Water Authority
of Western Australia

WATER RESOURCES DIRECTORATE

Rain Gauge Network Design For Bauxite Hydrology Research Catchments

Report No. WH 20

July 1986

Water Authority
of Western Australia

WATER RESOURCES DIRECTORATE

Hydrology Branch

Rain Gauge Network Design For Bauxite Hydrology Research Catchments

B.C. Bates

Report No. WH 20

July 1986

CONTENTS

PREFACE

This report describes the application of a rain gauge network design procedure to a bauxite research catchment (Yarragil 6C) in the south-west of Western Australia. The overall objective of the study was to gain an understanding of the network design required to estimate mean areal rainfall to a specified accuracy. Decisions could then be made as to appropriate network designs for the trial mining and control catchments to be established for the bauxite hydrology research programme.

A number of colleagues were involved at various stages of the project. The rainfall data described in this report were collected by K.R. Baldock, F. Davies, and K.F.F. Lewis. F. Davies was responsible for data processing, and G.W. Tyler, a vacation student from W.A.I.T., created many of the input data files and carried out several computer programme runs.

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1 Background

Bauxite mining began in the Darling Range in 1963 when Alcoa of Australia Limited opened a mine near Jarrahdale. To date Alcoa has confined its mining operations to the High Rainfall Zone (above 1100 mm mean annual rainfall).

Alcoa has made a legal undertaking not to begin routine mining in the eastern part of its mineral lease until hydrologic research has shown that bauxite mining operations would not result in an unacceptable increase in stream salinity. Most of the bauxite reserves within this part of the lease lie within the Intermediate Rainfall Zone (900 - 1100 mm mean annual rainfall).

Since the mid-1970's researchers have expressed the opinion that a trial mining experiment in the Intermediate Rainfall Zone would be necessary to assess the effects of bauxite mining on the hydrologic regime. Investigations for the selection of bauxite research catchments within this Zone have been underway since 1979. At present the proposed trial mining catchment is Yarragil North which is nested within the larger Yarragil 6C catchment.

Two major tasks within the bauxite research programme are the quantification of water balances and the modelling of hydrologic processes at the small catchment scale. Both of these tasks require precise estimates of areal rainfall if accurate results are to be obtained. Therefore, due consideration must be given to the rain gauge network designs for bauxite research catchments.

1.2 Study Objective

In 1985 a temporary pluviometer network was established in Yarragil 6C catchment to provide information for a permanent rain gauge network design. The main objective was to determine the number and placement of the pluviometers required to estimate mean areal rainfall to a specified accuracy.

1.3 Outline of Report

A survey of the literature pertinent to rain gauge networks revealed a number of alternative approaches to design. Section 2 presents a brief review of the various approaches and describes the adopted approach in some detail.

A description of the Yarragil 6C catchment and its instrumentation is given in Section 3. Details of the rainfall data and catchment stratifications utilised in the current study are also reported.

In Section 4 the results of rainfall variation analyses and network optimisations based on simple random and stratified random sampling are described. Curves relating number of rain gauges to specified levels of accuracy are presented, along with the optimal allocation of gauges to catchment subareas.

Finally, Section 5 discusses the implications of the rainfall variation analyses and makes recommendations on rain gauge network designs for the bauxite research catchments.

2. CATCHMENT RAIN GAUGE NETWORK DESIGN

2.1 General

The rainfall on a catchment as measured by a network of rain gauges is dependent on the network density. There is an upper limit for the number of gauges beyond which the measured mean rainfall will not change with an increase in network density.

The number and placement of rain gauges depend on the approach taken to network design, variability of rainfall, economics, required accuracy, access, and local site factors. Short-duration and small-area rainfall is generally more variable than long-duration and large-area rainfall, and thus has higher network density requirements for any given level of accuracy.

In any rational approach to network design, an initial period of measurement and analysis is needed prior to the establishment of a permanent network. This requires the operation of a temporary network to determine the variability of rainfall over the catchment. Once this variability has been assessed, statistical procedures can be used to decide the number of rain gauges needed for the required level of accuracy.

2.2 Approaches to Network Design

Several approaches to rain gauge network design have been proposed (Gray, 1970; Raudkivi, 1979). They include:

(i) saturation;
(ii) transposition;
(iii) simple random sampling (RS);
(iv) stratified random sampling (SRS); and
(v) complex stochastic analyses.

Saturation involves the installation of a very large number of gauges on the catchment so that the areal rainfall estimate approaches its true value. With the passage of time, the network can be reduced to a smaller number of gauges which provide estimates within specified confidence limits.

Transposition also involves the use of densely gauged catchments. If it is assumed that the rainfall characteristics of the study catchment are similar to a nearby densely gauged catchment, experience gained from the latter can be incorporated into the new network design.

Clearly, saturation is neither feasible nor practical in land use change studies involving forested catchments. Transposition is also unfeasible for the problem at hand since no densely gauged networks exist in the Intermediate Rainfall Zone.

Simple random sampling involves the assumption that the gauge locations in the temporary network have been selected purely by chance. The sample is considered to be unbiased, independent and homogeneous. To prevent bias the sample must be as representative as possible of the total population of rain gauge sites. However, problems with accessibility, local site factors and rainfall variability often affect the applicability of this approach.

Stratified random sampling (SRS) involves the splitting of the total population into several non-overlapping sub-populations, called strata. If from each of these strata random samples are drawn, the resulting pooled sample is called a stratified random sample (Cochran, 1977). SRS has several notable features:

(i) a heterogeneous population can be divided into strata that are internally more homogeneous;

(ii) if each stratum is homogeneous in that the measurements vary little from one gauge to another, a precise estimate of any stratum mean can be obtained from a small sample in that stratum; and

(iii) stratification may produce a gain in the precision of the estimate of the population mean.

Barnett (1974) states that the stratified sample mean (SSM) will be more efficient (in the sense of having a smaller variance) than the simple random sample mean (RSM) if the variation between the stratum means is sufficiently large compared with within-strata variation. The greater this advantage, the greater the efficiency of the SSM relative to the RSM. However, Barnett also warns that the SSM is not necessarily more efficient than the RSM in all situations.

Rodriguez-Iturbe and Mejia (1974) have proposed a detailed stochastic approach to network design. In this approach the rainfall process is viewed as a multidimensional random field, and the variance of the sample is expressed as a function of spatial and temporal correlation, the number of gauges and the network geometry. Unfortunately, the analysis involves more than a passing knowledge of the theory of stochastic processes, and there was insufficient time for the relevant knowledge to be acquired.

Of the above alternatives it would appear that the only feasible approaches to the current problem are RS and SRS. Consequently, RS and SRS are used in the present study.

2.3 Adopted Approach

Shih (1982) has developed a methodology for rain gauge network design based on SRS and the Neyman or optimum allocation principle (see Deming, 1950; Hald, 1952; Barnett, 1974; Cochran, 1977). The methodology can be used to:

(i) compute the mean areal rainfall and its variance;

(ii) calculate a stratum weighted ratio for the optimum allocation of rain gauges to the strata; and

(iii) determine the number of gauges needed to estimate mean areal rainfall with a desired level of statistical accuracy.

The catchment is split into strata denoting areas of hydrologic homogeneity. These areas should be relatively uniform with respect to vegetation, climate, topography, storm tracks, and isohyetal zones. (Note that the number of strata will become prohibitive if stratification is made according to all aspects of these features). A temporary network is established by installing at least two gauges within each stratum. This permits the estimation of the within-stratum variance (Kish, 1965; Barnett, 1974; Jessen, 1978). The network is then operated over a fixed period of time and a rainfall variation analysis applied to the collected rainfall data.

Adopting the notation used by Shih (1982), the stratified mean areal rainfall for any given time interval is given by

$$\bar{x} = \sum_{i=1}^{n} w_i \bar{x}_i \qquad (1)$$

where n is the number of strata, $\bar{x}_i$ is the mean rainfall for the ith stratum, and w_i is the weight of the ith stratum defined by

$$w_i = A_i / A \qquad (2)$$

in which A_i is the area of the ith stratum and A is the total catchment area. Note that:

$$\sum_{i=1}^{n} w_i = 1$$

The estimated variance of the mean rainfall is

$$s^2(\bar{x}) = \underbrace{\frac{1}{N}\left[\sum_{i=1}^{n} w_i\,(\bar{s}^2_{oi} - \bar{s}_{okli})^{1/2}\right]^2}_{s^2_r(\bar{x})}$$

$$\underbrace{+ \sum_{i=1}^{n} w_i^2\,\bar{s}_{okli} + 2\sum_{i=1}^{n}\sum_{\substack{j=1\\ i>j}}^{n} w_i\,w_j\,\bar{s}_{oklij}}_{s^2_c(\bar{x})} \qquad (3)$$

where N is the total number of rain gauges, $\bar{s}^2_{oi}$ is the estimated average variance within the ith stratum, $\bar{s}_{okli}$ is the estimated average covariance of the ith stratum, $\bar{s}_{oklij}$ is the estimated average covariance between the ith and jth strata, and k and l are gauge indices. Equation 3 assures minimum variance of the mean rainfall for optimum allocation of rain gauges to the strata. The interested reader is referred to Shih (1982) for the computational details.

