Status of Hydrological Network in South-Western Region of the Kingdom of Saudi Arabia

by

Muhammad Abdullah Mesfer Al-Zahrani

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

CIVIL ENGINEERING

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بسم الله الرحمن الرحيم

IN THE NAME OF ALLAH,

THE MERCIFUL, THE BENEFICIENT

This thesis is dedicated to my beloved parents and all members of my family.

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I would like to express my sincere appreciation and gratitude to the Chairman and Co-Chairman of my Thesis Committee, Dr. Rashid Allayla and Dr. Tahir Hussain, for their careful guidance, suggestions, keen interest and constant encouragement throughout the course of this study.

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THESIS ABSTRACT

FULL NAME OF STUDENT: Al-Zahrani, Muhammad A. Mesfer

TITLE OF STUDY: Status of Hydrological Network in South-Western Region of the Kingdom of Saudi Arabia

MAJOR FIELD: Water Resources & Environmental Engineering

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The planning, design and decision making of a water resources project demands accurate hydrological information. Having sufficient and accurate hydrological data not only reduces the chances of project failure but also the economic risk arising from inadequate information. Therefore, it is imperative that a hydrological network be planned and designed scientifically in such a way so as to yield a representative picture of hydrological information desired.

In Saudi Arabia, hydrological stations are installed on the basis of accessibility to the site and the amount of rainfall. However, the criteria for a hydrological network design should be optimum number of stations where maximum hydrological information is obtained.

In this study, two hydrological network design methods, namely Shannon's and Fisher's Information Theories, were applied to the existing hydrological network in hydrological Area III, located in the Southwestern region of the Kingdom of Saudi Arabia, to examine their suitability towards providing maximum hydrological information. The study shows that the present seventy hydrological stations can be reduced approximately to forty-five which includes a few stations at new sites.

خلاصة الرسالة

اسم الطالب الكامـل : محمد عبدالله مسفر الزهراني
عنوان الدراســـة : دراسة وضع شبكة الرصد الهيدرولوجي في جنوب غرب المملكة العربية السعودية .
التخصــــــص : مصادر مياه وهندسة بيئة .
تاريخ الشهـــادة : ديسمبر ١٩٨٩م .

إن التصاميم والدراسات وحسن إتخاذ القرار الصائب حول تنفيذ أي مشروع يتعلق بالمياه يعتمد بشكل كبير على المعلومات الهيدرولوجية . فإن توفر المعلومات الهيدرولوجية الدقيقة والكافية حول المنطقة المراد تنفيذ المشروع بها سوف يؤدي الى تقليل إحتمال فشل المشروع وبالتالي إلى تحقيق الفوائد الإقتصادية المرجوة منه ومن أجل الحصول على معلومات هيدرولوجية دقيقة فإن شبكات الرصد الهيدرولوجي يجب أن تكون موزعة بشكل يجعلها تمثل التغيرات الهيدرولوجية في المنطقة المعنية بشكل مناسب .

وفي المملكة العربية السعودية تم توزيع شبكات الرصد الهيدرولوجي إعتمادا على سهولة الوصول الى محطات الرصد بالإضافة إلى كثافة سقوط الأمطار . وفي الحقيقة أن هذه الأسس ليست الأسس التي تقوم عليها التصاميم العلمية المعمول بها في محطات الرصد الهيدرولوجي والتي تستطيع أن تحدد أقل عدد ممكن من المحطات بالإضافة إلى تعيين أماكنها بحيث يتم الحصول على أشمل وأدق معلومات هيدرولوجية عن المنطقة بأقل تكلفة إقتصادية ممكنة .

وفي هذه الأطروحة تم إستخدام طريقتين علميتين هما نظرية شانون ونظرية فيشر في إعادة تصميم شبكة الرصد الهيدرولوجي للمنطقة الهيدرولوجية الثالثة بالمملكة العربية السعودية والواقعة في جنوب غرب المملكة . وقد أظهرت هذه الدراسة بأنه بالإمكان تقليل عدد محطات الرصد من (٧٠) محطة الى مايقارب (٤٥) محطة بالإضافة إلى إقتراح إضافة عدد من المحطات لبعض المناطق الغير مشمولة بمحطات رصد سابقة .

