, P_i \tag{48}$$

where $w_i$ is a weight coefficient, a function of geometric factors such as $D$, $\Delta A$, $m$ and $A$ which are all constants. This method considers rainfall at an ungauged point as a function of measured rainfall at the nearby raingages and the distance between them and the point. Thus no distribution equation is required in the calculation. By limiting the affecting gauges to the closest few gauges and by assigning greater weight to the nearest gauge, the method minimizes the tendency to smooth out the rainfall distribution pattern. The method is objective and consistent. It is easily progrmmable and can be coupled with rainfall-runoff simulation models.

# DATA ANALYSIS AND DISCUSSION

Five application-examples are cited to illustrate the comparative performance of these methods. Two of them are from New Mexico, one from South Africa, and two from Great Britain. It is noted that these areas have contrastingly different physiographic and climatological features. In order to arrive at a definitive conclusions we feel that these methods must be applied to a number of events in a number of areas. This will minimize the degree of fortuity arising in their performance.

## Application Example 1: Area 1 in New Mexico

An area, designated as Area 1, selected in New Mexico, U.S.A. is shown in Fig. 11. It has an area of 16900 square kilometers, and is equipped with 13 raingages of the usual standard U.S. Weather Bureau pattern. General information on the raingage location including the latitude, longitude, and elevation is given in Table 2. From this table it is apparent that the area has mountainous topography varying in elevation from 1700 meters to 2500 meters.

Five daily, five monthly and five yearly rainfall events were chosen as shown in Tables 3-5. Computation of mean areal rainfall by different methods for these events is shown in the Tables 6-8. From these tables it is apparent that all methods yield comparable results except MYER. It is interesting to note that even those methods which do not explicitly account for

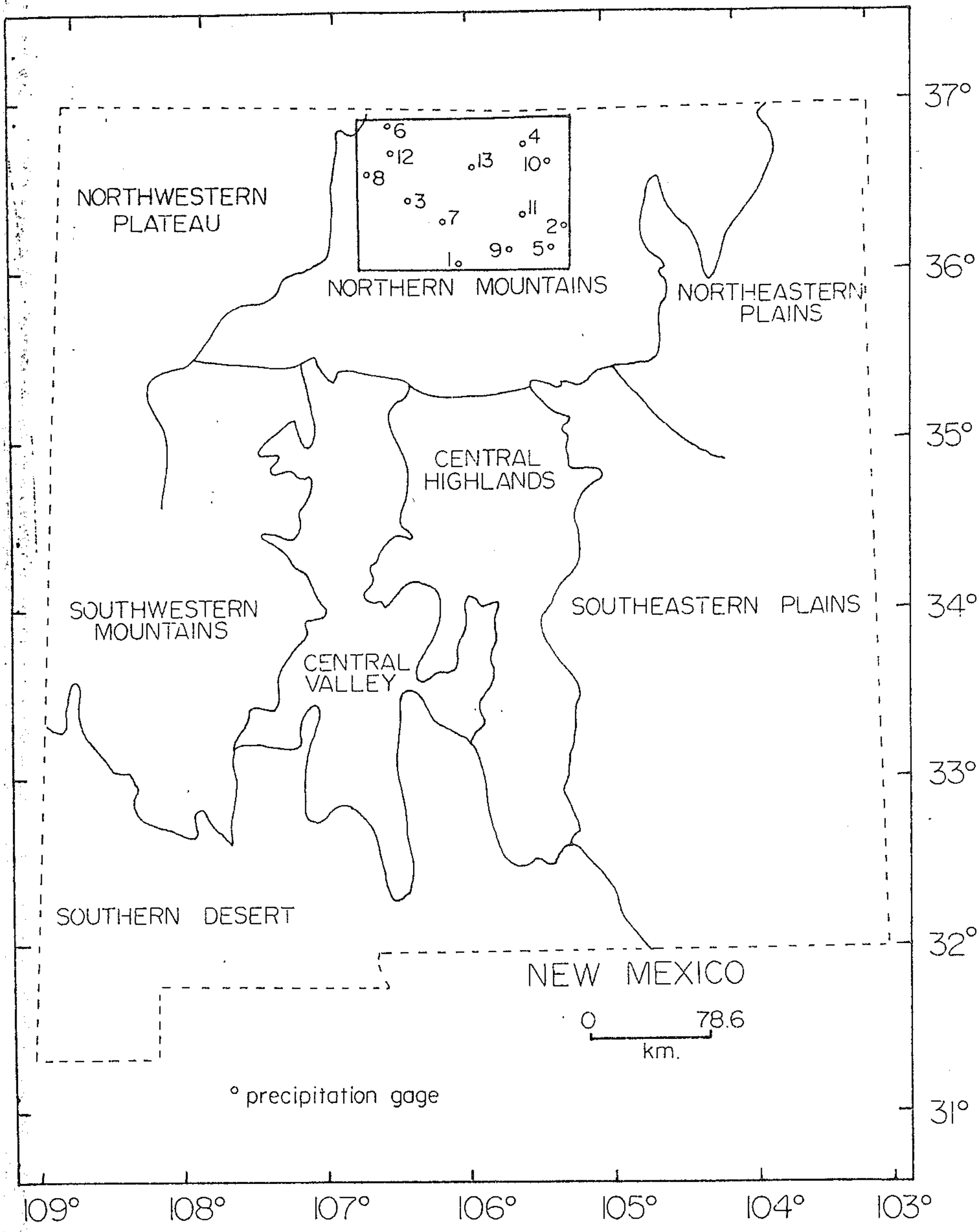



Fig. 11. Study Area 1 in New Mexico.

Table 2. General information on raingage stations in Area 1 of New Mexico, U.S.A.

| Station Number | Station | County | Latitude Deg. | Latitude Min. | Longitude Deg. | Longitude Min. | Altitude (m) |
|---|---|---|---|---|---|---|---|
| 1 | Alcade | Rio Arriba | 36 | 06 | 106 | 04 | 1731 |
| 2 | Black Lake | Colfax | 36 | 18 | 105 | 17 | 2548 |
| 3 | Canyilon | Rio Arriba | 36 | 29 | 106 | 27 | 2386 |
| 4 | Cerro | Taos | 36 | 49 | 105 | 35 | 2342 |
| 5 | Chacon | Mora | 36 | 10 | 105 | 23 | 2591 |
| 6 | Chama | Rio Arriba | 36 | 55 | 106 | 35 | 2393 |
| 7 | El Rito | Rio Arriba | 36 | 20 | 106 | 11 | 2094 |
| 8 | El Vado | Rio Arriba | 36 | 36 | 106 | 44 | 2057 |
| 9 | Penasco | Taos | 36 | 10 | 105 | 41 | 2414 |
| 10 | Red River | Taos | 36 | 42 | 105 | 24 | 2644 |
| 11 | Taos | Taos | 36 | 22 | 105 | 37 | 2117 |
| 12 | Tierra Amarilla | Rio Arriba | 36 | 45 | 106 | 34 | 2263 |
| 13 | Tres Piedras | Taos | 36 | 40 | 105 | 59 | 2472 |

Table 3. Daily rainfall data (cm) for Area 1 in New Mexico.

| Date | Stations | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| 12-3-1964 | 0.43 | 1.93 | 2.44 | 1.27 | 0.51 | 1.78 | 1.07 | 1.22 | 1.60 | 1.22 | 1.73 | 0.81 | 0.30 |
| 3-29-1973 | 0.46 | 1.60 | 0.38 | 0.33 | 1.37 | 0.76 | 0.79 | 0.51 | 0.08 | 1.50 | 0.10 | 0.25 | 1.02 |
| 3-30-1973 | 0.71 | 0.79 | 0.20 | 0.20 | 2.69 | 0.15 | 0.89 | 0.89 | 0.38 | 0.51 | 0.38 | 0.15 | 0.23 |
| 1-1-1974 | 0.61 | 1.32 | 0.38 | 3.23 | 1.60 | 0.76 | 2.77 | 0.28 | 0.0 | 1.02 | 1.42 | 1.52 | 1.40 |
| 2-1-1974 | 0.38 | 0.89 | 1.80 | 0.0 | 2.59 | 2.03 | 0.10 | 0.13 | 2.03 | 1.02 | 0.89 | 0.03 | 0.0 |
| $\overline{x}$ | 0.52 | 1.31 | 1.04 | 1.01 | 1.75 | 1.10 | 1.12 | 0.60 | 0.82 | 1.05 | 0.90 | 0.55 | 0.59 |
| $\sigma^2$ | 0.02 | 0.23 | 1.03 | 1.78 | 0.83 | 0.61 | 0.98 | 0.20 | 0.87 | 0.13 | 0.47 | 0.38 | 0.35 |
| $\sigma$ | 0.14 | 0.48 | 1.01 | 1.33 | 0.91 | 0.78 | 0.99 | 0.45 | 0.93 | 0.36 | 0.68 | 0.62 | 0.59 |
| $C_v$ | 0.27 | 0.37 | 0.97 | 1.33 | 0.52 | 0.71 | 0.88 | 0.74 | 1.14 | 0.34 | 0.75 | 1.12 | 1.00 |

Table 4. Monthly rainfall data (cm) for Area 1 in New Mexico.