Equation 3 may be written as

$$s^2(\bar{x}) = s^2_r(\bar{x}) + s^2_c(\bar{x}) \qquad (4)$$

where $s^2_r(\bar{x})$ is called the relative variance and $s^2_c(\bar{x})$ the spatial variation. Note that only $s_r(\bar{x})$ is affected by the number of gauges, and thus is the only component of $s^2(\bar{x})$ that can be reduced by increasing the network density. In contrast, $s_c(\bar{x})$ is independent of N and is thus considered to be a part of the catchment hydrologic characteristics.

Shih (1982) has also devised a stratum weighted ratio (C) for allocating gauges to strata. For the ith stratum

$$c_i = w_i\,(\bar{s}^2_{oi} - \bar{s}_{okli})^{1/2} / \sum_{j=1}^{n} w_j(\bar{s}^2_{oj} - \bar{s}_{oklj})^{1/2} \qquad (5)$$

Equation 5 indicates that the influence of the network density on the accuracy of the mean rainfall estimation is a function of the basin area size, the degree of rainfall variation at each gauge and the covariance between gauges. Note that

$\Sigma c_i = 1$, and that $c_i = w_i$ when the $(\bar{s}^2_{oj} - \bar{s}_{oklj})$ are all equal.

The number of rain gauges required in the catchment is derived from the t-statistic

$$t_{\alpha,N-1} = |\bar{x} - \mu| \; / \; s_r(\bar{x}) \qquad (6)$$

where α is the chosen level of significance and μ denotes the population mean.

Rearrangement of eq. 5 gives

$$s_r(\bar{x}) \; t_{\alpha,N-1} = \bar{x}\frac{|\bar{x} - \mu|}{\bar{x}} = \bar{x}\beta \qquad (7)$$

where β is called the desired degree of accuracy (see also Walpole and Myers, 1985). Shih (1982) describes α and β as desired levels of statistical accuracy.

It follows from eq. 7 for any given α, N, $\bar{x}$ and $s_r(\bar{x})$ that:

$$\beta = s_r(\bar{x}) t_{\alpha,N-1} \; / \; \bar{x} \qquad (8)$$

Hence eq. 8 can be used to determine N versus β curves for various levels of significance, (see Section 4.3).

For simple random sampling, the simple random sample mean is given by

$$\bar{x} = \frac{1}{N} \sum_{i=1}^{n} \bar{x}_i \qquad (9)$$

where $\bar{x}_i$ now denotes the mean rainfall for the ith gauge, and its variance by

$$s^2(\bar{x}) = \frac{1}{\bar{N}} (\bar{s}_o^2 - \bar{s}_{okl}) + \bar{s}_{okl} \qquad (10)$$

where $\bar{s}_o^2$ and $\bar{s}_{okl}$ are the average variances and covariances of rainfall for the N gauges, respectively.

Shih (1982) appears to adopt the convention of setting ß equal to α in the analysis. Rain gauge network designs are classified according to three different levels of statistical accuracy, (see Table 1). Shih recommends that the chosen level of confidence should not be less that 80% as the accuracy of the estimated mean rainfall will be poor. Also, levels in excess of 95% should not be used since a large increase in the network density at these levels will be required to produce a marginal improvement in the precision of the mean rainfall estimate.

TABLE 1

SHIH CLASSIFICATION SYSTEM FOR
RAIN GAUGE NETWORK DESIGNS
(Shih, 1982)

Range of α,ß values (α = ß)	Level of Confidence (percent)	Classification
0.12 to 0.2	88 to 80	low density
0.08 to 0.12	92 to 88	medium density
0.05 to 0.08	95 to 92	high density

2.4 Computer Programme - RSNET

A computer programme (RSNET) to carry out Shih's analysis was written in FORTRAN IV and implemented on the CYBER 180/825 computer operated by the Main Roads Department, Western Australia. A brief description of the programme and a worked example are given in Appendix A.

3. DESCRIPTION OF CATCHMENT AND DATA

3.1 Catchment Description

Yarragil 6C catchment (AWRC No. 614049) is located about 100 km south-east of Perth, (see Figure 1). Average annual rainfall and pan evaporation are approximately 1050 mm and 1600 mm, respectively. The catchment has an area of 4.6 km^2 and is covered principally by jarrah-marri forest. Lateritic gravels, sands, orange earths, and mottled clays are the major soil types. Figure 2 shows a topographic map of the catchment.

3.2 Instrumentation

The current rain gauge network on Yarragil 6C consists of four pluviometers located within the catchment boundary, (see Figure 2). Pluviometers were installed since the use of the daily read storage gauges was considered impractical for Perth-based hydrographic staff. The pluviometers use the tipping-bucket principle and are coupled with UNIDATA 64k-byte solid-state data loggers. Bulk rainfalls are recorded by the loggers at five minute time intervals. The pluviometer network commenced operation in July 1985.

Stream levels at the catchment outlet are monitored by a float-driven continuous LEUPOLD AND STEVENS graphical recorder. The control section consists of a V-notch weir installed by the Forests Department (now Department of Conservation and Land Management, CALM) in 1976.

Groundwater levels are currently monitored at nine ordinary observation bores operated by Alcoa and CALM and one multiport piezometer.