درجة الماجستير في العلوم
جامعة الملك فهد للبترول والمعادن
الظهران – المملكة العربية السعودية

STATUS OF HYDROLOGICAL NETWORK IN SOUTH-WESTERN REGION OF THE KINDGOM OF SAUDI ARABIA

Chapter 1

INTRODUCTION

1.1 Network - An Overview

Investment in water-resources projects demands hydrological data as a basis for the decisions and designs that have to be formulated. Hence, the information collected through the countrywide network is of prime importance for new projects and also for the operation and management of existing ones. Network is a group of stations distributed over an area to collect data involving one or more than one variable. The network consists of not only the gauging stations on rivers and streams where discharge is measured continuously, but also the rainfall stations, the climatological stations, and the wells and boreholes where groundwater levels are measured (Rodda, Downing and Law, 1976). In addition, the quality of water in rivers, lakes and reservoirs is monitored in terms of the principal dissolved constituents, and in some cases, suspended sediment load, biological characteristics and radioactive constituents (Palmer, 1985; Rodda, et al, 1976).

1.2 Objectives of Hydrological Network

The planning, management and development of water resources projects are mainly based on the information obtained from hydrological network. Planning usually requires extensive data with a long time base, to determine the natural variability of the phenomena. Management, on the other hand, may require less data, but what it does require may be real time for daily management or for future forecasting. Development requires intensive data at far higher precision than for other uses (Hoffmann, 1974). Based on the available information, an estimation model for the phenomenon to be predicted can be developed. The accuracy of these models depend on the basic data obtained from the network of stations. Without adequate information, the predicted performance may have serious deficiencies. With proper network density and station distribution, and with adequate record lengths, the uncertainties in models estimation can significantly be reduced (Moss, 1979). Furthermore, another objective of a network is to maximize the worth of data and minimize the cost (Hoffmann, 1974). Therefore, for sufficient and long-term water resources planning, it is necessary to design and install a network considering the interactions in both space and time domains and to optimize the number of stations with their locations to get maximum information with a minimum cost.

Chapter 2

RESEARCH OBJECTIVE

The Kingdom of Saudi Arabia is known to be an arid area because deserts occupy most of it. The mean annual precipitation of it is low compared to the other parts of the world, as shown in Figure 2.1. Within the Kingdom, the South-Western region receives the highest amount of rainfall with mean annual precipitation ranging from 16 mm to 492 mm (MAW, 1984).

Saudi Arabia has been divided into several hydrological regions, based on the sub-basins characteristics. These divisions are shown in Figure 2.2. Each one of these regions contains a number of hydrologic network stations. The total number of rainfall stations throughout the Kingdom is approximately 400 (MAW, 1984). These stations are installed according to the accessibility to the sites and the amount of rainfall. When the sites receive high amount of rain and can be reached easily, hydrological stations are installed. The cost associated with installation, operation, and management of these stations are quite high. The distribution of these stations in space has not been tested as yet. Thus it is essential that an optimization model, to test the status of the existing hydrologic network stations, be developed to optimize or expand the network configuration to maximize the amount of hydrological information with minimum cost by discarding those stations that give insufficient hydrological