| Month | Stations | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| March 1973 | 3.20 | 7.67 | 4.72 | 2.62 | 9.55 | 7.24 | 5.69 | 6.05 | 4.78 | 9.37 | 3.63 | 6.12 | 5.31 |
| April 1973 | 0.89 | 3.38 | 1.24 | 1.09 | 3.81 | 1.98 | 0.84 | 1.88 | 1.73 | 5.97 | 1.73 | 1.45 | 0.61 |
| October 1973 | 5.18 | 2.46 | 2.67 | 1.70 | 2.03 | 1.98 | 0.79 | 1.32 | 2.13 | 2.29 | 3.17 | 2.26 | 2.59 |
| January 1974 | 1.93 | 5.28 | 5.71 | 4.75 | 6.63 | 9.75 | 5.38 | 3.89 | 4.65 | 4.42 | 4.27 | 5.05 | 3.38 |
| February 1974 | 0.15 | 0.89 | 0.71 | 0.28 | 0.94 | 0.38 | 0.69 | 0.69 | 1.30 | 0.41 | 0.25 | 0.38 | 0.0 |
| $\overline{x}$ | 2.27 | 3.94 | 3.01 | 2.09 | 4.59 | 4.27 | 2.68 | 2.76 | 2.92 | 4.49 | 2.61 | 3.05 | 2.38 |
| $\sigma^2$ | 3.96 | 6.88 | 4.69 | 2.94 | 12.31 | 16.12 | 6.83 | 4.80 | 2.78 | 11.89 | 2.61 | 5.94 | 4.60 |
| $\sigma$ | 1.99 | 2.62 | 2.17 | 1.72 | 3.51 | 4.02 | 2.61 | 2.19 | 1.67 | 3.45 | 1.62 | 2.44 | 2.15 |
| $C_v$ | 0.88 | 0.67 | 0.72 | 0.82 | 0.76 | 0.94 | 0.98 | 0.79 | 0.57 | 0.77 | 0.62 | 0.80 | 0.90 |

Table 5. Yearly rainfall data (cm) for Area 1 in New Mexico.

| Year | Stations | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| 1958 | 23.72 | 48.16 | 37.49 | 24.00 | 37.64 | 47.37 | 26.52 | 33.63 | 33.15 | 35.81 | 28.96 | 35.89 | 30.43 |
| 1961 | 23.39 | 48.31 | 46.10 | 29.92 | 53.54 | 54.15 | 32.66 | 41.00 | 45.75 | 58.45 | 41.00 | 52.98 | 27.33 |
| 1964 | 19.71 | 40.87 | 42.82 | 29.36 | 29.59 | 47.96 | 26.80 | 39.22 | 32.05 | 45.16 | 27.08 | 43.87 | 27.51 |
| 1970 | 17.35 | 41.10 | 35.71 | 24.59 | 40.08 | 48.62 | 24.79 | 33.50 | 31.65 | 45.69 | 27.76 | 29.01 | 27.41 |
| 1973 | 20.70 | 44.42 | 30.45 | 24.23 | 54.15 | 40.49 | 24.54 | 34.70 | 32.28 | 38.99 | 28.63 | 37.11 | 23.55 |
| $\bar{x}$ | 20.98 | 44.57 | 38.52 | 26.42 | 43.00 | 47.72 | 27.06 | 36.41 | 34.98 | 44.82 | 30.68 | 39.77 | 27.24 |
| $\sigma^2$ | 7.06 | 13.16 | 37.50 | 8.73 | 13.14 | 23.67 | 10.82 | 12.01 | 36.55 | 75.41 | 33.78 | 82.34 | 5.98 |
| $\sigma$ | 2.66 | 3.63 | 6.12 | 2.95 | 10.64 | 4.86 | 3.29 | 3.47 | 6.05 | 8.68 | 5.81 | 9.07 | 2.45 |
| $C_v$ | 0.13 | 0.08 | 0.16 | 0.11 | 0.25 | 0.10 | 0.12 | 0.10 | 0.17 | 0.19 | 0.19 | 0.23 | 0.09 |

Table 6. Mean areal rainfall estimates by different methods.

Areal 1 in New Mexico, daily totals (cm)

| Date | UM | GAAM | TP | AAM | TAM | MYER | ISO | TREN | | | RDS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | LIN | QUAD | CUB | |
| 1-1-1974 | 1.24 | 1.17 | 1.30 | 1.40 | 1.30 | 1.66 | 1.35 | 1.34 | 1.26 | 1.85 | 1.35 |
| 2-1-1974 | 0.91 | 0.91 | 0.91 | 0.81 | 0.81 | 1.18 | 0.89 | .92 | .79 | 1.07 | 0.79 |
| 3-29-1973 | 0.71 | 0.97 | 0.76 | 0.84 | 0.61 | .92 | 0.66 | .76 | .80 | 1.05 | 0.74 |
| 3-30-1973 | 0.64 | 0.58 | 0.58 | 0.51 | 0.48 | .85 | 0.56 | .61 | .62 | .84 | 0.71 |
| 12-3-1964 | 1.27 | 1.22 | 1.24 | 1.22 | 1.19 | 1.47 | 1.27 | 1.26 | 1.18 | 1.50 | 1.35 |
| $\bar{x}$ | .95 | .97 | .96 | .96 | .88 | 1.22 | .95 | .98 | .93 | 1.26 | .99 |
| $\sigma^2$ | .09 | .06 | .10 | .13 | .13 | .12 | .13 | .10 | .08 | .17 | .11 |
| $\sigma$ | .29 | .25 | .31 | .35 | .36 | .35 | .35 | .31 | .28 | .41 | .33 |
| $C_v$ | .31 | .26 | .32 | .37 | .41 | .29 | .37 | .32 | .30 | .32 | .34 |

$\bar{x}$ = mean; $\sigma^2$ = unbiased variance; $\sigma$ = unbiased standard deviation; $C_v$ = coefficient of variation.

Table 7. Mean areal rainfall estimates by different methods.

Areal 1 in New Mexico, monthly totals (cm)

| Month | UM | GAAM | TP | AAM | TAM | MYER | ISO | TREN | | | RDS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | LIN | QUAD | CUB | |
| Feb 1974 | 0.53 | 0.33 | 0.51 | 0.41 | 0.48 | .64 | 0.53 | .53 | .48 | .61 | 0.61 |
| Jun 1974 | 5.00 | 4.75 | 4.78 | 4.65 | 4.78 | 6.30 | 4.80 | 5.06 | 4.58 | 5.91 | 4.72 |
| March 1973 | 5.84 | 6.99 | 5.84 | 5.92 | 5.33 | 7.41 | 5.89 | 5.97 | 5.95 | 6.15 | 5.49 |
| April 1973 | 2.06 | 3.33 | 2.13 | 2.31 | 1.60 | 2.54 | 2.21 | 2.23 | 2.63 | 2.37 | 1.50 |
| Oct 1973 | 2.36 | 2.36 | 2.41 | 2.41 | 2.39 | 2.83 | 2.41 | 2.31 | 2.58 | 1.96 | 2.34 |
| $\overline{x}$ | 3.16 | 3.55 | 3.13 | 3.14 | 2.92 | 3.94 | 3.17 | 3.22 | 3.24 | 3.40 | 2.93 |
| $\sigma^2$ | 4.83 | 6.28 | 4.61 | 4.67 | 4.31 | 7.92 | 4.63 | 5.00 | 4.39 | 6.20 | 4.38 |
| $\sigma$ | 2.20 | 2.51 | 2.15 | 2.16 | 2.08 | 2.81 | 2.15 | 2.24 | 2.10 | 2.49 | 2.09 |
| $C_v$ | 0.70 | 0.71 | 0.69 | 0.69 | 0.71 | 0.71 | 0.68 | 0.69 | 0.65 | 0.73 | 0.71 |

Table 8. Mean areal rainfall estimates by different methods.

Area 1 in New Mexico, yearly totals (cm)

| Year | UM | GAAM | TP | AAM | TAM | MYER | ISO | TREN | | | RDS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | LIN | QUAD | CUB | |
| 1973 | 33.43 | 34.98 | 32.28 | 32.00 | 30.50 | 41.84 | 32.72 | 33.88 | 32.76 | 33.55 | 29.97 |
| 1958 | 34.06 | 34.37 | 33.45 | 33.60 | 32.59 | 42.08 | 32.72 | 34.32 | 32.68 | 34.67 | 32.60 |
| 1961 | 42.67 | 47.63 | 41.68 | 41.63 | 39.80 | 52.72 | 41.88 | 43.31 | 42.25 | 40.46 | 38.10 |
| 1964 | 34.77 | 38.00 | 34.43 | 35.13 | 32.89 | 41.48 | 34.34 | 35.15 | 35.17 | 35.80 | 29.54 |
| 1970 | 32.84 | 36.78 | 32.59 | 33.88 | 30.91 | 40.73 | 33.27 | 33.64 | 33.23 | 35.58 | 29.85 |
| $\bar{x}$ | 35.55 | 38.35 | 34.89 | 35.25 | 33.34 | 43.77 | 34.99 | 36.06 | 35.22 | 36.01 | 31.99 |
| $\sigma^2$ | 16.34 | 28.98 | 15.12 | 13.97 | 14.12 | 25.29 | 15.29 | 16.76 | 16.47 | 6.97 | 12.79 |
| $\sigma$ | 4.04 | 5.38 | 3.89 | 3.74 | 3.76 | 5.03 | 3.91 | 4.09 | 4.06 | 2.64 | 3.58 |
| $C_v$ | 0.11 | 0.14 | 0.11 | 0.11 | 0.11 | 0.11 | 0.11 | 0.11 | 0.12 | 0.07 | 0.11 |

altitudinal effects are comparable to those which do. Even more interesting observation is that UM and LIN, the easiest and fastest methods, provide comparable results. The general contention that such simple methods cannot provide adequate mean areal rainfall estimates is no longer valid here. The reason for higher estimates by MYER is its elevation factor. A considerable part (approximately 30%) of the high elevation area is not covered by the raingage network because of its uneven distribution. The elevation factor is, therefore, heavily biased by the ungaged high elevation area and turns out to be higher than it should. Consequently it makes the estimates by MYER higher. It is not, however, plausible to argue whether these estimates are realistic. It has long been believed that the isohyetal method has higher capability to describe spatial distributional characteristics of rainfall, especially in higher altitude areas. If this is true, the estimates by MYER are then certainly biased.

Another interesting observation is that QUD and CUB, more complex TREN, do not have any particular advantage over LIN, a simpler TREN - an apparent contradiction to the traditional thinking (Mandeville and Rodda, 1970). For other methods also it can be argued that simple methods are just as good as complex ones, even in the physiographically complex area.