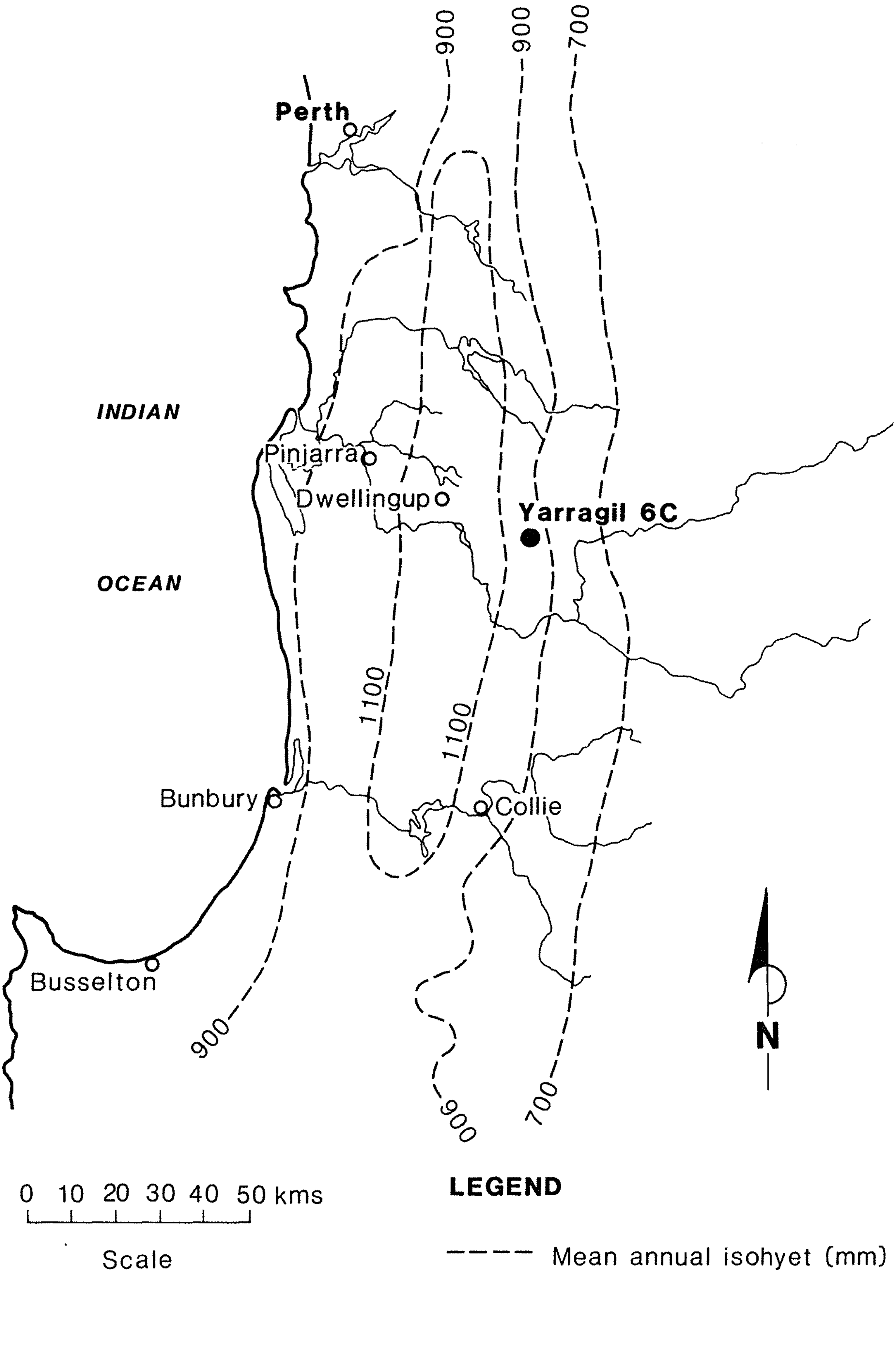
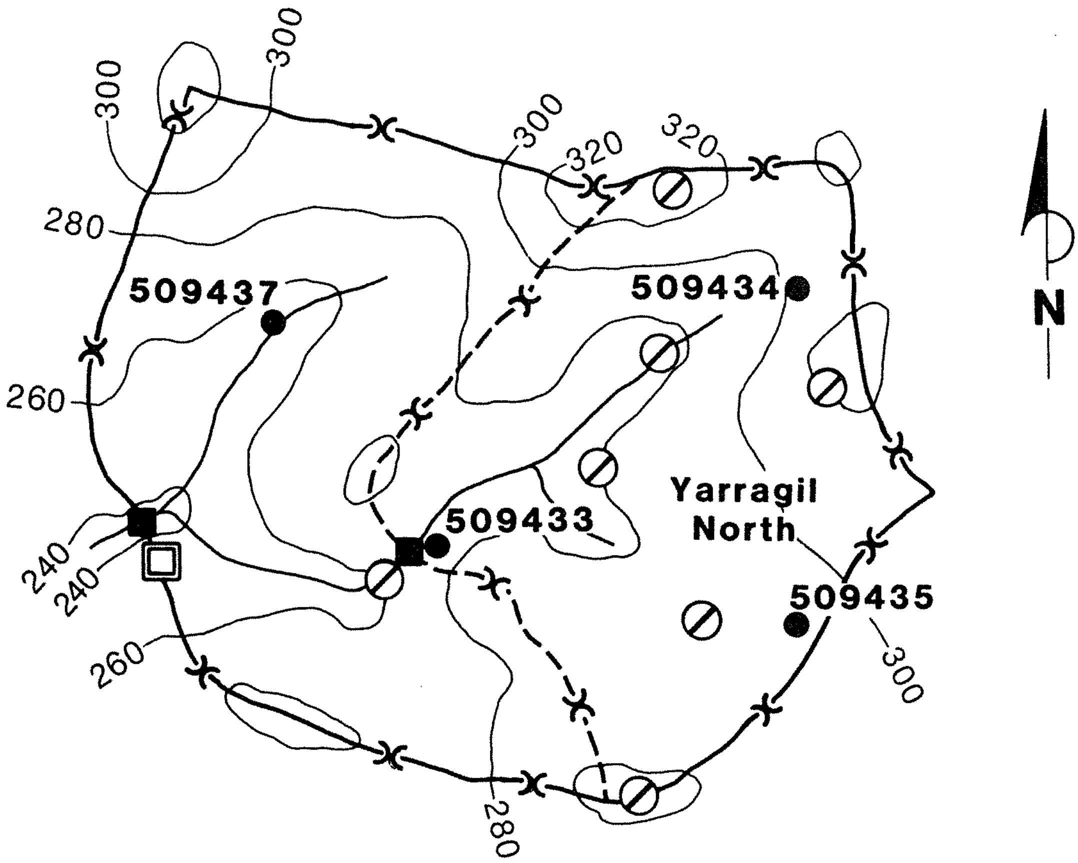


Fig. 1 Locality Map of Yarragil 6C Catchment



LEGEND

- ● Pluviometer
- ■ Gauging station
- ⊘ Alcoa Piezometer
- ▣ Multiport piezometer

0 0.5 1 1.5 2 kms

Scale

Fig. 2 Instrumentation and Topography, Yarragil 6C Catchment

3.3 Rainfall Data

Rainfall data for 65 rain-days between July and October 1985 were utilised in the study. Emphasis was placed on daily data since this is the time interval that is likely to be adopted in deterministic catchment modelling. In addition, the estimation of mean areal rainfall for a longer time interval generally has lower network density requirements for a given level of statistical accuracy (Shih, 1982).

Table 2 summarises the daily rainfall data for each pluviometer. Observe that the mean daily rainfall for the pluviometers are quite similar. However, comparison of the means does not give complete information. Investigations revealed that the percent difference between the maximum and minimum gauged rainfall for any given rain-day often exceeded 20 percent. Moreover, the maximum percent difference between maximum and minimum rainfalls greater than 10 mm was 25 percent. Thus the need for a rainfall variation analysis is apparent.

TABLE 2

DAILY RAINFALL DATA FOR 65 RAIN-DAYS
DURING JULY-OCTOBER, 1985

Quantity	Pluviometer No. *			
	509433	509434	509435	509437
Total	340.9	319.1	334.3	343.7
Mean	5.2	4.9	5.1	5.3
Minimum	0.	0.	0.	0.
Maximum	36.6	32.7	36.7	38.7

* see Fig. 2 for pluviometer locations

Further investigation showed that the largest spatial variations in gauge catch occurred during trace rainfalls (i.e., maximum daily catch less than 1 mm). This suggests that trace rainfalls may have an unwarranted effect on the rainfall variation analysis.

Table 3 reports the number of rain-days available when the maximum catch for any given rain-day is required to be greater than a certain threshold. Observe the large reduction in the sample size for thresholds greater than or equal to 1 mm. Since the analysis described in Section 2.3 uses linear statistical theory, it was decided that the sample should be at least moderate in size. Hence two analyses were carried out using the daily rainfall data sets corresponding to thresholds of 0 and 2 mm.

TABLE 3

STRUCTURE OF DAILY RAINFALL DATA

Threshold (mm)	Number of Raindays
0.	65
1.0	37
2.0	32
5.0	20

3.4 Strata Determination

Strata determination requires decisions on the number of strata and the location of strata boundaries. Clearly, Yarragil 6C can only be divided into two strata if unbiased estimates of the sampling errors are required. However, the appropriate position for the boundary between these strata is less certain.

Figure 3 shows the four alternative boundaries considered in the present study. Boundaries A-A and D-D were selected because of the general orientations of storm tracks and frontal rains. Boundary B-B coincides with the 280 m A.H.D. contour on the catchment. Field inspections revealed that this boundary divides the catchment into two subareas that are reasonably uniform with respect to vegetation and topography. In contrast, boundary C-C was selected solely on the basis of changing the pluviometers allocated to each stratum, (see Table 4).

In this study, the best catchment subdivision was considered to be the one which produced the most precise mean areal rainfall estimate. That is, the boundary which led to the smallest values of $s^2(\bar{x})$ and $s_r(\bar{x})$.