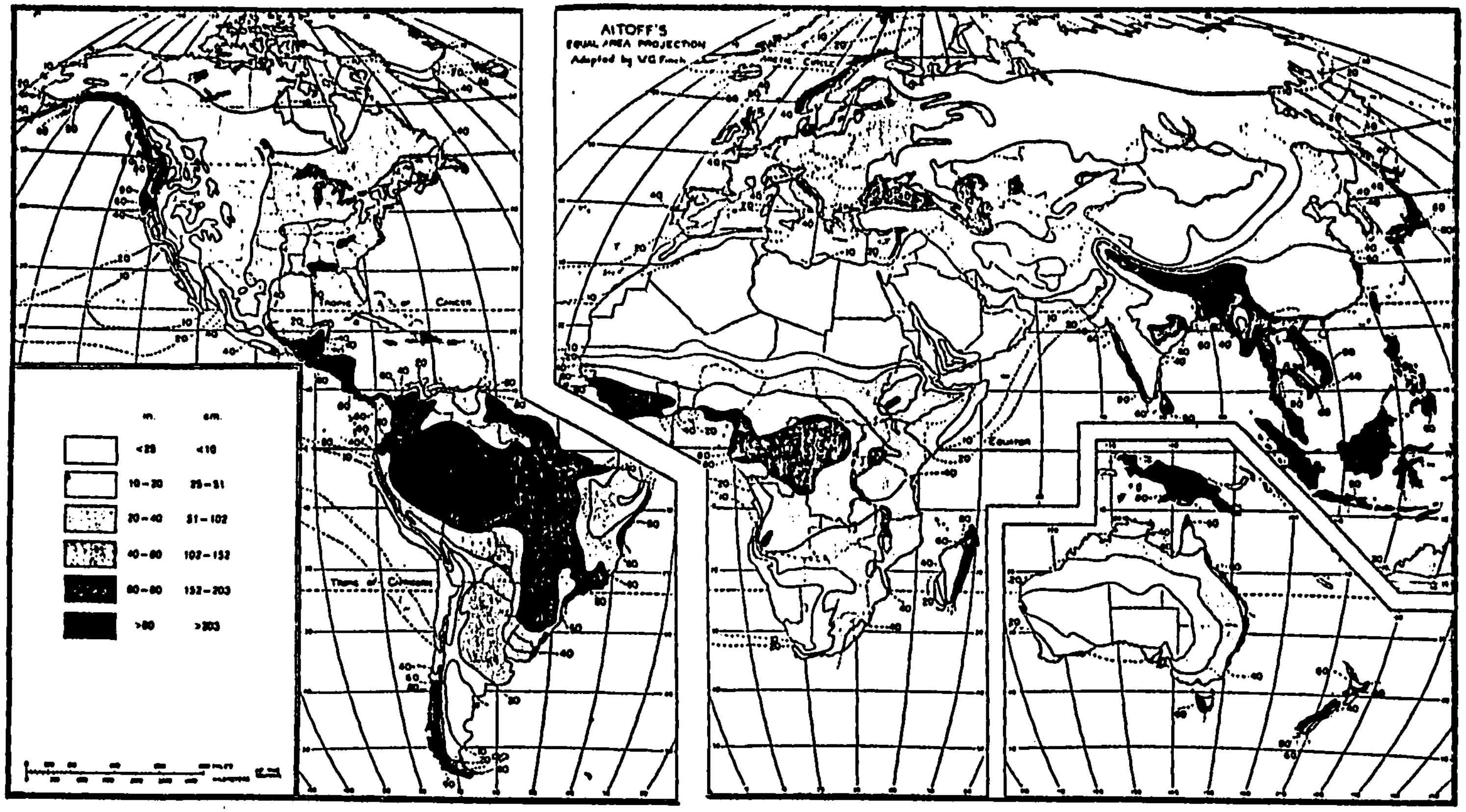


Fig. 2.1: World Distribution of Mean Annual Precipitation (Linsley, 1975).