Application Example 2: Area 2 in New Mexico

Another area selected in New Mexico, U.S.A., designated as Area 2, is shown in Fig. 12. This area is much larger in size, about 155,400 square kilometers. It has 20 raingages of the usual standard U.S. Weather Bureau pattern. General information on the raingage location,

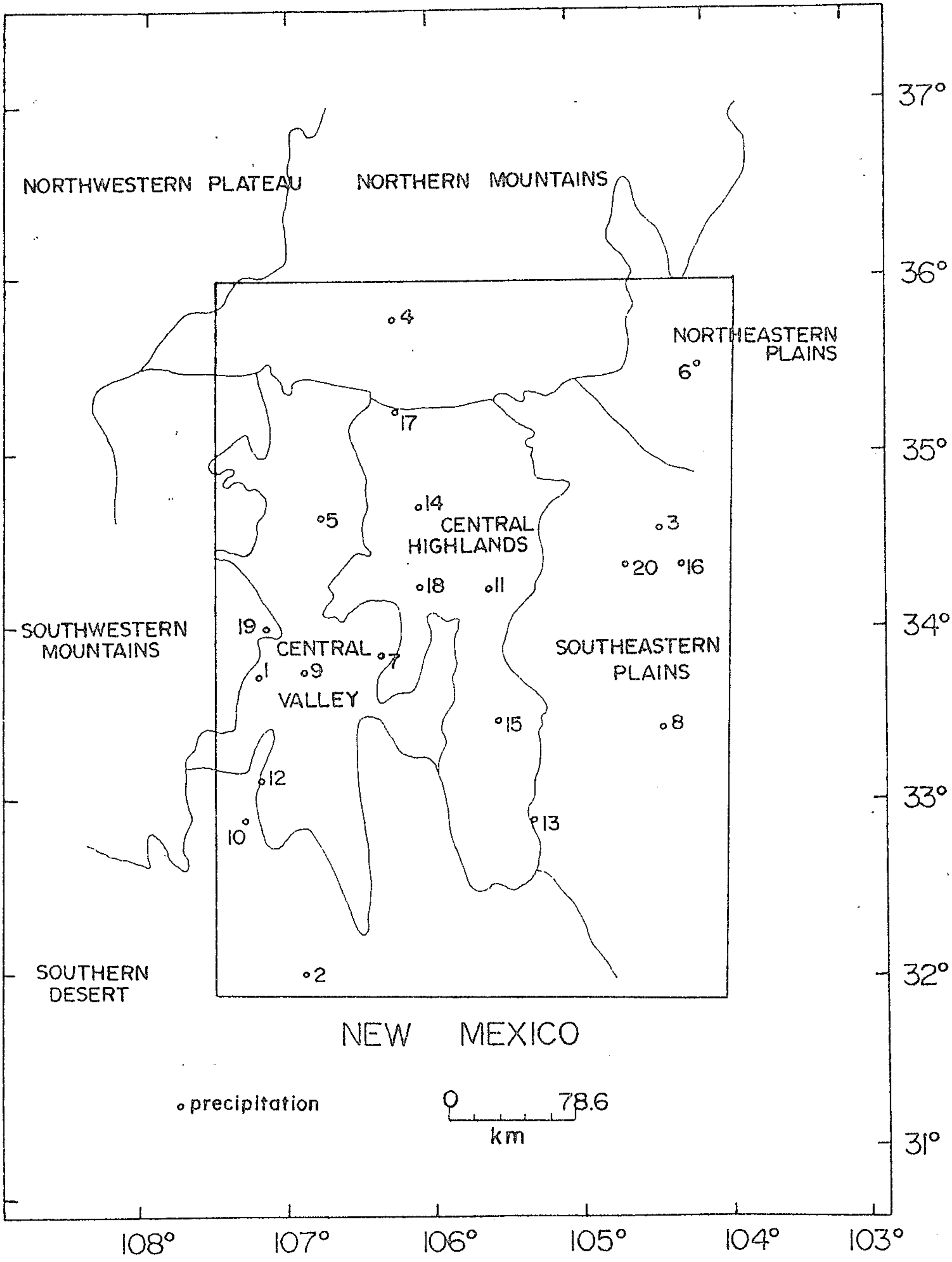



Fig. 12. Study Area 2 in New Mexico.

including latitude, longitude, and elevation, is given in Table 9. It is clear from the table that the area has varying topography, mountainous in some parts while flat in the others.

Twenty daily, twenty monthly and nineteen yearly rainfall events, as shown in Tables 10-12, were chosen in this area. Computation of mean areal rainfall by different methods is shown for these events in Tables 13-15. Statistical parameters were computed for these events as shown in the tables. From these tables, again it is clear that all methods of estimating mean areal rainfall are comparable. MYER gives higher estimates. The reason appears to be the same as explained in the previous example. That same observation that one method does not have any particular advantage over the other as far as results are concerned holds true in this example as well. This observation cannot be attributed to chance because it is true for almost all events under study, and because a large number of events have been considered.

Application Example 3: The River Ray Catchment, Great Britain

The River Ray catchment at Grendon (Hydrological Research Unit, 1966) is relatively flat and dry. As shown in Fig. 13, it has an area of 18.6 $km^2$ and is sampled by 17 daily raingages of the usual British Meteorological Office pattern (30.5 cm tall with an aperture of 123 $cm^2$). This example has been extracted from the work done by Mandeville and Rodda (1970). Four different methods of estimating mean areal rainfall were applied to daily and yearly values as shown in Tables 16 and 17. Lack of sufficient information did not permit computation by other methods. It is clear form these tables that all four methods yielded practically identical results. Despite identical performance of the

Table 9. General information about raingage stations in Area 2 of New Mexico, U.S.A.

| Station No. | Name of the Station | County | Latitude Deg. | Latitude Min. | Longitude Deg. | Longitude Min. | Elevation (m) |
|---|---|---|---|---|---|---|---|
| 1 | Reinhardt Ranch | Socorro | 33 | 45 | 107 | 13 | 1661 |
| 2 | Afton 5 ESE | Dona Ana | 32 | 03 | 106 | 52 | 1280 |
| 3 | Alamogordo Dam | De Baca | 34 | 36 | 104 | 23 | 1312 |
| 4 | Bandalier Nat. Mon. | San Doval | 35 | 47 | 106 | 16 | 1847 |
| 5 | Belen | Valencia | 34 | 40 | 106 | 46 | 1463 |
| 6 | Bell Ranch | San Miguel | 35 | 32 | 104 | 06 | 1372 |
| 7 | Bingham | Socorro | 33 | 53 | 106 | 22 | 1662 |
| 8 | Bitter Lake Wildlife Refuge | Chavez | 33 | 29 | 104 | 24 | 1119 |
| 9 | Bosque Del Apache | Socorro | 33 | 46 | 106 | 54 | 1378 |
| 10 | Caballo Dam | Sierra | 32 | 54 | 107 | 18 | 1277 |
| 11 | Corona | Lincoln | 34 | 15 | 105 | 36 | 2031 |
| 12 | Elephant Butte | Sierra | 33 | 09 | 107 | 11 | 1395 |
| 13 | Elk | Chavez | 32 | 56 | 105 | 17 | 1737 |
| 14 | Estancia | Torrance | 34 | 45 | 106 | 04 | 1861 |
| 15 | Fort Stanton | Lincoln | 33 | 30 | 105 | 31 | 1899 |
| 16 | Fort Summers 5S | De Baca | 34 | 22 | 105 | 15 | 1234 |
| 17 | Golden | Santa Fe | 35 | 16 | 106 | 13 | 2042 |
| 18 | Gran Quivira Nat. Mon. | Socorro | 34 | 16 | 106 | 05 | 2018 |
| 19 | Kelly Ranch | Socorro | 34 | 02 | 107 | 08 | 2042 |
| 20 | Yeso | De Baca | 34 | 24 | 104 | 37 | 1478 |

Table 10. Daily rainfall data (cm) for Area 2 in New Mexico (contd).

| | Stations | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Date | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| 5-17-1952 | 0.36 | 0.0 | 0.0 | 4.83 | 0.36 | 0.51 | 0.30 | 0.0 | 0.51 | 0.0 |
| 6-17-1953 | 0.51 | 0.0 | 5.11 | 0.81 | 0.0 | 0.0 | 0.0 | 0.0 | 1.57 | 0.0 |
| 8-7-1954 | 0.30 | 0.0 | 0.0 | 0.13 | 0.25 | 0.33 | 3.89 | 0.08 | 0.30 | 3.94 |
| 9-25-1955 | 0.0 | 0.0 | 1.24 | 1.22 | 0.0 | 1.14 | 0.0 | 1.57 | 0.10 | 0.0 |
| 8-1-1956 | 0.25 | 0.33 | 0.0 | 0.48 | 0.0 | 0.0 | 0.0 | 0.0 | 0.08 | 0.81 |
| 4-29-1957 | 0.0 | 0.0 | 0.30 | 0.69 | 0.0 | 0.46 | 0.0 | 0.0 | 0.51 | 1.60 |
| 5-2-1958 | 0.08 | 0.0 | 0.05 | 0.0 | 0.0 | 0.0 | 0.28 | 0.0 | 0.28 | 0.03 |
| 7-8-1959 | 0.23 | 0.0 | 0.0 | 0.08 | 0.0 | 0.0 | 0.38 | 1.47 | 0.0 | 0.0 |
| 6-10-1960 | 0.61 | 0.43 | 1.17 | 0.46 | 0.74 | 0.38 | 0.84 | 1.02 | 0.74 | 0.10 |
| 9-3-1961 | 0.20 | 0.0 | 0.28 | 0.81 | 0.0 | 0.0 | 0.18 | 0.0 | 0.0 | 0.0 |
| 8-21-1962 | 0.0 | 0.0 | 0.58 | 0.63 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 5-22-1963 | 0.0 | 0.0 | 0.13 | 0.0 | 0.0 | 1.02 | 0.03 | 0.38 | 0.0 | 0.0 |
| 4-4-1964 | 0.99 | 0.28 | 0.0 | 0.63 | 0.94 | 0.61 | 0.56 | 0.0 | 1.57 | 1.04 |
| 6-10-1966 | 0.10 | 0.0 | 0.20 | 1.75 | 0.0 | 0.53 | 1.14 | 0.0 | 0.63 | 0.0 |
| 8-2-1966 | 1.09 | 0.0 | 0.15 | 3.89 | 0.41 | 0.0 | 0.15 | 0.10 | 0.0 | 0.0 |
| 7-17-1967 | 0.15 | 0.0 | 0.66 | 4.09 | 0.18 | 0.63 | 0.0 | 0.0 | 0.0 | 0.0 |
| 5-12-1968 | 1.09 | 0.0 | 0.79 | 1.60 | 0.0 | 0.08 | 0.0 | 1.55 | 0.0 | 0.13 |
| 9-8-1969 | 0.0 | 0.0 | 1.45 | 0.05 | 0.0 | 0.15 | 0.25 | 5.84 | 0.0 | 0.46 |
| 4-18-1970 | 0.0 | 0.0 | 3.10 | 0.0 | 0.15 | 1.73 | 0.15 | 0.0 | 0.0 | 0.0 |
| 7-20-1971 | 0.25 | 0.0 | 1.45 | 1.78 | 0.30 | 1.37 | 1.75 | 2.29 | 0.0 | 0.0 |
| $\overline{x}$ | 0.31 | 0.05 | 0.83 | 1.20 | 0.17 | 0.45 | 0.50 | 0.72 | 0.31 | 0.41 |
| $\sigma^2$ | 0.13 | 0.02 | 1.61 | 2.10 | 0.07 | 0.26 | 0.84 | 1.97 | 0.24 | 0.88 |
| $\sigma$ | 0.37 | 0.13 | 1.27 | 1.45 | 0.27 | 0.51 | 0.92 | 1.40 | 0.49 | 0.94 |
| $C_v$ | 1.18 | 2.49 | 1.52 | 1.21 | 1.62 | 1.15 | 1.86 | 1.96 | 1.57 | 2.32 |