TABLE 4

ALLOCATION OF PLUVIOMETERS TO STRATA

	Pluviometer Numbers			
Boundary	Stratum 1		Stratum 2	
A-A	509433	509437	509434	509435
B-B	509433	509437	509434	509435
C-C	509433	509435	509434	509437
D-D	509433	509437	509434	509435

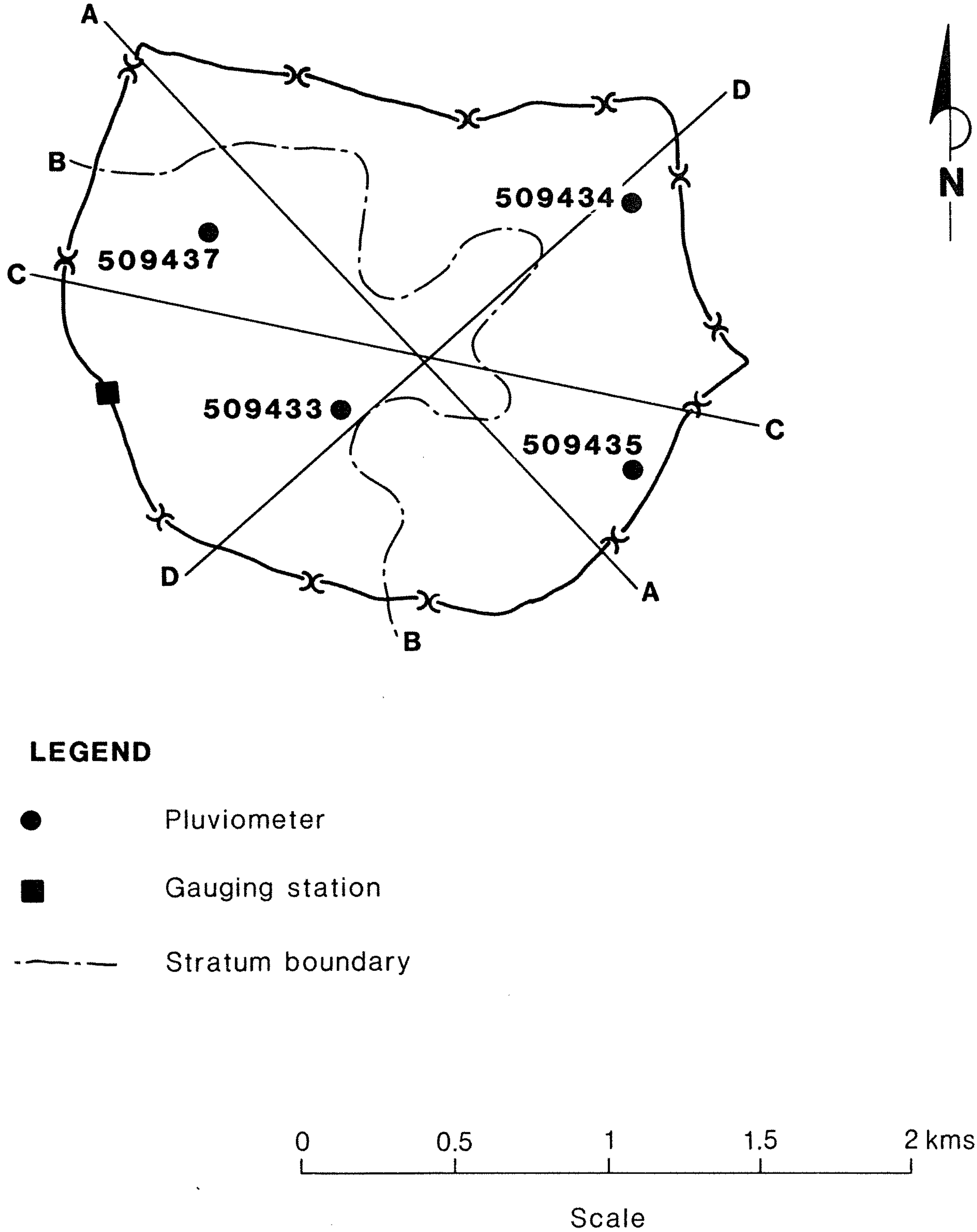


Fig. 3 Catchment Stratification, Yarragil 6C Catchment

4. RESULTS

4.1 Stratum Determination

Tables 5a and b report the stratified means and variances for the 65 and 32 rain-day data sets (designated hereafter as sets A and B), respectively. Observe the close agreement between the values of these measures, suggesting that the recorded rainfalls were fairly uniform over the catchment. Close inspection of the results revealed that the stratification based on boundary B-B gave estimates that were marginally (but not significantly) more precise that the estimates based on the other stratifications. Hence the stratified means and variances based on boundary B-B were adopted for all subsequent comparisons and analyses.

4.2 Comparison of Sampling Techniques

Table 6 compares the estimated means and variances obtained by RS and SRS. Observe that SRS is noticeably superior to RS for set A, and that the methods give similar results for set B. This suggests that the inclusion of trace rainfalls in a particular data set can affect the results of a rainfall variation analysis.

TABLE 5a

EFFECT OF STRATUM BOUNDARY ON THE PRECISION
OF MEAN DAILY RAINFALL ESTIMATES - DATA SET A

Statistical	Stratum	Boundary		
Measure	A - A	B - B	C - C	D - D
$\bar{x}$	5.1	5.1	5.1	5.2
$s_r(\bar{x})$	0.3	0.3	0.4	0.3
$s_c(\bar{x})$	8.1	8.1	8.1	8.1

TABLE 5b

EFFECT OF STRATUM BOUNDARY ON THE PRECISION OF MEAN DAILY RAINFALL ESTIMATES - DATA SET B

Statistical Measure	Stratum Boundary			
	A - A	B - B	C - C	D - D
$\bar{x}$	10.2	10.2	10.2	10.2
$s_r(\bar{x})$	0.5	0.5	0.5	0.5
$s_c(\bar{x})$	9.1	9.1	9.1	9.2

TABLE 6

COMPARISON OF SAMPLING TECHNIQUES

Statistical Measure	Data Set A		Data Set B	
	RS	SRS	RS	SRS
$\bar{x}$	5.1	5.1	10.2	10.2
$s_r(\bar{x})$	0.4	0.3	0.5	0.5
$s_c(\bar{x})$	8.1	8.1	9.1	9.1

4.3 Adequacy of Current Pluviometer Network

Figures 4 and 5 show β-α curves for data sets A and B, respectively. The Figures also show the line corresponding to Shih's convention of setting β equal to α. Observe that the levels of statistical accuracy indicated by the analyses of sets A and B are approximately 0.13 and 0.10, respectively. Hence the first analysis suggests that the current pluviometer network constitutes a low density design while the second indicates a medium density design. Clearly, the inclusion of trace rainfalls in the rainfall variation analysis has adversely affected the assessment of the level of statistical accuracy provided by the current network.

Figures 6 and 7 show N-β-α curves for sets A and B, respectively. Table 7 summarises the pertinent information. Inspection of the Table reveals that the density requirements suggested by set A for different levels of accuracy are higher than those suggested by set B. This indicates that the inclusion of trace rainfalls in the network optimisation can have a considerable effect on the number of gauges required to achieve a specified statistical accuracy, particularly for high levels of confidence. Notice also the relatively large number of gauges required to achieve a 0.05 level of accuracy.

Table 7 also reports the number of gauges required to estimate mean weekly rainfall to certain levels of statistical accuracy. Note that, as expected, the required number of gauges for a given level of statistical accuracy is generally less than that required for mean daily rainfall estimates. However, the required number of gauges is based on a small sample size (13 rain-weeks), and thus must be adopted with some degree of caution.