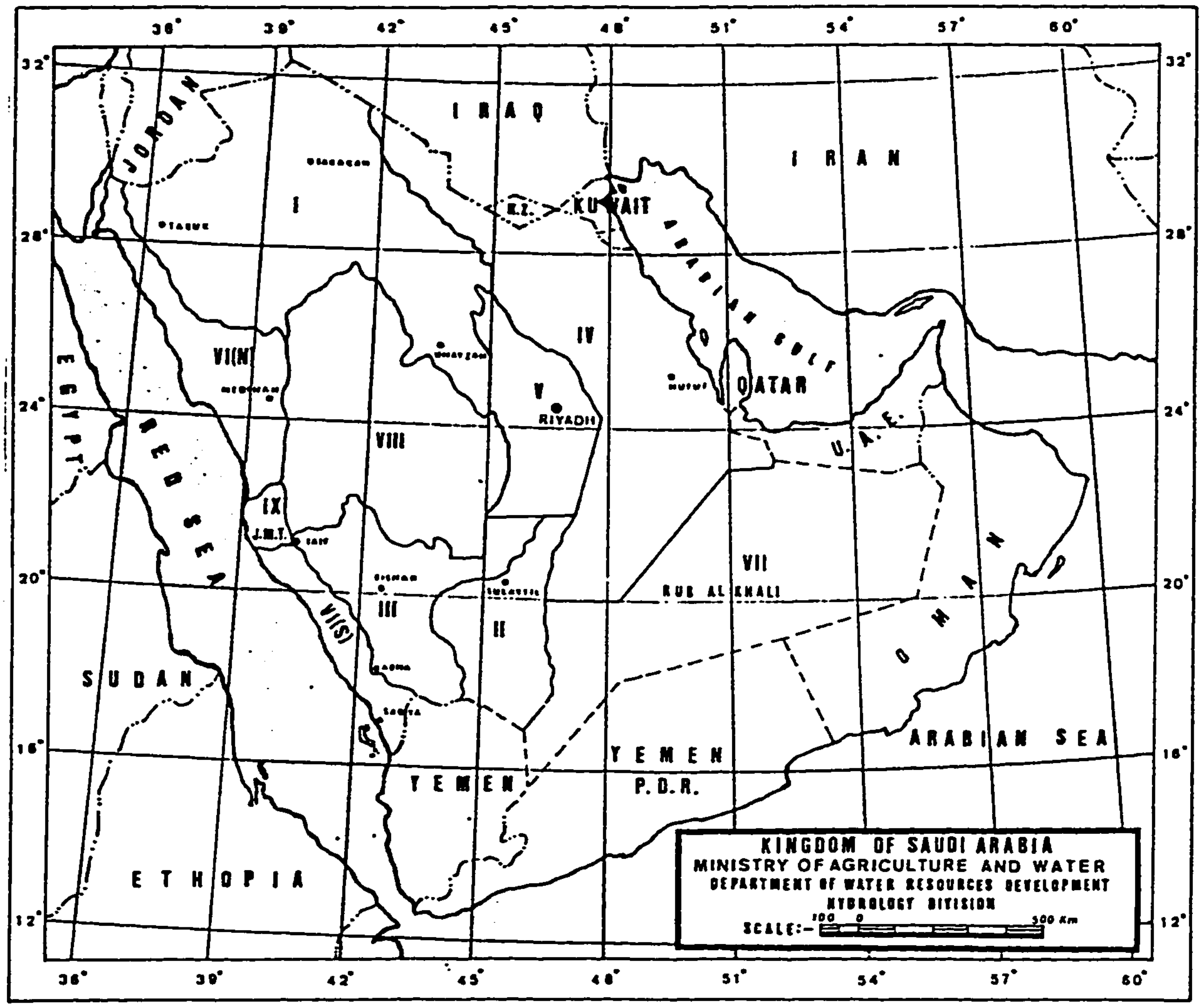


Fig. 2.2: Map of Hydrological Areas of the Kingdom of Saudi Arabia (MAW, 1984).

Table 2.1: Description of the Locations of Rain Gages in Hydrological Area III in Saudi Arabia (MAW, 1984).