Table 10. Daily rainfall data (cm) for Area 2 in New Mexico.

| | Stations | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Date | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| 5-17-1952 | 0.0 | 0.0 | 0.23 | 1.37 | 0.0 | 0.0 | 2.64 | 0.10 | 2.03 | 0.0 |
| 6-17-1953 | 0.0 | 0.13 | 1.52 | 0.36 | 0.15 | 0.0 | 0.0 | 1.19 | 2.54 | 0.0 |
| 8-7-1954 | 0.25 | 1.47 | 2.13 | 0.0 | 0.13 | 1.65 | 1.02 | 3.12 | 1.78 | 0.43 |
| 9-25-1955 | 0.0 | 0.0 | 0.63 | 0.0 | 3.17 | 0.0 | 7.11 | 0.05 | 0.0 | 2.74 |
| 8-1-1956 | 0.13 | 2.59 | 1.14 | 0.38 | 0.13 | 0.0 | 0.0 | 0.28 | 0.0 | 0.79 |
| 4-29-1957 | 1.24 | 1.35 | 0.84 | 0.0 | 0.28 | 0.30 | 1.02 | 0.0 | 2.39 | 0.23 |
| 5-2-1958 | 0.13 | 0.0 | 0.0 | 0.0 | 0.03 | 0.0 | 0.0 | 0.25 | 0.0 | 0.0 |
| 7-8-1959 | 0.0 | 0.84 | 0.56 | 0.0 | 0.05 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| 6-10-1960 | 1.22 | 0.53 | 1.27 | 3.43 | 2.62 | 1.07 | 0.56 | 0.86 | 3.25 | 1.09 |
| 9-3-1961 | 0.10 | 0.18 | 0.23 | 0.0 | 0.0 | 0.0 | 0.0 | 0.20 | 0.0 | 0.18 |
| 8-21-1962 | 1.78 | 0.38 | 0.0 | 0.25 | 0.61 | 0.0 | 0.0 | 0.84 | 0.0 | 0.0 |
| 5-22-1963 | 0.51 | 0.0 | 0.15 | 0.08 | 0.0 | 0.38 | 0.0 | 0.05 | 0.0 | 0.46 |
| 4-4-1964 | 1.02 | 1.52 | 0.38 | 1.85 | 0.25 | 0.0 | 1.14 | 1.50 | 2.03 | 0.0 |
| 6-10-1966 | 0.30 | 0.41 | 0.0 | 1.14 | 0.0 | 0.0 | 0.0 | 0.91 | 0.0 | 0.18 |
| 8-2-1966 | 6.65 | 0.0 | 1.12 | 2.77 | 0.0 | 10.67 | 1.35 | 1.32 | 0.0 | 4.09 |
| 7-17-1967 | 1.63 | 0.0 | 0.0 | 0.63 | 0.0 | 0.33 | 0.0 | 0.25 | 0.0 | 0.51 |
| 5-12-1968 | 0.53 | 0.18 | 0.69 | 2.41 | 0.0 | 1.60 | 1.78 | 1.65 | 1.24 | 0.89 |
| 9-8-1969 | 1.90 | 0.56 | 1.78 | 0.25 | 1.78 | 0.63 | 0.84 | 1.09 | 0.0 | 0.43 |
| 4-18-1970 | 0.0 | 0.20 | 0.0 | 0.0 | 0.0 | 0.51 | 0.0 | 0.51 | 0.0 | 0.94 |
| 7-20-1971 | 1.37 | 0.0 | 0.0 | 2.59 | 0.46 | 1.12 | 4.32 | 0.15 | 0.13 | 1.75 |
| $\bar{x}$ | 0.94 | 0.52 | 0.63 | 0.88 | 0.48 | 0.91 | 1.09 | 0.72 | 0.77 | 0.74 |
| $\sigma^2$ | 2.25 | 0.49 | 0.44 | 1.27 | 0.83 | 5.57 | 3.26 | 0.61 | 1.26 | 1.10 |
| $\sigma$ | 1.50 | 0.70 | 0.66 | 1.12 | 0.92 | 2.36 | 1.80 | 0.78 | 1.12 | 1.05 |
| $C_v$ | 1.60 | 1.36 | 1.05 | 1.28 | 1.91 | 2.58 | 1.66 | 1.09 | 1.46 | 1.43 |

Table 11. Monthly rainfall data (cm) for Area 2 in New Mexico (contd).

| | Stations | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Date | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| May 1952 | 2.36 | 0.79 | 0.28 | 5.71 | 0.91 | 1.90 | 0.36 | 0.48 | 0.74 | 2.08 |
| June 1953 | 2.69 | 0.36 | 6.20 | 1.93 | 2.62 | 0.13 | 1.22 | 0.94 | 3.68 | 0.81 |
| Aug 1954 | 8.05 | 4.52 | 4.65 | 4.39 | 0.97 | 2.39 | 10.64 | 3.71 | 5.61 | 10.95 |
| Sept 1955 | 1.65 | 0.0 | 3.96 | 1.78 | 0.0 | 3.58 | 0.91 | 12.22 | 0.84 | 0.03 |
| Aug 1956 | 3.99 | 2.67 | 0.20 | 2.62 | 0.08 | 3.68 | 2.06 | 1.45 | 2.51 | 1.98 |
| Apr 1957 | 1.57 | 0.71 | 1.42 | 3.28 | 0.79 | 3.23 | 0.56 | 0.05 | 0.61 | 1.60 |
| May 1958 | 0.46 | 3.23 | 0.63 | 4.19 | 0.63 | 5.11 | 0.28 | 0.94 | 4.67 | 1.68 |
| July 1959 | 4.67 | 0.71 | 3.23 | 6.22 | 2.51 | 10.39 | 5.92 | 12.17 | 4.06 | 1.04 |
| June 1960 | 2.97 | 0.71 | 6.38 | 2.39 | 3.38 | 9.55 | 4.27 | 3.12 | 3.94 | 3.86 |
| Sept 1961 | 4.75 | 4.22 | 5.00 | 2.72 | 0.61 | 9.98 | 6.25 | 3.17 | 3.71 | 6.38 |
| Aug 1962 | 1.90 | 0.0 | 1.17 | 0.89 | 0.08 | 0.56 | 0.20 | 1.93 | 0.63 | 0.69 |
| May 1963 | 0.08 | 0.0 | 1.14 | 0.33 | 0.53 | 4.29 | 0.10 | 4.62 | 0.0 | 0.36 |
| Apr 1964 | 1.47 | 0.28 | 0.0 | 1.90 | 1.27 | 2.13 | 0.84 | 0.0 | 2.13 | 1.35 |
| June 1966 | 6.91 | 7.49 | 8.28 | 7.32 | 7.06 | 2.16 | 7.57 | 1.93 | 6.96 | 5.64 |
| Aug 1966 | 4.93 | 4.95 | 10.85 | 9.17 | 4.34 | 8.18 | 5.21 | 9.17 | 5.31 | 3.94 |
| July 1967 | 2.36 | 2.08 | 5.03 | 9.58 | 3.66 | 12.42 | 3.73 | 3.12 | 2.97 | 2.62 |
| May 1968 | 1.09 | 0.0 | 1.19 | 4.88 | 0.71 | 1.17 | 1.22 | 1.55 | 1.12 | 0.13 |
| Sept 1969 | 2.87 | 3.61 | 11.84 | 5.66 | 0.38 | 2.69 | 2.95 | 8.94 | 2.26 | 2.97 |
| Apr 1970 | 0.0 | 0.0 | 3.35 | 1.37 | 0.15 | 2.21 | 0.15 | 0.0 | 0.0 | 0.0 |
| July 1971 | 4.22 | 2.18 | 3.02 | 6.88 | 1.93 | 7.82 | 6.45 | 8.36 | 1.98 | 2.34 |
| $\bar{x}$ | 2.95 | 1.93 | 3.89 | 4.16 | 1.63 | 4.68 | 3.04 | 3.89 | 2.69 | 2.52 |
| $\sigma^2$ | 4.67 | 4.57 | 11.98 | 7.29 | 3.31 | 13.53 | 9.38 | 16.14 | 4.05 | 7.08 |
| $\sigma$ | 2.16 | 2.14 | 3.46 | 2.70 | 1.82 | 3.68 | 3.06 | 4.02 | 2.01 | 2.66 |
| $C_v$ | 0.73 | 1.11 | 0.89 | 0.65 | 1.12 | 0.79 | 1.01 | 1.03 | 0.75 | 1.06 |

Table 11. Monthly rainfall data (cm) for Area 2 in New Mexico.