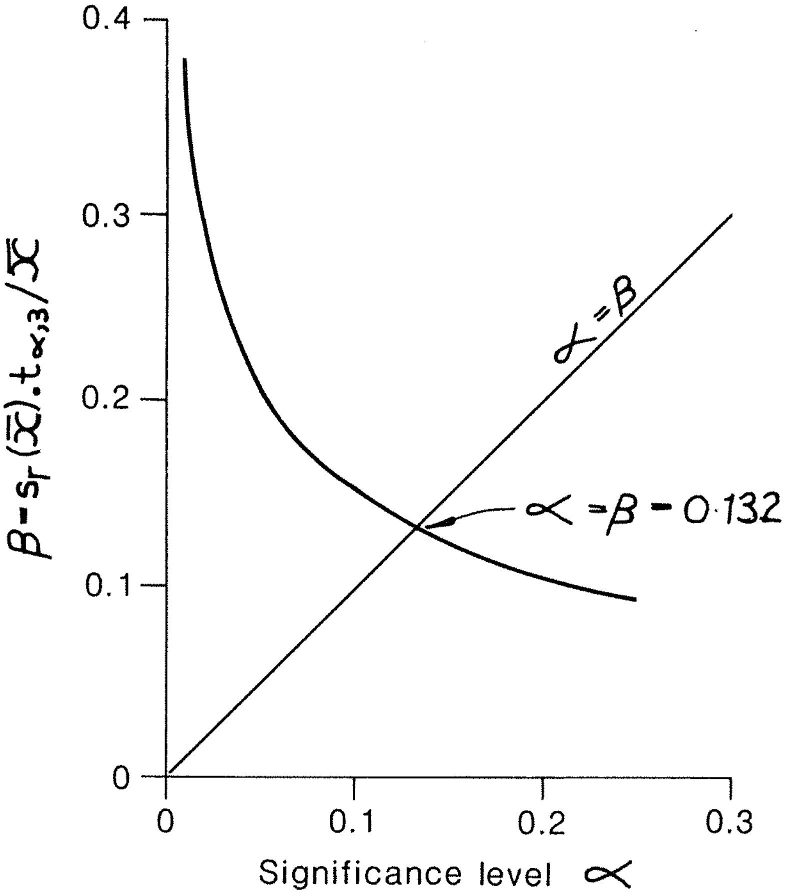


Fig. 4 β-α Curves for Data Set A

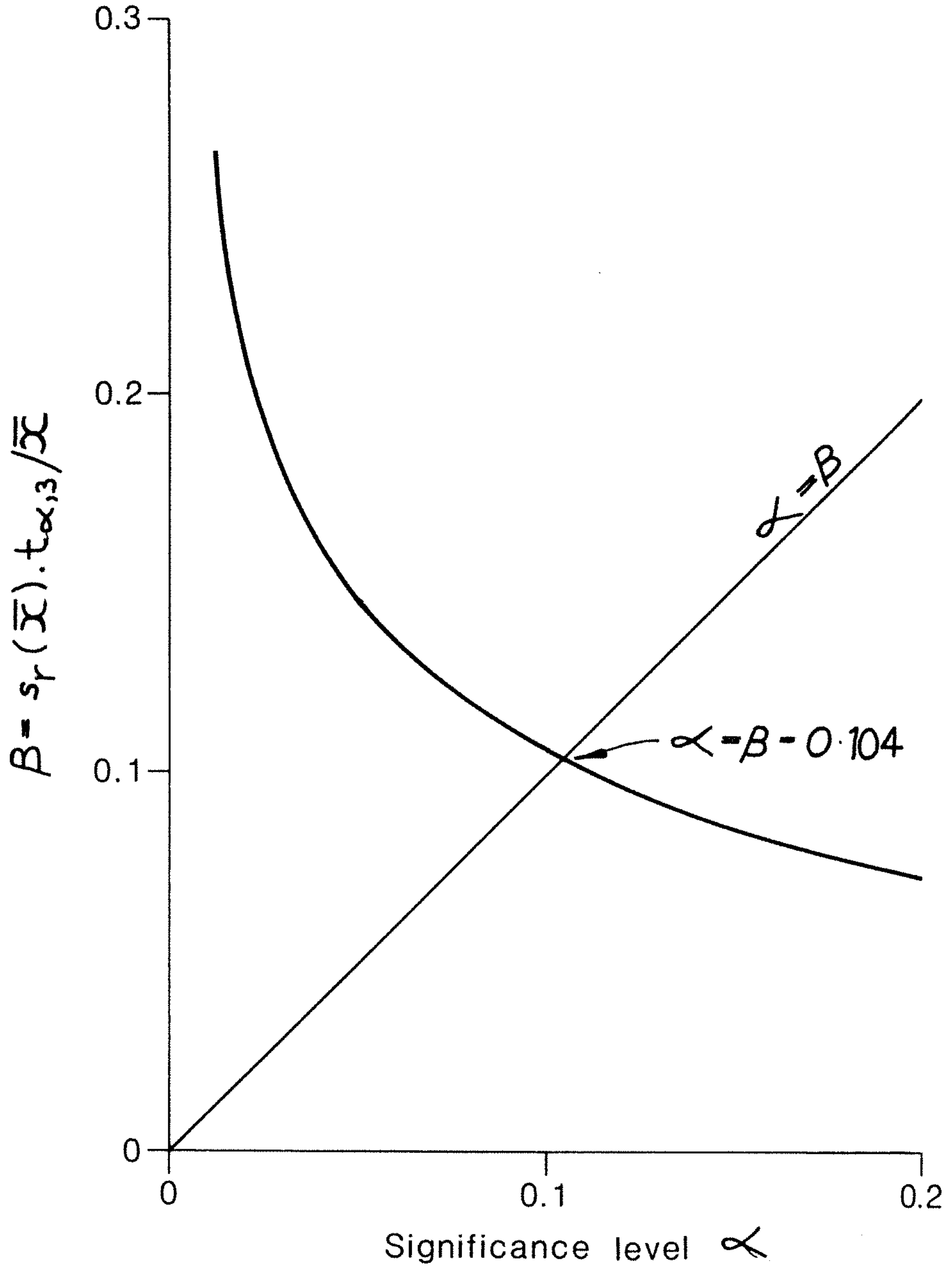


Fig. 5 β-α **Curves for Data Set B**

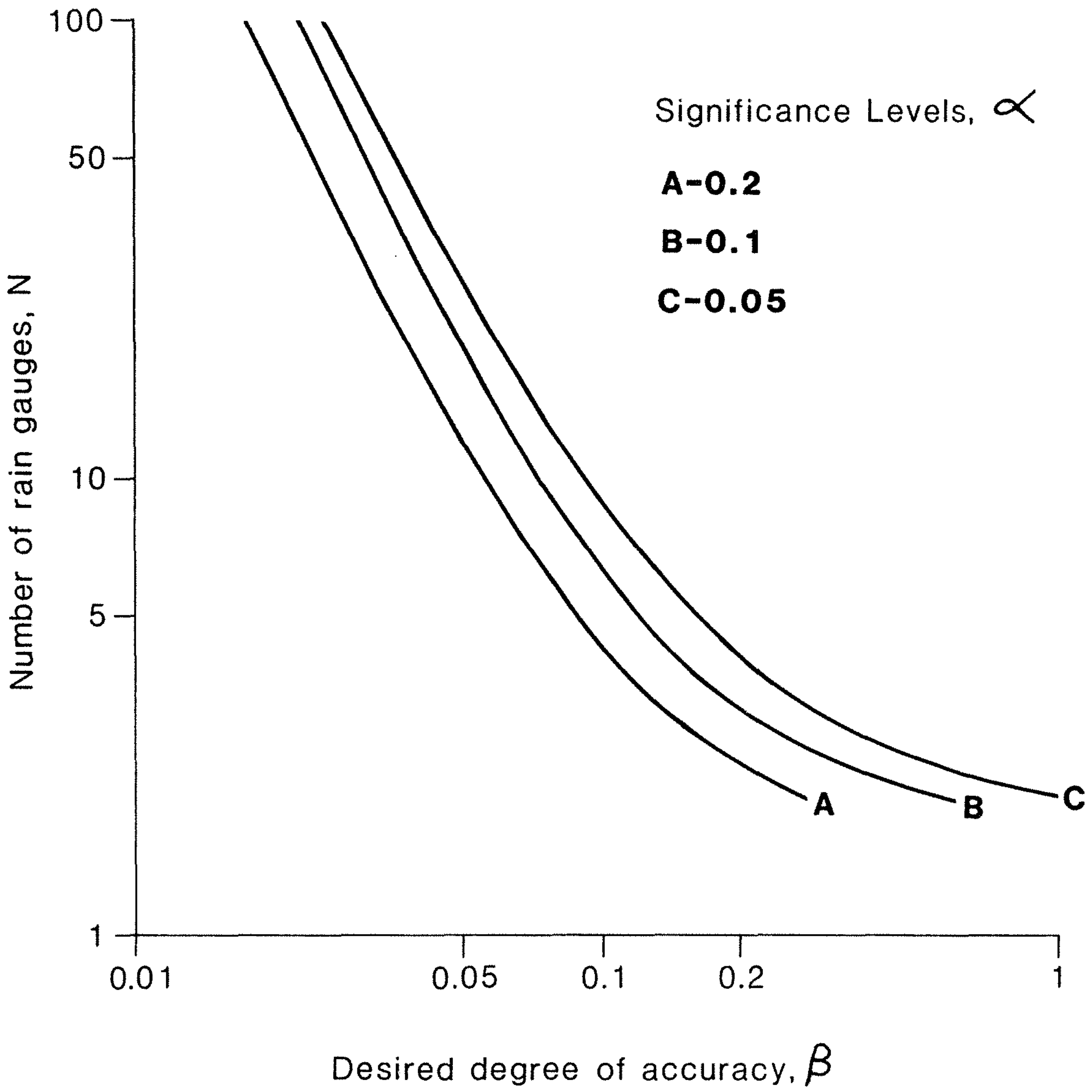


Fig.6 N-β-α Curves for Data Set A

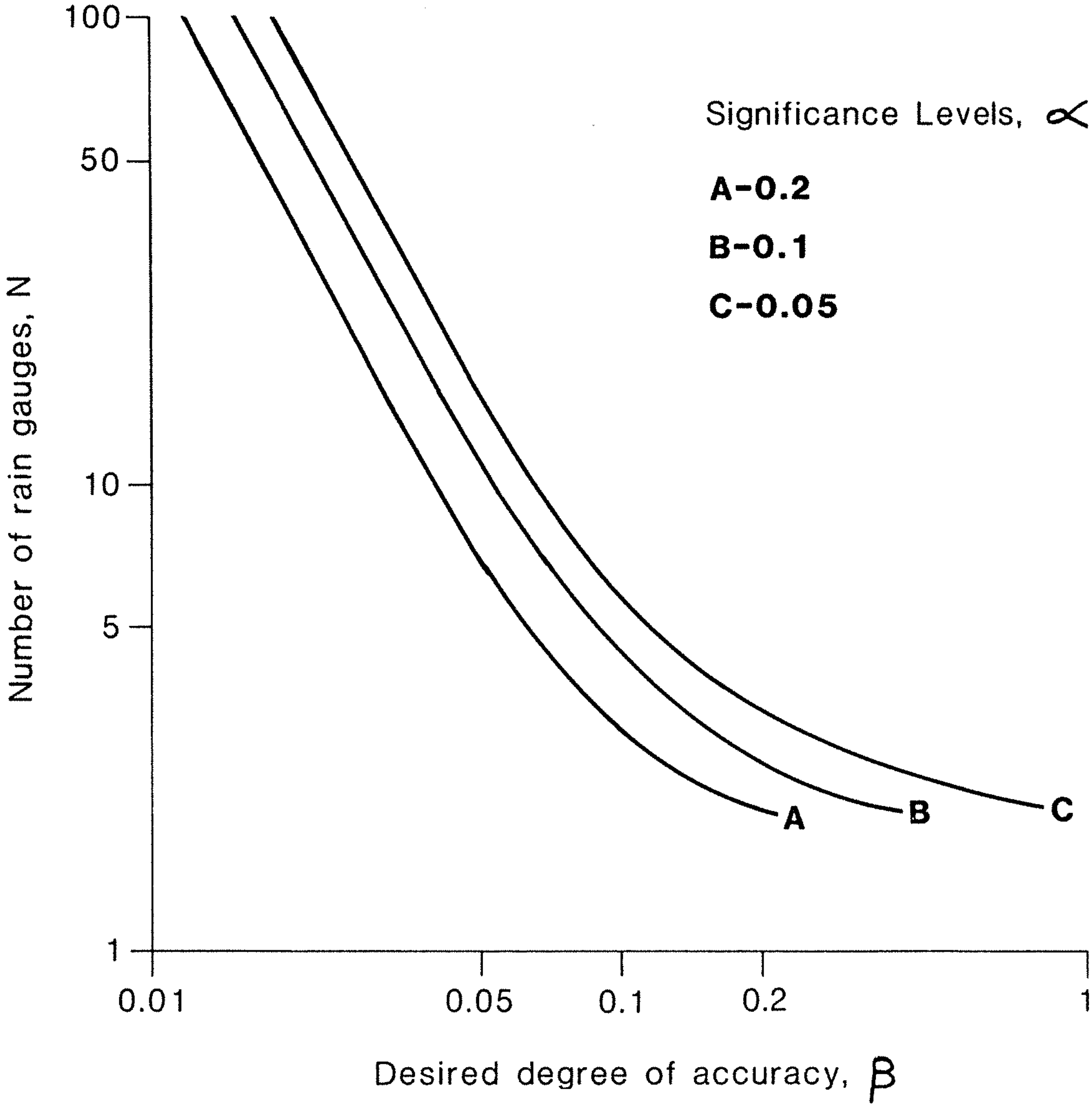


Fig. 7 N-β-α **Curves for Data Set B**

TABLE 7

NUMBER OF RAIN GAUGES REQUIRED FOR SPECIFIED LEVELS OF STATISTICAL ACCURACY (BASED ON STRATIFIED RANDOM SAMPLING)

Level of Accuracy	Percent Level of Confidence	Number of Gauges Required		
		Daily Rainfall		Weekly Rainfall
		Set A	Set B	Set A
0.05	95	27	15	11
0.1	90	> 6	> 4	> 3
0.2	80	> 2	2	> 1

5. CONCLUSIONS

A number of conclusions can be drawn from this study:

(i) the pluviometer network currently operating within Yarragil 6C catchment provides adequate estimates of daily areal rainfalls;

(ii) a considerable and unwarranted increase in the network density would be required to achieve a conspicuous gain in the precision of the daily rainfall estimates;

(iii) the inclusion of trace rainfalls in rainfall data sets can have a detrimental and an unwarranted effect on the rainfall variation analysis and network optimisation;

(iv) output from computer programme RSNET can give valuable insight into the performance of rain gauge networks; and

(v) stratified random sampling based on strata boundaries determined by catchment characteristics and/or the orientation of storm tracks can give more precise estimates of mean areal rainfall than simple random sampling.

6. RECOMMENDATIONS

The following recommendations are made:

(i) operation of the Yarragil 6C pluviometer network should be continued for a further winter, and the analysis performed here repeated;

(ii) the future of the network and the need for a similar network on the control catchment for Yarragil 6C should then be reassessed;

(iii) the effect of a 5 mm threshold on the N-β-α curves should be investigated once sufficient data becomes available;

(iv) the feasibility of applying RSNET to data collected from other rain gauge networks operated by the Water Authority should be investigated. Application of the computer programme to this data will permit assessment of the accuracy of current areal rainfall estimates, and facilitate rationalisation of current network designs.

REFERENCES

Barnett, V., 1974. Elements of sampling theory. English Universities Press, London.

Cochran, W.G., 1977. Sampling techniques. Wiley, New York, N.Y., 3rd ed.

Deming, W.E., 1950. Some theory of sampling. Wiley, New York, N.Y.

Gray, D.M.(ed),1970. Handbook on the principles of hydrology. Water Information Centre, Inc., National Res. Council of Canada.