STATION ID	NAME	SUB-BASIN	ELEVATION (Meter)	LATITUDE		LONGITUDE		NO.*
				Degree	Minutes	Degree	Minutes	
A004,A119, A207	Serat Abida	Bishah	2400	18°	10	43°	06	1
A001,A005	Abha	Bishah	2200	18	15	42	36	2
A003,A006	Sir Lasan	Bishah	2100	18	15	42	36	3
A103	Amir	Bishah	2100	18	06	42	47	4
A104	Haraja	Tathlith	2350	17	56	43	22	5
A105	Jawf	Tathlith	2060	18	14	43	11	6
A106	Kam	Bishah	2200	18	16	42	29	7
A107	Mowayn	Bishah	2150	18	36	42	34	8
A108,A202	Tajer	Bishah	2300	18	31	42	23	9
A110	Yaara	Tathlith	1880	18	41	42	59	10
A112	Bani Malik	Bishah	1980	18	22	42	34	11
A113	Bani Thawr	Bishah	1700	18	38	42	41	12
A117	Sabah	Bishah	2200	18	37	42	16	13
A118,A203	Sawdah	Bishah	2820	18	15	42	22	14
A120	Tenomah	Bishah	2100	18	53	42	10	15
A121	Tenomah	Bishah	2300	18	02	42	45	16
A123	Tindahah	Bishah	1900	18	19	42	52	17
A124	Zahra	Bishah	2400	18	25	42	20	18
A127	Belesmer	Bishah	2250	18	47	42	15	19
A128	Wadi Bin Hushbel	Bishah	1800	18	28	42	42	20
A130	Teyhan	Bishah	2440	18	20	42	19	21
A201	Hani	Bishah	2030	18	25	42	31	22
A206	Ibalah	Bishah	2480	18	41	42	15	25
A211	Tenomah	Bishah	2100	18	55	42	10	26
A213	Mala	Bishah	2030	18	10	42	50	27
A216	Ashran	Bishah	2160	18	19	42	29	28
A217	Kharif	Bishah	2200	18	50	42	20	29
B001	Mindak	Turabah	2400	20	06	41	17	30
B002	Nimas	Bishah	2600	19	06	42	09	31
B004	Bishah	Bishah	1020	20	01	42	36	32

Table # (Contd.)

Table 2.1 (continued)

STATION ID	NAME	SUB-BASIN	ELEVATION (Meter)	LATITUDE		LONGITUDE		NO.*
				Degree	Minutes	Degree	Minutes	
B005	Heifah	Bishah	1090	19	52	42	32	33
B006,B113	Tathlith	Tathlith	975	19	32	43	31	34
B003,B007	Biljurshi	Ranyah	2400	19	52	41	33	35
B101	Ajaeda	Ranyah	2330	19	54	41	35	36
B103,B220	Aqiq	Ranyah	1470	20	15	41	39	37
B110	Khaybar	Tathlith	1650	18	48	42	53	38
B111	Ranyah	Ranyah	810	21	15	42	51	39
B114	Tubalah	Bishah	1305	20	01	42	14	41
B208	Abu Jinniyah at Bathana	Bishah	1650	19	01	42	44	42
B212	Wadi Fig	Ranyah	2240	19	57	41	31	43
B216	Thuluth-Bani Amer	Bishah	2000	19	28	41	59	44
B217	Ademah	Ranyah	1715	19	45	41	56	45
B219	Samakh	Bishah	1480	19	20	42	48	46
B221	Alayah	Bishah	1850	19	32	41	54	48
B222	Upper Ranyah	Ranyah	1450	20	05	41	53	49
B240	Karra	Ranyah	2100	20	04	41	30	50
N103	Zahran Al-Janub	Habawnah	2020	17	40	43	38	51
N203	Thawila Police Post	Habawnah	2000	17	40	43	37	52
N210	Homran	Tathlith	1800	18	10	43	32	53
N211	Badr	Habawnah	1700	17	50	43	40	54
TA005	Turabah	Turabah	1126	21	11	41	40	55
TA111	Garith	Turabah	1100	21	37	41	53	56
TA112	Khurmah	Turabah	1060	21	54	42	02	57
TA121	New Mowayh	Shal Rakbah	970	22	27	41	47	58
TA215	Wadi Turabah	Turabah	1310	20	49	41	22	59

Table 2.1 (continued).

STATION ID	NAME	SUB-BASIN	ELEVATION (Meter)	LATITUDE		LONGITUDE		NO. *
				Degree	Minutes	Degree	Minutes	
TA219	Bani Sar	Turabah	2140	20	07	41	26	60
TA228	Tira Thaqif	Turabah	1820	20	45	40	50	61
TA229	Qa Bani Malik	Turabah	1820	20	23	41	06	62
TA234	Atawhah	Turabah	2070	20	15	41	22	63
TA235	Haddad Bani Malik	Turabah	1940	20	35	41	03	64
TA236	Martad	Turabah	1640	20	50	41	02	65
TA237	Mahawiyah	Turabah	2040	20	17	41	20	66
TA238	Qiya Bel-Harith	Turabah	1390	20	56	41	09	67
TA239	Znieb Al-Raha	Turabah	1650	20	49	40	47	68
TA247	Wadi Buwah Sayyadah	Turabah	1670	20	40	41	58	69
A218	Wadi Hani of Mujammil	Bishah	2200	18	17	42	32	71
A210	Shaaf	Bishah	2670	18	11	42	25	72
B209	Madha	Tathlith	1410	18	52	43	16	73
B223	Wadi Tarj near Bahim	Bishah	1500	19	45	42	20	74
B224	Wadi Awja	Bishah	1600	19	15	42	20	75
TA221	Sut	Turabah	1880	20	23	41	18	76
TA113	Turabah	Turabah	1130	21	13	41	39	77