| Date | Stations 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|
| May 1952 | 0.71 | 1.52 | 3.94 | 1.98 | 0.69 | 0.0 | 3.25 | 0.97 | 2.03 | 0.38 |
| June 1953 | 2.51 | 0.94 | 3.66 | 1.55 | 2.67 | 0.0 | 1.50 | 2.01 | 5.92 | 2.77 |
| Aug 1954 | 4.98 | 4.57 | 13.56 | 3.86 | 6.53 | 5.13 | 7.37 | 6.73 | 6.50 | 6.78 |
| Sept 1955 | 2.36 | 0.0 | 6.07 | 0.23 | 6.50 | 4.93 | 7.11 | 3.02 | 0.84 | 6.12 |
| Aug 1956 | 3.30 | 4.47 | 4.85 | 3.71 | 3.48 | 4.17 | 0.76 | 1.63 | 8.51 | 3.25 |
| Apr 1957 | 3.73 | 3.02 | 2.11 | 0.03 | 0.61 | 1.65 | 1.78 | 0.69 | 3.76 | 2.01 |
| May 1958 | 1.17 | 0.89 | 2.31 | 0.0 | 4.04 | 2.82 | 0.0 | 1.27 | 0.63 | 1.42 |
| July 1959 | 4.22 | 1.65 | 5.23 | 2.29 | 9.60 | 3.25 | 2.03 | 6.10 | 8.18 | 1.30 |
| June 1960 | 4.57 | 2.54 | 4.57 | 10.11 | 5.64 | 6.73 | 2.95 | 4.29 | 7.26 | 3.91 |
| Sept 1961 | 8.05 | 3.71 | 3.86 | 5.71 | 7.90 | 6.78 | 3.30 | 4.62 | 2.21 | 3.17 |
| Aug 1962 | 3.33 | 0.38 | 1.40 | 0.25 | 0.91 | 0.38 | 0.0 | 1.45 | 2.59 | 0.61 |
| May 1963 | 1.42 | 0.0 | 3.30 | 0.61 | 0.0 | 2.59 | 0.58 | 0.08 | 0.0 | 1.65 |
| Apr 1964 | 1.12 | 1.52 | 0.38 | 1.85 | 0.25 | 0.0 | 3.02 | 2.26 | 2.03 | 0.0 |
| June 1966 | 8.81 | 3.28 | 11.91 | 6.22 | 10.69 | 7.92 | 7.32 | 3.38 | 2.87 | 5.69 |
| Aug 1966 | 19.51 | 6.65 | 14.86 | 6.15 | 8.69 | 21.51 | 5.16 | 7.16 | 2.13 | 19.43 |
| July 1967 | 6.45 | 1.40 | 5.51 | 4.55 | 5.26 | 4.29 | 6.05 | 10.82 | 2.84 | 8.20 |
| May 1968 | 0.53 | 0.18 | 0.69 | 2.82 | 0.0 | 2.11 | 2.49 | 2.03 | 1.24 | 2.67 |
| Sept 1969 | 6.88 | 7.04 | 8.10 | 3.23 | 2.79 | 13.39 | 3.99 | 5.54 | 4.09 | 11.71 |
| Apr 1970 | 0.13 | 0.20 | 0.0 | 0.0 | 0.0 | 2.79 | 1.09 | 0.76 | 0.0 | 3.86 |
| July 1971 | 6.78 | 2.18 | 5.94 | 9.12 | 6.60 | 2.77 | 11.58 | 9.65 | 5.00 | 5.38 |
| $\bar{x}$ | 4.53 | 2.31 | 5.11 | 3.22 | 4.14 | 4.66 | 3.57 | 3.72 | 3.43 | 4.52 |
| $\sigma^2$ | 19.19 | 4.43 | 17.41 | 8.99 | 12.32 | 26.11 | 9.17 | 9.45 | 7.00 | 20.82 |
| $\sigma$ | 4.38 | 2.11 | 4.17 | 3.00 | 3.51 | 5.11 | 3.03 | 3.07 | 2.65 | 4.56 |
| $C_v$ | 0.97 | 0.91 | 0.82 | 0.93 | 0.85 | 1.10 | 0.85 | 0.83 | 0.77 | 1.01 |

Table 12. Yearly rainfall data (cm) for Area 2 in New Mexico (contd).

| Year | Stations 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1952 | 13.11 | 19.46 | 28.45 | 40.89 | 16.33 | 31.60 | 22.07 | 17.45 | 12.45 | 19.86 |
| 1953 | 15.24 | 10.57 | 19.28 | 35.56 | 14.88 | 25.58 | 26.87 | 22.48 | 23.98 | 16.10 |
| 1954 | 21.89 | 11.38 | 16.33 | 29.92 | 14.81 | 22.53 | 26.95 | 22.43 | 14.43 | 26.47 |
| 1955 | 25.04 | 14.81 | 26.57 | 24.49 | 15.14 | 28.12 | 15.11 | 38.81 | 9.88 | 12.95 |
| 1956 | 5.82 | 9.45 | 7.44 | 12.55 | 5.46 | 22.28 | 7.21 | 7.90 | 6.91 | 13.41 |
| 1958 | 28.73 | 39.29 | 43.66 | 42.14 | 22.02 | 37.82 | 27.66 | 33.53 | 32.51 | 33.27 |
| 1959 | 19.35 | 17.07 | 32.41 | 51.99 | 20.27 | 57.68 | 22.48 | 31.88 | 17.37 | 17.30 |
| 1960 | 21.74 | 17.04 | 57.02 | 45.85 | 25.43 | 55.09 | 18.29 | 39.57 | 15.11 | 25.20 |
| 1961 | 33.20 | 19.76 | 27.53 | 39.65 | 16.69 | 49.38 | 23.01 | 21.46 | 27.10 | 27.79 |
| 1962 | 32.08 | 24.99 | 32.92 | 31.42 | 14.78 | 30.94 | 27.86 | 31.60 | 23.62 | 34.52 |
| 1963 | 15.54 | 19.05 | 37.11 | 35.46 | 16.03 | 32.49 | 20.07 | 20.55 | 12.12 | 14.58 |
| 1964 | 14.68 | 20.52 | 15.49 | 27.10 | 14.63 | 24.69 | 15.04 | 14.94 | 17.25 | 17.63 |
| 1965 | 26.14 | 19.76 | 28.50 | 62.38 | 22.28 | 44.98 | 25.96 | 22.99 | 31.11 | 17.88 |
| 1966 | 23.98 | 22.56 | 25.48 | 28.98 | 17.25 | 19.56 | 24.46 | 25.60 | 26.77 | 18.26 |
| 1967 | 26.97 | 21.36 | 24.56 | 46.86 | 21.56 | 34.29 | 25.53 | 34.29 | 30.89 | 26.01 |
| 1968 | 99.53 | 36.22 | 37.41 | 41.02 | 28.35 | 22.45 | 23.52 | 36.19 | 20.52 | 19.02 |
| 1969 | 29.92 | 18.92 | 45.80 | 59.16 | 27.05 | 57.99 | 27.81 | 34.37 | 22.61 | 19.05 |
| 1970 | 22.86 | 14.02 | 30.07 | 28.96 | 8.99 | 17.81 | 18.24 | 18.72 | 15.95 | 17.60 |
| 1971 | 21.26 | 13.54 | 23.55 | 43.38 | 21.95 | 32.64 | 27.28 | 32.23 | 14.78 | 17.65 |
| $\overline{x}$ | 21.95 | 19.46 | 29.45 | 38.30 | 19.10 | 34.10 | 22.39 | 26.68 | 19.76 | 20.77 |
| $\sigma^2$ | 49.24 | 59.02 | 134.21 | 148.67 | 33.83 | 168.75 | 30.97 | 78.02 | 57.54 | 39.59 |
| $\sigma$ | 7.02 | 7.68 | 11.58 | 12.19 | 5.82 | 12.99 | 5.56 | 8.83 | 7.59 | 6.29 |
| $C_v$ | 0.32 | 0.39 | 0.39 | 0.32 | 0.32 | 0.38 | 0.25 | 0.33 | 0.38 | 0.30 |

Table 12. Yearly rainfall data (cm) for Area 2 in New Mexico.

| Year | Stations 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1952 | 33.30 | 16.05 | 30.02 | 25.04 | 32.00 | 26.92 | 33.35 | 36.40 | 31.62 | 30.12 |
| 1953 | 29.51 | 13.26 | 22.73 | 27.97 | 34.49 | 26.52 | 25.55 | 29.87 | 34.70 | 15.44 |
| 1954 | 37.06 | 13.84 | 28.57 | 12.88 | 36.22 | 32.16 | 22.22 | 24.31 | 30.76 | 28.57 |
| 1955 | 30.84 | 16.64 | 44.98 | 13.23 | 36.80 | 19.10 | 27.00 | 29.08 | 22.99 | 24.64 |
| 1956 | 25.10 | 15.80 | 21.72 | 12.37 | 23.80 | 13.69 | 14.91 | 15.90 | 20.37 | 14.88 |
| 1958 | 55.80 | 24.89 | 58.06 | 44.48 | 48.54 | 47.57 | 22.33 | 40.94 | 49.56 | 52.48 |
| 1959 | 43.43 | 16.66 | 26.49 | 22.78 | 40.03 | 32.77 | 31.72 | 47.14 | 36.32 | 32.99 |
| 1960 | 40.44 | 24.33 | 43.76 | 30.84 | 39.09 | 62.71 | 19.99 | 31.17 | 42.09 | 45.82 |
| 1961 | 52.88 | 20.88 | 32.74 | 31.62 | 30.81 | 36.04 | 22.25 | 36.45 | 32.33 | 28.88 |
| 1962 | 39.17 | 29.36 | 52.37 | 25.30 | 38.20 | 40.06 | 29.51 | 30.76 | 31.27 | 31.09 |
| 1963 | 27.08 | 11.81 | 40.06 | 23.47 | 22.53 | 29.64 | 25.98 | 33.81 | 28.47 | 23.93 |
| 1964 | 30.00 | 19.71 | 22.45 | 19.71 | 24.76 | 18.01 | 38.30 | 26.87 | 29.82 | 15.09 |
| 1965 | 39.88 | 19.48 | 35.64 | 36.58 | 39.04 | 28.55 | 44.91 | 41.45 | 41.81 | 36.30 |
| 1966 | 41.96 | 18.97 | 46.20 | 19.58 | 27.48 | 40.21 | 22.58 | 25.81 | 24.97 | 36.88 |
| 1967 | 35.18 | 29.18 | 29.08 | 35.64 | 28.65 | 29.51 | 31.32 | 46.89 | 30.10 | 25.83 |
| 1968 | 31.39 | 17.48 | 52.83 | 22.99 | 31.85 | 34.06 | 33.53 | 31.88 | 46.05 | 39.73 |
| 1969 | 51.64 | 24.10 | 47.98 | 45.19 | 35.79 | 58.57 | 57.84 | 44.50 | 43.54 | 54.38 |
| 1970 | 27.13 | 11.30 | 24.00 | 23.83 | 21.13 | 43.18 | 22.96 | 28.96 | 30.99 | 26.49 |
| 1971 | 38.02 | 19.89 | 34.47 | 31.39 | 33.81 | 28.17 | 37.64 | 44.83 | 31.90 | 39.73 |
| $\bar{x}$ | 37.36 | 19.14 | 36.54 | 26.57 | 32.90 | 34.08 | 29.68 | 34.05 | 33.65 | 31.75 |
| $\sigma^2$ | 79.93 | 20.21 | 132.64 | 90.53 | 49.23 | 160.00 | 100.44 | 72.84 | 61.14 | 129.97 |
| $\sigma$ | 8.94 | 5.31 | 11.52 | 9.51 | 7.02 | 12.65 | 10.02 | 8.53 | 7.82 | 11.40 |
| $C_v$ | 0.24 | 0.28 | 0.32 | 0.36 | 0.21 | 0.37 | 0.34 | 0.25 | 0.23 | 0.36 |