Hald, A., 1952. Statistical theory with engineering applications. Wiley, New York, N.Y.

Jackson, I.J., 1969. Tropical rainfall variations over a small area. Jour. Hydrology, 8:99-110.

Jessen, R.J., 1978. Statistical survey techniques. Wiley, New York, N.Y.

Kish, L., 1965. Survey sampling. Wiley, New York, N.Y.

Raudkivi, A.J.,1979. Hydrology. Pergamon Press, Oxford.

Rodriquez-Iturbe, I. and Mejia, J.M., 1974. The design of rainfall networks in time and space. Water Resour. Res., 10(4):713-728.

Sarkadi, K. and Vincze, I., 1974. Mathematical methods of statistical quality control. Academic Press, New York, N.Y.

Schilling, E.G.,1982. Acceptance sampling in quality control. Marcel Dekker, New York, N.Y.

Shih, S.F., 1982. Rainfall variation analysis and optimization of gauging systems. Water Resour. Res. 18(4):1269-1277.

Walpole, R.E. and Myers, R.H., 1985 Probability and statistics for engineers and scientists. Macmillan, New York, N.Y.

APPENDIX A

DESCRIPTION OF COMPUTER PROGRAMME RSNET

A.1 Structure of RSNET

RSNET (an acronym for Rainfall-Saltfall Networks) is a library of computer subprograms which describes the rainfall variation analysis and rain gauge network optimisation technique proposed by Shih (1982). The library consists of a main program and 14 subroutines, and contains approximately 500 lines of source code. This appendix will describe the application of the programme to rainfall data only.

A.2 Representation of Rainfall, Strata and Network Geometry

Currently, RSNET uses up to 15 rain gauges and 100 readings per gauge. The readings are rainfall depths in mm within the time period (e.g. day, week, month, etc.) specified by the user. There must be a reading for every gauge during any particular time period.

The user is required to specify the number and boundaries of the strata, and their respective weights. This allows the user to incorporate "local knowledge" into the rainfall variation analysis, and may improve the precision of the mean rainfall estimates. As mentioned in Section 2.3, each stratum must contain at least two rain gauges. The number of strata is presently limited to five.

The geometry of the rain gauge network is specified as follows. First, the strata are numbered consecutively from one end of the the catchment (N = 1) to the other (N = NS, where NS is the number of strata). Second, the rain gauges are numbered consecutively from the first gauge in stratum 1 (N = 1) to the last gauge in stratum NS (N = NG, where NG is the number of rain gauges). Third, the number of gauges per stratum is specified by the elements of the array NSS where NSS(J) indicates the number of gauges within the jth stratum. An example is given in Figure A.1.