* Stations location according to the numbers shown in Fig. # 2.3.

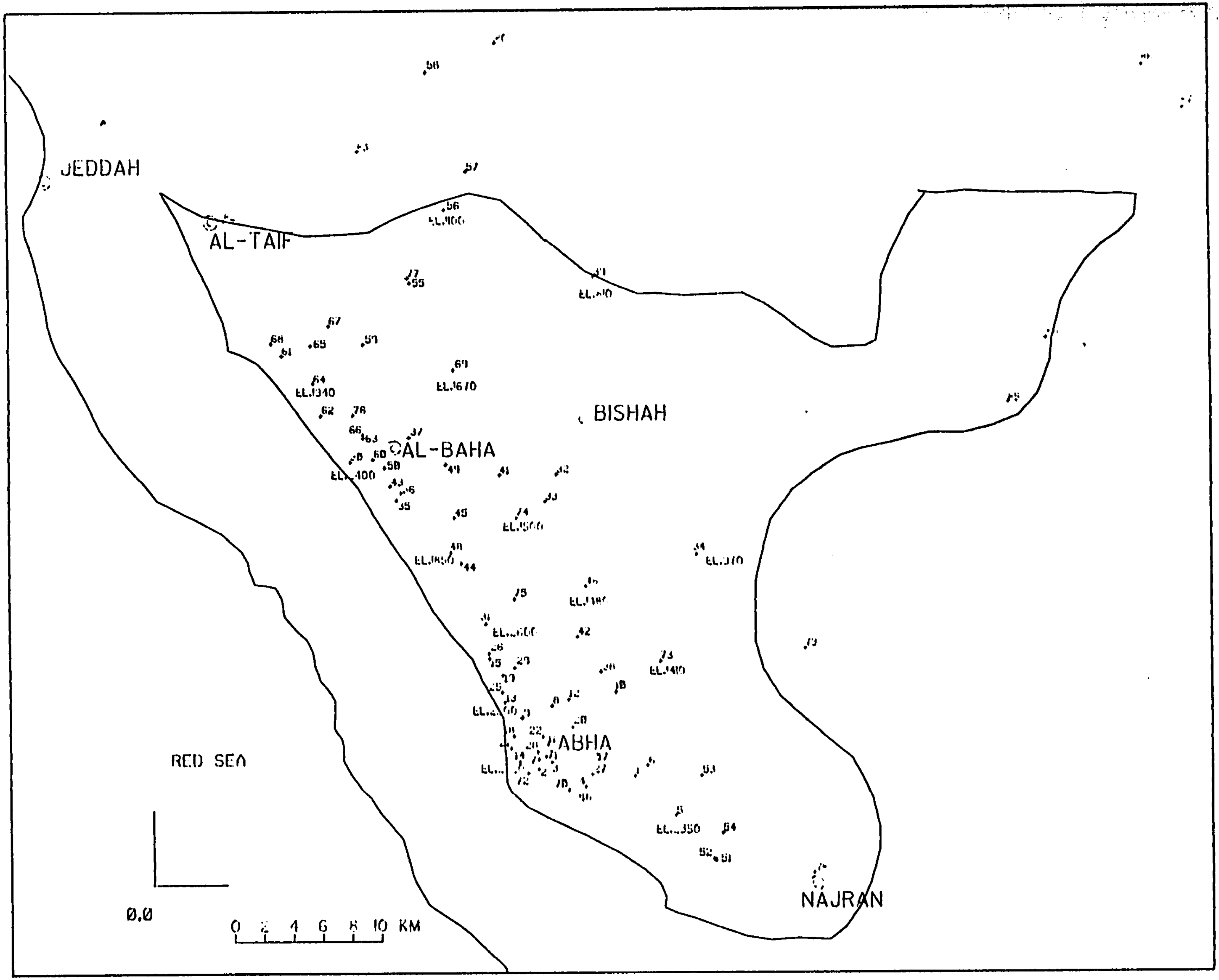


Figure 2.3: Topographical Map Showing Hydrological Stations in Hydrological Area III.

information.