Table 13. Mean areal rainfall estimates by different methods.

Area 2 in New Mexico, daily totals (cm)

| Date | UM | GAAM | TP | AAM | TAM | MYER | ISO | TREN | | | RDS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | LIN | QUAD | CUB | |
| May 17, 1952 | .66 | .58 | .74 | 1.19 | .74 | .25 | .99 | .38 | .97 | .81 | .53 |
| June 17, 1953 | .69 | .91 | .66 | .51 | .66 | 1.30 | .71 | .71 | .63 | .56 | .71 |
| Aug 7, 1954 | 1.07 | .91 | .94 | .66 | .97 | 1.55 | .97 | 1.07 | .79 | .58 | .94 |
| Sep 25, 1955 | .94 | 1.02 | 1.14 | 1.30 | 1.02 | .89 | 1.17 | .91 | 1.27 | 1.55 | 1.19 |
| Aug 1, 1956 | .38 | .25 | .43 | .41 | .38 | .48 | .53 | .38 | .38 | .36 | .36 |
| Apr 29, 1957 | .56 | .43 | .53 | .48 | .56 | .84 | .71 | .51 | .48 | .58 | .51 |
| May 2, 1958 | .05 | .05 | .03 | .03 | .05 | .08 | .08 | .05 | .03 | -.03 | .03 |
| July 8, 1959 | .18 | .28 | .25 | .33 | .20 | .23 | .36 | .23 | .36 | .46 | .33 |
| June 10, 1960 | 1.12 | 1.12 | 1.07 | 1.09 | 1.04 | 1.22 | 1.30 | 1.12 | 1.07 | 1.32 | 1.09 |
| Sep 3, 1961 | .13 | .13 | .13 | .20 | .13 | .10 | .23 | .10 | .15 | .05 | .10 |
| Aug 21, 1962 | .25 | .25 | .23 | .28 | .20 | .25 | .30 | .25 | .18 | .05 | .20 |
| May 22, 1963 | .15 | .15 | .18 | .18 | .18 | .10 | .25 | .18 | .13 | .23 | .23 |
| Apr 4, 1964 | .81 | .71 | .66 | .58 | .74 | .86 | .79 | .69 | .53 | .86 | .58 |
| June 10, 1966 | .36 | .38 | .33 | .51 | .36 | .25 | 1.02 | .28 | .30 | .10 | .25 |
| Aug 2, 1966 | 1.68 | 1.37 | 1.40 | 1.88 | 1.63 | .89 | 1.80 | 1.75 | 1.73 | .38 | 1.57 |
| July 17, 1967 | .46 | .43 | .53 | .94 | .51 | .20 | .84 | .33 | .63 | .15 | .38 |
| May 12, 1968 | .81 | .89 | .76 | .97 | .81 | .58 | .91 | .76 | .97 | 1.19 | .84 |
| Sep 8, 1969 | .86 | 1.30 | 1.14 | 1.42 | .91 | 1.27 | 1.14 | 1.14 | 1.52 | 1.85 | 1.50 |
| Apr 18, 1970 | .36 | .51 | .36 | .23 | .38 | .58 | .48 | .43 | .18 | .10 | .43 |
| July 20, 1971 | 1.04 | 1.27 | 1.09 | 1.30 | 1.07 | .76 | 1.14 | .99 | 1.19 | 1.47 | 1.19 |
| $\bar{x}$ | .63 | .65 | .63 | .72 | .63 | .63 | .79 | .61 | .67 | .63 | .65 |
| $\sigma^2$ | .17 | .18 | .16 | .26 | .16 | .21 | .19 | .19 | .25 | .32 | .21 |
| $\sigma$ | .42 | .42 | .40 | .51 | .41 | .46 | .43 | .44 | .50 | .57 | .46 |
| $C_v$ | .67 | .65 | .63 | .70 | .65 | .72 | .55 | .72 | .73 | .90 | .71 |

Table 14. Mean areal rainfall estimates by different methods.

Area 2 in New Mexico, monthly total (cm)

| Month | UM | GAAM | TP | AAM | TAM | MYER | ISO | TREN | | | RDS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | LIN | QUAD | CUB | |
| May 1952 | 1.55 | 1.30 | 1.93 | 2.18 | 1.70 | 1.30 | 2.01 | 1.32 | 2.06 | 2.41 | 1.63 |
| Jun 1953 | 2.21 | 2.36 | 2.13 | 1.90 | 2.06 | 2.97 | 2.64 | 2.16 | 2.08 | 2.24 | 2.11 |
| Aug 1954 | 6.10 | 5.77 | 6.35 | 5.74 | 5.97 | 7.75 | 6.38 | 6.27 | 6.30 | 6.45 | 6.22 |
| Sep 1955 | 3.10 | 3.81 | 3.84 | 4.47 | 3.33 | 3.45 | 4.01 | 3.68 | 4.70 | 5.33 | 4.60 |
| Aug 1956 | 2.97 | 2.57 | 2.95 | 2.92 | 2.95 | 3.02 | 3.23 | 2.97 | 2.84 | 3.25 | 2.84 |
| Apr 1957 | 1.65 | 1.45 | 1.73 | 1.73 | 1.70 | 1.60 | 1.73 | 1.55 | 1.52 | 1.57 | 1.57 |
| May 1958 | 1.83 | 1.47 | 2.06 | 2.41 | 2.01 | 2.18 | 2.31 | 1.90 | 2.03 | 1.24 | 1.93 |
| Jul 1959 | 4.75 | 5.44 | 5.21 | 6.07 | 4.85 | 5.18 | 5.66 | 4.95 | 5.49 | 5.99 | 5.61 |
| Jun 1960 | 4.65 | 4.60 | 4.52 | 4.22 | 4.55 | 5.21 | 4.72 | 4.67 | 3.81 | 4.78 | 4.72 |
| Sep 1961 | 4.80 | 4.78 | 4.67 | 4.55 | 4.78 | 5.82 | 4.85 | 5.03 | 3.96 | 3.84 | 4.80 |
| Aug 1962 | 0.97 | 1.09 | 0.94 | 0.99 | 0.91 | 1.14 | 1.19 | 0.99 | 0.99 | 1.27 | 1.02 |
| May 1963 | 1.09 | 1.22 | 1.55 | 1.57 | 1.27 | 0.97 | 1.80 | 1.37 | 1.63 | 2.39 | 1.85 |
| Apr 1964 | 1.19 | 1.04 | 1.07 | 1.04 | 1.14 | 1.07 | 1.22 | 0.94 | 0.86 | 1.32 | 0.91 |
| Jun 1966 | 6.48 | 6.07 | 6.93 | 6.63 | 6.40 | 7.44 | 6.63 | 6.60 | 6.98 | 5.97 | 6.65 |
| Aug 1966 | 8.86 | 8.46 | 9.35 | 9.78 | 8.89 | 8.92 | 9.02 | 9.80 | 9.55 | 7.72 | 9.91 |
| Jul 1967 | 5.16 | 4.83 | 5.51 | 5.84 | 5.23 | 4.34 | 5.49 | 5.03 | 4.88 | 5.21 | 5.26 |
| May 1968 | 1.40 | 1.45 | 1.37 | 1.88 | 1.42 | 0.97 | 1.52 | 1.22 | 1.63 | 1.35 | 1.32 |
| Sep 1969 | 5.54 | 5.99 | 5.66 | 6.12 | 5.69 | 6.45 | 5.74 | 6.20 | 6.38 | 4.98 | 6.65 |
| Apr 1970 | 0.81 | 0.86 | 0.74 | 0.79 | 0.86 | 0.84 | 0.97 | 0.86 | 0.66 | 0.15 | 0.84 |
| Jul 1971 | 5.51 | 5.74 | 5.84 | 6.30 | 5.46 | 4.67 | 5.87 | 5.38 | 5.77 | 7.54 | 5.98 |
| $\bar{x}$ | 3.53 | 3.51 | 3.72 | 3.86 | 3.56 | 3.76 | 3.85 | 3.65 | 3.71 | 3.75 | 3.80 |
| $\sigma^2$ | 5.33 | 5.24 | 5.85 | 6.11 | 5.23 | 6.61 | 5.28 | 6.23 | 6.09 | 5.40 | 6.41 |
| $\sigma$ | 2.31 | 2.29 | 2.42 | 2.47 | 2.29 | 2.57 | 2.30 | 2.50 | 2.47 | 2.32 | 2.53 |
| $C_v$ | 0.65 | 0.65 | 0.65 | 0.64 | 0.64 | 0.68 | 0.60 | 0.68 | 0.67 | 0.62 | 0.68 |

Table 15. Mean areal rainfall estimates by different methods.