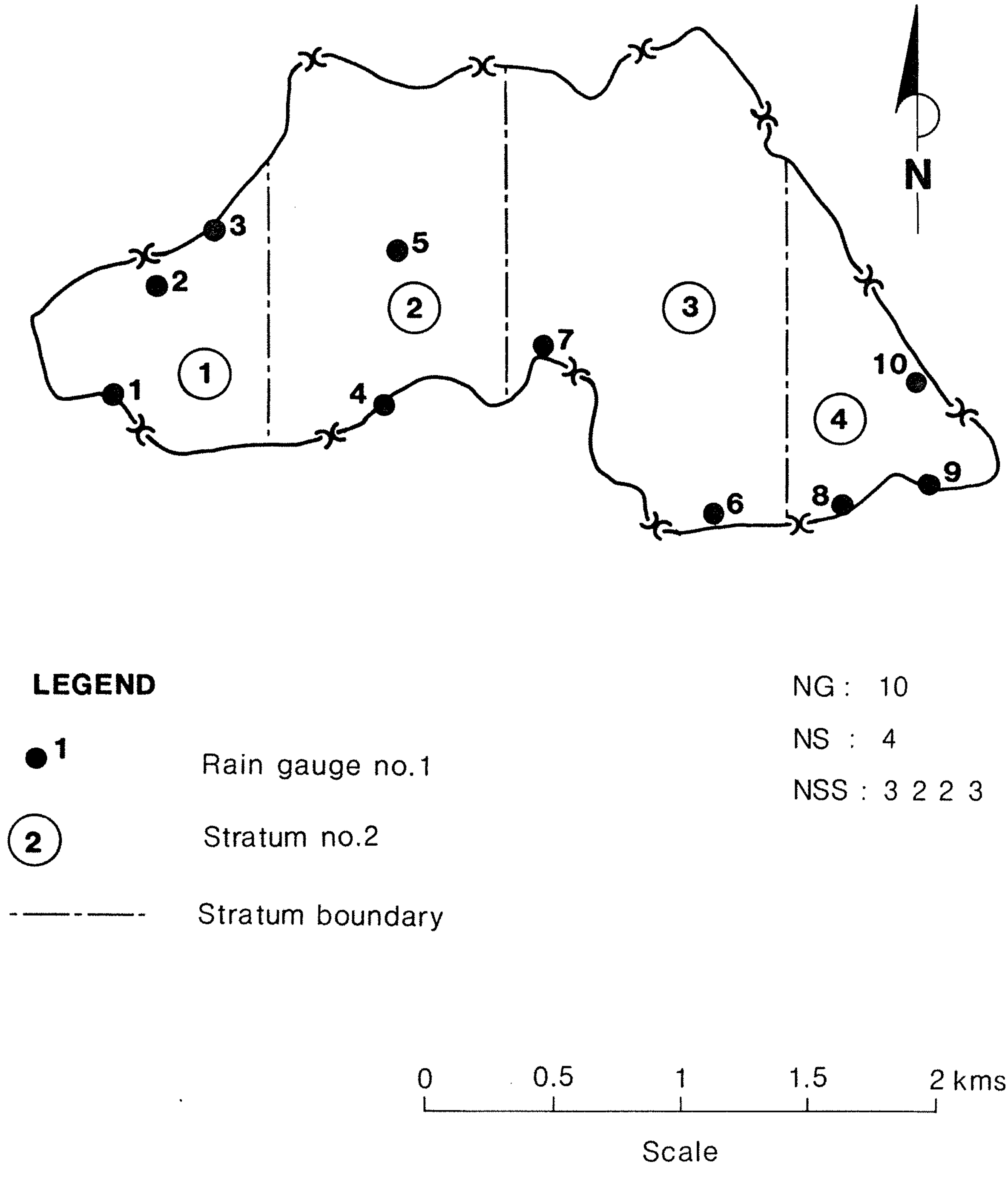


Fig. A.1 Catchment Stratification and Network Geometry Specification, Jackson's Study Catchment (Jackson, 1969)

A.3 List of Input Variables

Table A.1 lists details of the input variables in RSNET. The Table gives information on variable names, roles, types, units of measurement (where applicable), and array dimensions.

A.4 Configuration of Data File

The order of the data in the input data file is given below, set out as items within the file. Each item should appear on a new line of the file.

Item 1	ICAT				
Item 2	IU				
Item 3	NP NG NS				
Item 4	NSS(1)	NSS(2)	...	NSS(NS)	
Item 5	P(1,1)	P(2,1)	...	P(NP,1)	stratum 1
	P(1,2)	P(2,2)	...	P(NP,2)	.
	.	.		.	.
	.	.		.	.
	P(1,NG)	P(2,NG)	...	P(NP,NG)	stratum NS
Item 6	W(1)	W(2)	...	W(NS)	
Item 7	end - of - file				

TABLE A.1

DETAILS OF INPUT VARIABLES

Variable Name	Description	Type (I=Integer (R=Real	Array Dimensions
ICAT	Catchment or network identification	I	(8)
IU	Units of measurement identification	I	(4)
NG	Number of rain gauges	I	
NP	Number of rainfall ordinates per gauge	I	
NS	Number of strata	I	
NSS	Number of gauges per stratum, starting with the first	I	(5)
P	Rainfall ordinates matrix (ordinates in mm)	R	(100, 15)
W	Stratum weights	R	(5)

A.5 Input Format

Numerical data in the programme are read by free-format READ statements.

Alphanumeric data for variables ICAT and IU are read under A-format. ICAT may be a alphanumeric string up to 80 characters in length. In contrast, the total field length of the string for IU is limited to 33 characters. The first five characters specify the time period (e.g., DAILY), the next 15 characters the quantity being measured (e.g., RAINFALL), the next five characters the unit of measurement (e.g., MM), and the last eight characters specify the unit of variance (e.g., MM2).

A.6 Worked Example

In this Section, programme RSNET is demonstrated for the case study examined by Shih (1982) and originally presented by Jackson (1969). Details of the catchment and rain gauge network are given in Table A.2 and Figure A.1. Listings of the input data file (see Figure A.2) and corresponding programme output (Figure A.3) are also provided.

Comparison of Table 4 in the programme output with that reported by Shih reveals a discrepancy. Hand calculations suggest that the table given by Shih is in fact incorrect.

TABLE A.2

DETAILS OF CATCHMENT EXAMINED
BY JACKSON (1969) AND SHIH (1982)

LOCATION	Mulalakuwa River, Tanzania
SIZE	4.9 km^2
RELIEF	53 m to 114 m above mean sea level
METEOROLOGICAL NETWORK	3 pluviographs and 7 storage rain gauges.

```
DATA FROM JACKSON (1969) - COMPLETE RAINFALL SET
DAILY      RAINFALL  MM   MM2
 27  10    4
 3  2  2  3
 20.4   54.9  33.3   2.3  13.5  13.5  11.5  18.5  26.7  18.5
 44.5   14.2  21.1  20.0  14.4  16.2   7.7  25.9   5.3  16.4
  7.4    1.7  50.2  20.1  10.6  19.9  87.9
 23.7   61.0  27.1   2.3  14.2  11.2  17.2  28.7  30.5  18.6
 46.5    8.1  25.7  18.1  17.7  18.4   6.2  25.9   2.9  16.3
  8.4    2.5  54.1  24.1   8.5  30.0  82.6
 24.2   68.1  25.9   2.3  12.7  12.7  17.2  31.2  33.8  19.4
 46.0    7.4  21.3  18.3  20.1  18.5   5.9  25.0   3.5  16.3
 10.6    2.5  52.7  25.7   6.5  32.0  80.6
 27.7  101.3  19.3   2.5  14.2  10.7  18.5  38.6  24.4  21.9
 48.8   10.7  14.5  25.4  20.1  19.0   5.1  32.8   8.2  17.8
 19.1    5.5  42.2  26.5   9.3  30.4  79.2
 29.7   79.2  13.9   3.3  23.4  13.7  19.3  39.4  27.9  20.4
 48.0   10.9  12.7  21.5  19.9  19.1   5.5  34.3   7.7  16.2
 17.0    5.8  40.7  25.3   6.9  33.0  77.6
 42.5   59.7   5.8  14.2  52.8   4.6  11.7  46.0  23.6  24.9
 49.0   10.4   3.6  22.8  16.8  24.4   5.0  36.5  12.4  17.1
 15.0   11.3  39.7  24.6   7.7  30.4  62.2
 36.6   83.3   9.2   6.6  33.0   8.9  16.7  40.1  25.1  22.1
 49.5   12.7   4.3  23.4  18.7  21.8   5.4  35.9  12.7  16.3
 20.5    6.2  29.5  25.4   8.3  31.6  68.4
 41.7   75.4   3.5  27.2  59.7   2.3  14.3  43.2  23.4  26.4
 50.5    9.1   3.0  20.8  15.9  22.5   4.9  42.7   8.4  15.1
 16.5   17.0  38.6  26.5   4.6  30.1  53.1
 41.8  100.3   3.3  31.8  64.8   5.1  14.5  40.1  23.1  28.4
 53.1    8.4   0.8  19.1  16.8  21.1   4.8  41.4   9.8  16.9
 11.4   12.3  45.8  31.4   3.1  33.4  53.5
 43.4  108.5   2.8  35.1  55.4   4.1  21.4  36.8  23.6  29.5
 51.8    5.6   0.8  14.0  16.8  17.7   4.6  39.4   9.4  17.9
 10.4   10.2  41.8  30.1   8.1  33.1  56.0
 0.151  0.289  0.422  0.138
```