In this research, a study will be focused on hydrological Area III in Saudi Arabia to check the distribution and optimize and expand the existing hydrological stations. The station locations and their altitudes above mean sea level are listed in Table 2.1. Also, a topographic map of hydrological Area III indicating the hydrological stations distribution is shown in Figure 2.3. The topographic map was produced by locating the stations on large scale relief maps using longitudes and altitudes, then transfering it to intergraph computers from which the topographic map was generated. Hydrological Area III is selected because of its heterogeneity, available hydrological data, and the high number of gauging stations existing compared to other hydrological areas. This study will cover the following:

1) application of hydrological network design methods, namely, Fisher's information, and Shannon's information to check the status of the existing stations in Area III using the available daily rainfall data for the years 1966 to 1984 for each station; and,

2) evaluation of the limitations of the above hydrological network design methods.

Chapter 3

LITERATURE REVIEW

3.1 Background

Good estimates of areal rainfall are needed as inputs of hydrological models. When based on ground measurements, their accuracy depends on the spatial variability of the rainfall process and on the raingage network density. The number of raingage stations relies upon several factors such as the cost of installation and maintenance and the accessibility of the gauge site. Thus it is difficult to anticipate a station at every point location of interest in the region. Therefore, a hydrological network should be designed and planned scientifically to provide observational data from every part of the country with maximum information and minimum uncertainty of data to yield a representative picture of the areal distribution of precipitation.

The World Meteorological Organization (WMO) (Kupriianov,1974) recommended a minimum density of hydrometric networks based on the type of region as shown in Table 3.1. However, the density of rain gauges varies greatly from country to country, as shown in Figure 3.1, and even within the same country. This variation depends on the topography of the concerned area as well as areas where there is a great economic significance in local variations of rainfall, i.e.,

Table 3.1: Recommended Minimum Density of Hydrometric Network (Kupriianov,1974).

Type of Region	Range of Norms for Minimum Network Area in km^2 for for 1 Station	Range of Provisional Norms Tolerated in Difficult Conditions (1) Area in km^2 for 1 station
I. Flat regions of temperate, mediterranean and tropical zones	1,000-2,500	3,000-10,000
II. Mountaneous regions of temperate, mediterranean and tropical zones	300-1,000	1,000- 5,000 (4)
Small mountaneous islands, with very regular precipitations, very dense stream network	140- 300	
III. Arid and polar zones (2)	5,000-20,000 (3)	

(1) Last figure of the range should be tolerated only for exceptionally difficult conditions.

(2) Great deserts are not included

(3) Depending on feasibility.

(4) Under very difficult conditions this may be extended to 10,000 km^2.