Area 2 in New Mexico, yearly totals (cm)

| Year | UM | GAAM | TP | AAM | TAM | MYER | ISO | TREN | | | RDS |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | LIN | QUAD | CUB | |
| 1952 | 25.83 | 24.87 | 26.90 | 28.22 | 25.96 | 26.03 | 27.48 | 25.53 | 26.42 | 25.53 | 26.16 |
| 1953 | 23.53 | 23.44 | 23.42 | 25.68 | 23.06 | 25.15 | 22.86 | 22.91 | 23.57 | 21.92 | 23.32 |
| 1954 | 23.70 | 23.16 | 23.85 | 25.17 | 23.37 | 26.72 | 23.95 | 24.05 | 24.18 | 21.18 | 24.03 |
| 1955 | 23.80 | 24.64 | 27.10 | 27.84 | 24.28 | 25.30 | 27.08 | 25.22 | 28.04 | 31.85 | 27.91 |
| 1956 | 13.84 | 12.12 | 14.88 | 14.50 | 13.82 | 14.66 | 14.48 | 14.17 | 13.36 | 15.11 | 14.43 |
| 1958 | 39.27 | 37.72 | 40.77 | 41.20 | 39.27 | 43.38 | 40.97 | 40.84 | 40.77 | 40.61 | 40.77 |
| 1959 | 30.91 | 30.99 | 32.11 | 35.20 | 31.37 | 30.28 | 32.44 | 30.66 | 31.06 | 30.43 | 31.93 |
| 1960 | 35.03 | 35.61 | 36.80 | 38.61 | 36.07 | 38.91 | 37.52 | 36.70 | 37.01 | 34.06 | 38.63 |
| 1961 | 30.53 | 29.44 | 30.48 | 31.32 | 30.40 | 31.85 | 31.98 | 30.38 | 28.37 | 29.46 | 30.12 |
| 1962 | 31.60 | 30.89 | 33.32 | 33.25 | 31.83 | 36.63 | 33.65 | 32.89 | 33.60 | 33.65 | 33.81 |
| 1963 | 24.49 | 24.23 | 26.64 | 26.85 | 24.99 | 24.66 | 27.79 | 24.89 | 26.49 | 27.33 | 26.57 |
| 1964 | 21.34 | 20.12 | 21.87 | 22.15 | 21.36 | 21.46 | 21.89 | 20.57 | 21.41 | 23.47 | 21.13 |
| 1965 | 33.27 | 31.93 | 34.44 | 37.62 | 33.40 | 31.78 | 34.14 | 31.58 | 34.04 | 34.01 | 32.82 |
| 1966 | 26.87 | 25.76 | 28.24 | 28.52 | 26.77 | 28.45 | 28.50 | 28.09 | 29.13 | 27.46 | 28.52 |
| 1967 | 30.68 | 30.63 | 30.73 | 33.53 | 30.61 | 32.03 | 31.88 | 30.00 | 31.14 | 31.11 | 30.48 |
| 1968 | 31.29 | 30.86 | 34.39 | 34.95 | 32.11 | 32.41 | 34.16 | 32.23 | 36.96 | 37.46 | 34.34 |
| 1969 | 40.31 | 39.45 | 41.96 | 43.92 | 40.79 | 37.59 | 40.61 | 40.03 | 41.50 | 43.05 | 42.19 |
| 1970 | 22.66 | 22.89 | 21.67 | 22.99 | 22.48 | 24.54 | 22.22 | 22.91 | 22.86 | 19.89 | 22.61 |
| 1971 | 29.41 | 29.16 | 30.56 | 32.79 | 29.16 | 28.02 | 30.48 | 29.11 | 30.66 | 31.90 | 30.28 |
| $\bar{x}$ | 28.33 | 27.78 | 29.48 | 30.75 | 28.48 | 29.47 | 29.69 | 28.58 | 29.50 | 29.45 | 29.48 |
| $\sigma^2$ | 41.63 | 42.16 | 46.29 | 52.08 | 43.74 | 45.36 | 45.87 | 43.91 | 49.02 | 51.71 | 48.24 |
| $\sigma$ | 6.45 | 6.49 | 6.80 | 7.22 | 6.61 | 6.73 | 6.77 | 6.63 | 7.00 | 7.19 | 6.95 |
| $C_v$ | .23 | .23 | .23 | .23 | .23 | .23 | .23 | .23 | .24 | .24 | .24 |

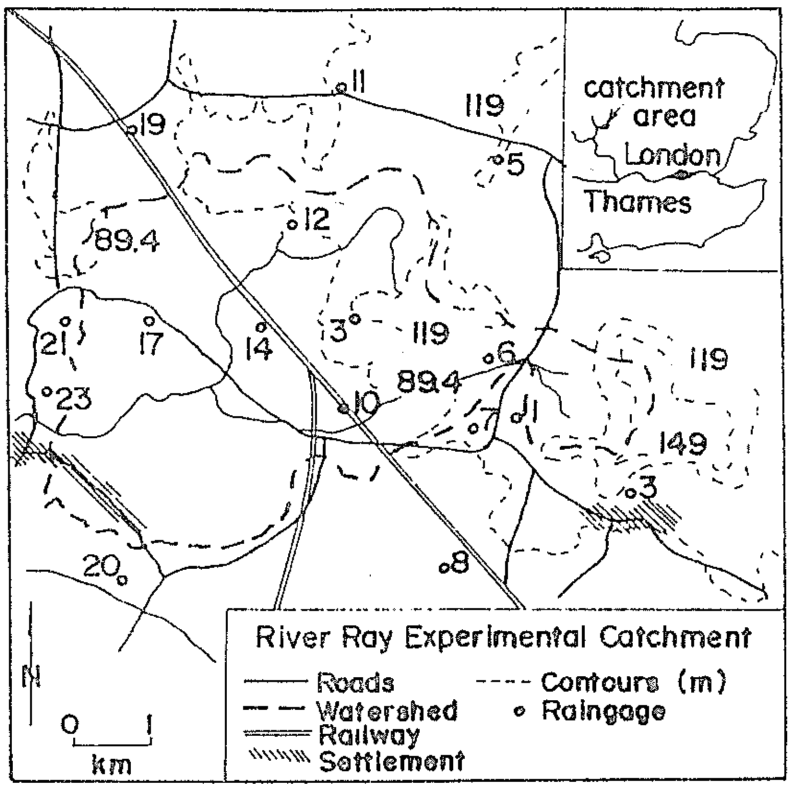



Fig. 13. Location and instrumentation of the River Ray catchment, Great Britain.

Table 16. Mean areal rainfall estimates by different methods (after Mandeville and Rodda, 1970).

River Ray catchment, daily totals (cm)

| Date | UM | TP | ISO | TREN LIN | TREN QUAD | TREN CUM |
|---|---|---|---|---|---|---|
| CONVECTIVE STORMS | | | | | | |
| 7-21-1964 | 5.87 | 6.30 | 6.60 | 5.87 | 6.81 | 6.25 |
| 7-14-1965 | 0.99 | 1.04 | 0.94 | 1.04 | 1.02 | 1.17 |
| 2-20-1966 | 0.94 | 0.94 | 0.94 | 0.94 | 0.94 | 0.97 |
| 6-16-1966 | 0.79 | 0.84 | 0.84 | 0.86 | 0.81 | 0.94 |
| 10-4-1968 | 0.61 | 0.64 | 0.64 | 0.64 | 0.64 | 0.58 |
| 3-21-1968 | 0.41 | 0.38 | 0.36 | 0.38 | 0.38 | 0.38 |
| 5-13-1968 | 0.56 | 0.56 | 0.53 | 0.53 | 0.56 | 0.58 |
| 8-9-1968 | 0.82 | 0.76 | 0.76 | 0.74 | 0.76 | 0.79 |
| $\bar{x}$ | 1.37 | 1.43 | 1.45 | 1.37 | 1.49 | 1.48 |
| $\sigma^2$ | 3.34 | 3.91 | 4.37 | 3.35 | 4.66 | 3.81 |
| $\sigma$ | 1.83 | 1.98 | 2.09 | 1.83 | 2.16 | 1.95 |
| $C_v$ | 1.33 | 1.38 | 1.44 | 1.33 | 1.45 | 1.34 |
| FRONTAL STORMS | | | | | | |
| 6-1-1964 | 1.35 | 1.30 | 1.27 | 1.27 | 1.30 | 1.30 |
| 4-26-1965 | 0.81 | 0.84 | 0.84 | 0.86 | 0.84 | 0.86 |
| 9-17-1965 | 0.66 | 0.66 | 0.64 | 0.66 | 0.64 | 0.66 |
| 1-21-1965 | 0.64 | 0.69 | 0.71 | 0.66 | 0.69 | 0.74 |
| 4-18-1966 | 1.24 | 1.24 | 1.22 | 1.24 | 1.24 | 1.30 |
| 10-2-1966 | 1.30 | 1.32 | 1.32 | 1.30 | 1.32 | 1.27 |
| 12-9-1966 | 1.65 | 1.58 | 1.73 | 1.68 | 1.70 | 1.73 |
| 5-14-1967 | 2.26 | 2.31 | 2.31 | 2.31 | 2.29 | 2.34 |
| $\bar{x}$ | 1.24 | 1.25 | 1.25 | 1.25 | 1.25 | 1.27 |
| $\sigma^2$ | .30 | .31 | .31 | .31 | .31 | .31 |
| $\sigma$ | .55 | .55 | .56 | .56 | .55 | .56 |
| $C_v$ | .44 | .44 | .45 | .45 | .44 | .44 |

Table 17. Mean areal rainfall estimates by different methods (after Mandeville and Rodda, 1970).