Fig. A.2 Listing of Data File for Worked Example

Fig. A3 Output from RSNET for Worked Example

RAINFALL GAUGE NETWORK DESIGN FOR DATA FROM JACKSON (1969)

TABLE 1. DAILY RAINFALL IN MM

GAUGE	1	2	3	4	5	6	7	8	9	10
	20.4	23.7	24.2	27.7	29.7	42.5	36.6	41.7	41.8	43.4
	54.9	61.0	68.1	101.3	79.2	59.7	83.3	75.4	100.3	108.5
	33.3	27.1	25.9	19.3	13.9	5.8	9.2	3.5	3.3	2.8
	2.3	2.3	2.3	2.5	3.3	14.2	6.6	27.2	31.8	35.1
	13.5	14.2	12.7	14.2	23.4	52.8	33.0	59.7	64.8	55.4
	13.5	11.2	12.7	10.7	13.7	4.6	8.9	2.3	5.1	4.1
	11.5	17.2	17.2	18.5	19.3	11.7	16.7	14.3	14.5	21.4
	18.5	28.7	31.2	38.6	39.4	46.0	40.1	43.2	40.1	36.8
	26.7	30.5	33.8	24.4	27.9	23.6	25.1	23.4	23.1	23.6
	18.5	18.6	19.4	21.9	20.4	24.9	22.1	26.4	28.4	29.5
	44.5	46.5	46.0	48.8	48.0	49.0	49.5	50.5	53.1	51.8
	14.2	8.1	7.4	10.7	10.9	10.4	12.7	9.1	8.4	5.6
	21.1	25.7	21.3	14.5	12.7	3.6	4.3	3.0	.8	.8
	20.0	18.1	18.3	25.4	21.5	22.8	23.4	20.8	19.1	14.0
	14.4	17.7	20.1	20.1	19.9	16.8	18.7	15.9	16.8	16.8
	16.2	18.4	18.5	19.0	19.1	24.4	21.8	22.5	21.1	17.7
	7.7	6.2	5.9	5.1	5.5	5.0	5.4	4.9	4.8	4.6
	25.9	25.9	25.0	32.8	34.3	36.5	35.9	42.7	41.4	39.4
	5.3	2.9	3.5	8.2	7.7	12.4	12.7	8.4	9.8	9.4
	16.4	16.3	16.3	17.8	16.2	17.1	16.3	15.1	16.9	17.9
	7.4	8.4	10.6	19.1	17.0	15.0	20.5	16.5	11.4	10.4
	1.7	2.5	2.5	5.5	5.8	11.3	6.2	17.0	12.3	10.2
	50.2	54.1	52.7	42.2	40.7	39.7	29.5	38.6	45.8	41.8
	20.1	24.1	25.7	26.5	25.3	24.6	25.4	26.5	31.4	30.1
	10.6	8.5	6.5	9.3	6.9	7.7	8.3	4.6	3.1	8.1
	19.9	30.0	32.0	30.4	33.0	30.4	31.6	30.1	33.4	33.1
	87.9	82.6	80.6	79.2	77.6	62.2	68.4	53.1	53.5	56.0
TOTAL	596.6	630.5	640.4	693.7	672.3	674.7	672.2	696.4	736.3	728.3
MEAN	22.1	23.4	23.7	25.7	24.9	25.0	24.9	25.8	27.3	27.0

RAINFALL GAUGE NETWORK DESIGN FOR DATA FROM JACKSON (1969)

TABLE 2. VARIANCE AND COVARIANCE OF DAILY RAINFALL

FOR ALL GAUGES

GAUGE	1	2	3	4	5	6	7	8	9	10
1	346	342	342	354	316	227	274	212	254	266
2		356	360	376	337	250	296	241	288	301
3			369	395	351	259	313	254	308	323
4				484	413	312	396	328	405	429
5					369	297	352	305	364	378
6						311	309	327	373	368
7							358	327	389	401
8								368	430	429
9									523	528
10										547

TABLE 3. AREA RATIO, NUMBER OF GAUGES, MEAN DAILY RAINFALL, VARIANCE, COVARIANCE, AND STRATUM WEIGHTED RATIO IN EACH STRATUM

STRATUM	AREA RATIO	NO. OF GAUGES	MEAN RAINFALL	VARIANCE	COVARIANCE	STRATUM WEIGHTED RATIO
1	.151	3	23.1	357.	348.	.1060
2	.289	2	25.3	426.	413.	.2455
3	.422	2	24.9	335.	309.	.5139
4	.138	3	26.7	479.	463.	.1346

RAINFALL GAUGE NETWORK DESIGN FOR DATA FROM JACKSON (1969)

TABLE 4.. COVARIANCE BETWEEN STRATUM FOR DAILY RAINFALL DATA

STRATUM	2	3	4
1	355	270	272
2		339	368
3			364

RESULTS FOR SIMPLE RANDOM SAMPLING

SAMPLE MEAN = 24.96815 MM
RELATIVE VARIANCE = 6.74517 MM2
SPATIAL VARIATION = 335.588 MM2

RESULTS FOR STRATIFIED RANDOM SAMPLING
WITHOUT OPTIMAL ALLOCATION

SAMPLE MEAN = 24.99950 MM
RELATIVE VARIANCE = 3.03418 MM2
SPATIAL VARIATION = 337.461 MM2

RESULTS FOR STRATIFIED RANDOM SAMPLING
WITH OPTIMAL ALLOCATION

SAMPLE MEAN = 24.99950 MM
RELATIVE VARIANCE = 1.76455 MM2
SPATIAL VARIATION = 337.461 MM2

RAINFALL GAUGE NETWORK DESIGN FOR DATA FROM JACKSON (1969)

TABLE 5. DATA FOR N-BETA-ALPHA PLOTS. (BETA-1 AND BETA-2 ARE BETA VALUES FOR SIMPLE RANDOM SAMPLING AND STRATIFIED RANDOM SAMPLING WITH OPTIMAL ALLOCATION, RESPECTIVELY.)

NO. OF GAUGES	ALPHA	BETA-1	BETA-2
2	.05	2.9553	1.5097
	.10	1.4686	.7502
	.20	.7159	.3657
3	.05	.8172	.4174
	.10	.5545	.2833
	.20	.3582	.1830
4	.05	.5233	.2673
	.10	.3870	.1977
	.20	.2694	.1376
5	.05	.4084	.2086
	.10	.3136	.1602
	.20	.2255	.1152
6	.05	.3453	.1764
	.10	.2706	.1382
	.20	.1982	.1013
7	.05	.3042	.1554
	.10	.2416	.1234
	.20	.1790	.0915
8	.05	.2750	.1405
	.10	.2204	.1126
	.20	.1646	.0841
9	.05	.2528	.1292
	.10	.2039	.1042
	.20	.1532	.0782
10	.05	.2353	.1202
	.10	.1907	.0974
	.20	.1439	.0735
11	.05	.2210	.1129
	.10	.1797	.0918
	.20	.1361	.0695
21	.05	.1497	.0765
	.10	.1238	.0633
	.20	.0951	.0486
31	.05	.1206	.0616
	.10	.1003	.0512
	.20	.0774	.0395
41	.05	.1038	.0530
	.10	.0865	.0442
	.20	.0669	.0342
61	.05	.0842	.0430
	.10	.0704	.0359
	.20	.0546	.0279
121	.05	.0592	.0302
	.10	.0496	.0253
	.20	.0385	.0197