River Ray catchment, annual totals (cm)

| Year | UM | TP | ISO | TREN LIN | TREN QUAD | TREN CUB |
|---|---|---|---|---|---|---|
| 1963 | 60.20 | 59.54 | 62.56 | 59.64 | 59.46 | 60.17 |
| 1964 | 50.67 | 51.05 | 51.03 | 50.19 | 51.60 | 51.54 |
| 1965 | 70.10 | 69.72 | 69.27 | 69.16 | 69.32 | 69.88 |
| 1966 | 77.85 | 78.56 | 79.12 | 77.80 | 78.89 | 79.27 |
| 1967 | 69.99 | 68.83 | 68.43 | 68.94 | 68.66 | 68.76 |
| $\bar{x}$ | 65.76 | 65.53 | 66.07 | 65.15 | 65.58 | 65.91 |
| $\sigma^2$ | 110.38 | 110.94 | 106.16 | 108.38 | 108.38 | 110.45 |
| $\sigma$ | 10.51 | 10.53 | 10.30 | 10.41 | 10.41 | 10.51 |
| $C_v$ | 0.16 | .16 | .16 | .16 | .16 | .16 |

methods, Mandeville and Rodda (1970) reached a conclusion that has little support; that is, they concluded that complex TREN performed better, but the truth of the matter is that it did not, as clearly evidenced by Tables 16 and 17. This observation is supported further by work done in New Mexico, U.S.A., as elaborated previously. A complex TREN may be mathematically more attractive but its performance is no better than a simple TREN.

Application Example 4: River Rheidal Basin, Great Britain

This basin, as shown in Fig. 14 has an area of 146 $km^2$, and is equipped with 13 monthly storage gauges of the same dimensions as those in the Ray catchment. This example is also taken from the work done by Mandeville and Rodda (1970). By comparison with the Ray catchment, this basin is characterized by considerable rain and relief differences. In the absence of sufficient information, only four methods were applied to monthly rainfall values. The mean areal estimates of these methods are shown in Table 18. Statistical parameters are also given there. Results of Table 18 support the same observations made previously.

Application Example 5: Area in South Africa

This example is taken from the work done by Whitmore et al (1961) for an area in South Africa. No information is available on physiographic features of the area, rainfall characteristics and observation, and rain-gage network. The only quantitative information available is that seven different methods of estimating mean areal rainfall were applied to a yearly event, the results of which are as follows:

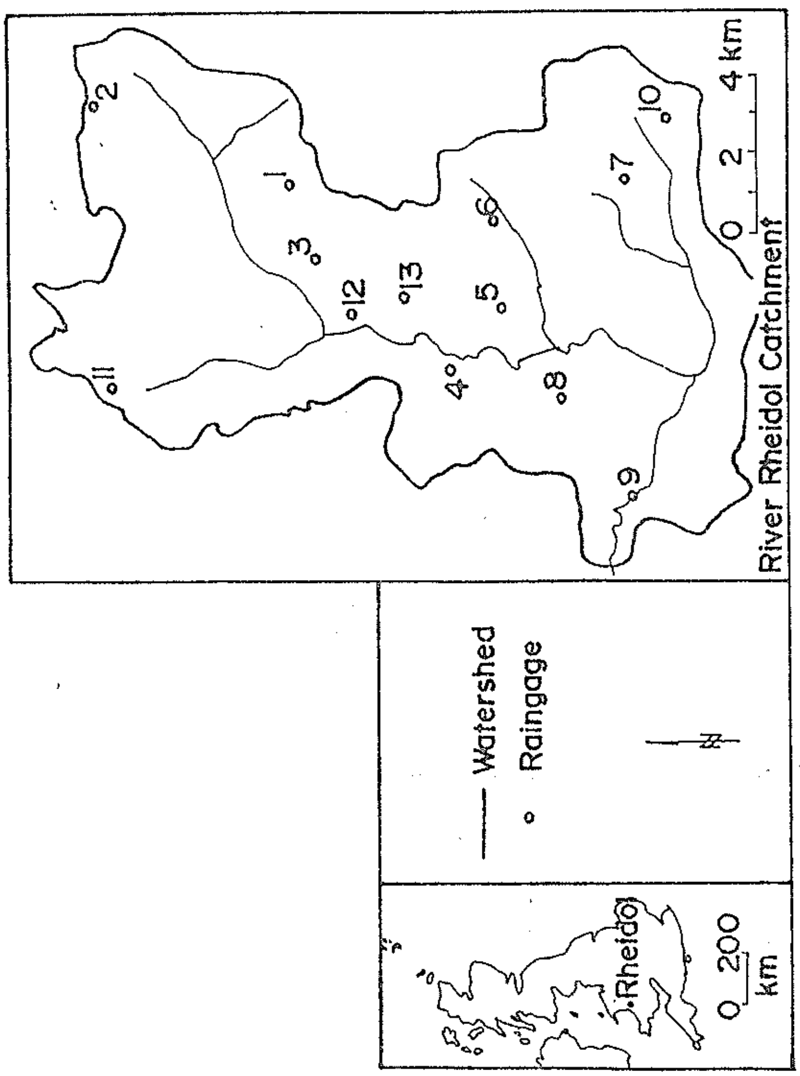



Fig. 14. River Rheidol raingage network Great Britain.

Table 18. Mean areal rainfall estimates by different methods (after Mandeville and Rodda, 1970).

River Rheidol basin, monthly totals (cm)

| Month | | UM | TP | ISO | TREN LIN | QUAD | CUB |
|---|---|---|---|---|---|---|---|
| Feb | 1966 | 15.54 | 15.98 | 16.69 | 15.37 | 15.70 | 18.69 |
| Mar | 1966 | 11.63 | 11.81 | 11.07 | 11.51 | 11.51 | 10.57 |
| Apr | 1966 | 12.01 | 12.07 | 11.30 | 11.89 | 12.75 | 10.00 |
| May | 1966 | 14.58 | 14.61 | 14.38 | 14.48 | 14.30 | 13.26 |
| June | 1966 | 22.76 | 22.83 | 21.74 | 22.56 | 22.63 | 21.92 |
| July | 1966 | 16.43 | 16.66 | 15.19 | 16.33 | 16.03 | 16.03 |
| Aug | 1966 | 9.63 | 9.32 | 9.91 | 9.58 | 9.88 | 8.20 |
| Sept | 1966 | 11.81 | 12.07 | 11.15 | 11.66 | 12.01 | 10.95 |
| Oct | 1966 | 17.25 | 16.99 | 16.36 | 17.25 | 16.56 | 16.76 |
| Nov | 1966 | 19.43 | 19.89 | 17.96 | 19.25 | 20.00 | 20.40 |
| Dec | 1966 | 40.84 | 40.67 | 40.82 | 40.54 | 39.40 | 37.03 |
| Jan | 1967 | 14.50 | 14.30 | 13.56 | 14.35 | 14.10 | 12.04 |
| Feb | 1967 | 16.56 | 16.48 | 15.67 | 16.38 | 16.33 | 14.20 |
| Mar | 1967 | 11.07 | 11.10 | 10.92 | 11.05 | 11.58 | 10.46 |
| Apr | 1967 | 8.94 | 8.61 | 7.75 | 8.86 | 8.56 | 6.73 |
| May | 1967 | 21.44 | 21.03 | 20.27 | 21.30 | 21.21 | 19.91 |
| June | 1967 | 8.28 | 7.98 | 7.92 | 8.26 | 8.20 | 6.25 |
| July | 1967 | 21.44 | 22.48 | 21.46 | 21.29 | 22.45 | 25.35 |
| Aug | 1967 | 18.00 | 17.81 | 17.70 | 17.83 | 17.20 | 18.82 |
| Sept | 1967 | 26.57 | 27.46 | 26.49 | 26.37 | 26.52 | 28.75 |
| Oct | 1967 | 39.57 | 40.08 | 39.42 | 39.17 | 38.89 | 38.35 |
| $\bar{x}$ | | 18.01 | 18.11 | 17.51 | 17.87 | 17.90 | 17.37 |
| $\sigma^2$ | | 77.66 | 102.88 | 104.96 | 99.20 | 95.57 | 104.48 |
| $\sigma$ | | 8.81 | 10.14 | 10.24 | 9.96 | 9.78 | 10.22 |
| $C_v$ | | .49 | .56 | .59 | .56 | .55 | .59 |

Annual totals (cm)

| WM | GAAM | TP | AAM | TAM | MYER | ISO |
|---|---|---|---|---|---|---|
| 65.7 | 59.6 | 61.0 | 61.0 | 63.3 | 65.6 | 61.3 |

This further indicates that results of all seven methods are comparable. WM and MYER, however, give slightly higher estimates. But on the basis of a single event a definitive conclusion cannot be reached.

In the wake of more of less identical performances of the methods one cannot make a strong argument for or against a given method. Nevertheless, all methods will be not equally suitable for all problems. For rapid computation of mean areal estimate, simple trend surface analysis may be preferable to time consuming graphical techniques. Unweighted mean method is simple, yields reasonable estimates if the raingage density is representative and if the spatial distributional characteristics of rainfall are close to homogeneous, and may be preferred to any other method. Simple graphical methods are useful when computer facilities are not available and when the use of unweighted mean is not advisable. The choice of a given method will be contigent upon the problem at hand. Nonetheless, a comparison criterion must consider: (a) accuracy of the method, (b) simplicity of the method, (c) data requirements of the method, (d) physiographic features of the area, (e) raingage network characteristics, (f) types of data available, and (g) above all, the problem at hand. Although choosing among method is a qualitative undertaking, it is not at all difficult to choose the right method for a given problem.

The identicality of performances of different methods leads one to ask: Has the evolution of these methods led to our increased understanding of space-time distributional characteristics of rainfall, or are they simply different alternatives? Although this question is of fundamental significance, its answer is not encouraging. Judging the methods on the basis of their performance one is bound to conclude that our understanding of space-time distributional characteristics of rainfall has not advanced much. If it has, one is forced to conclude that evolution of these methods has remained divorced from our increased understanding, although it is very unlikely. Then these methods can only be labelled as different alternatives to meet the same end.

## CONCLUSIONS

Nine different methods of estimating mean areal rainfall have been compared in five different hydrologic environments. These methods perform more or less identically. There is no particular basis to claim that one method is superior to the other, although in a given situation one method may be preferrable to another. The identicality of performances of the methods contradicts some of the beliefs advanced in the hydrologic literature.

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