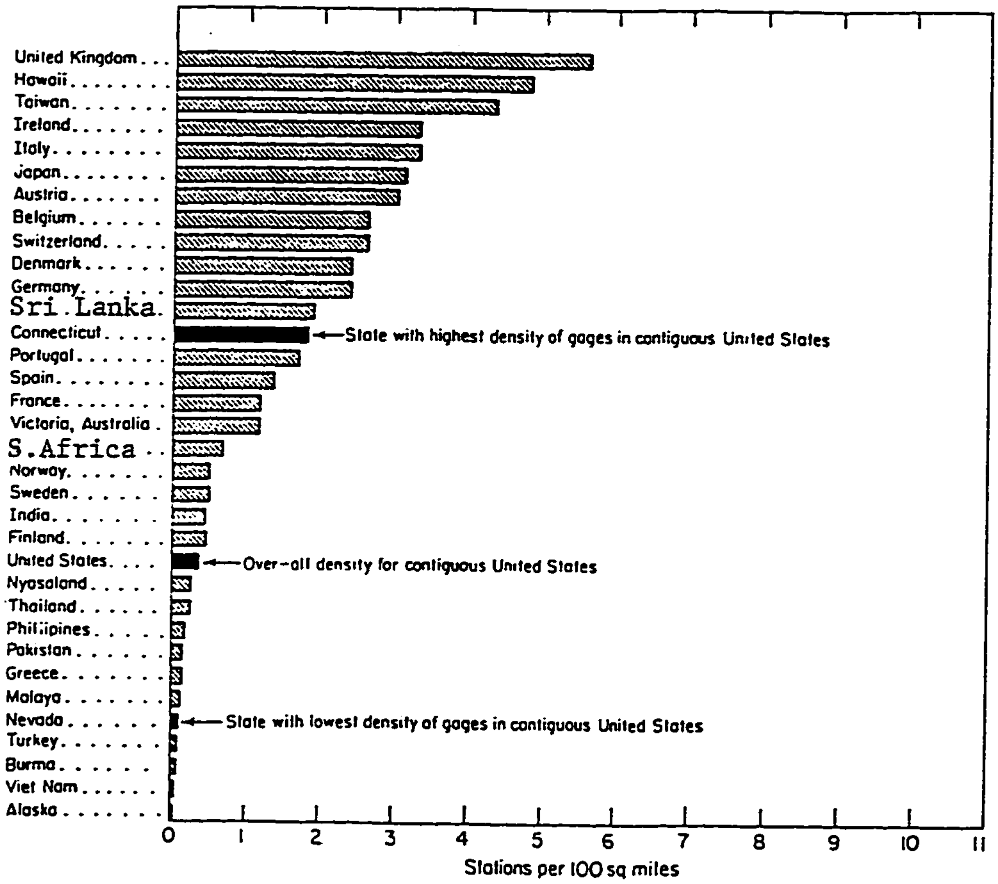


Fig. 3.1: Comparative Rain Gage Density (Chow, 1964).

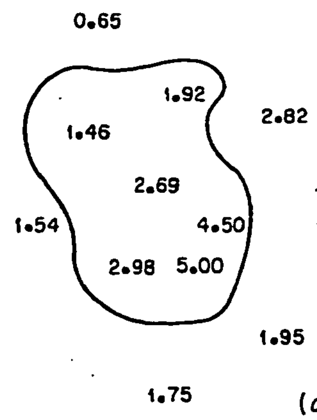
agriculture areas that are closely related to rainfall.

Some approximation methods have been used to estimate hydrological parameters such as rainfall of ungauged locations. Three commonly used methods are: (a) Theissen Method which estimates the value at any given point as the observed value of the neighboring station; (b) Arithmetic Mean Method which assumes that the rainfall depth is theoretically constant over a given region and can be estimated by the average of the observed values within this region; and (c) Isohyetal Method by which station locations and amounts are plotted on a map, and contours of equal precipitation are then drawn (Creutin and Obled, 1982). The computations of areal average precipitation when using each method are shown in Figure 3.2 (Linsley, et al, 1975). These three simplest methods cannot substitute the need of hydrological network because they do not consider the heterogeneity of the area and variability of rainfall. Thus, scientific methods should be used when designing hydrological networks.

3.2 Network Design Methods

There are usually three basic questions involved in the network design (Rodda, et al., 1976), they are :

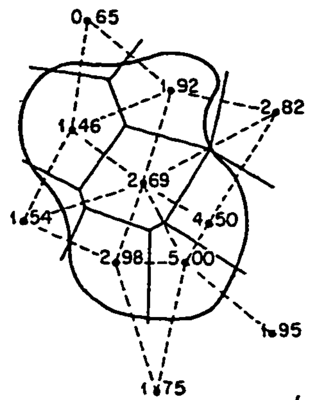
1. How many sites need to be established?
2. Where are these sites to be located?
3. How long is the network to be operated?



Arithmetic mean:

$$\frac{1.46 + 1.92 + 2.69 + 4.50 + 2.98 + 5.00}{6} = 3.09 \text{ in.}$$

(*a*)



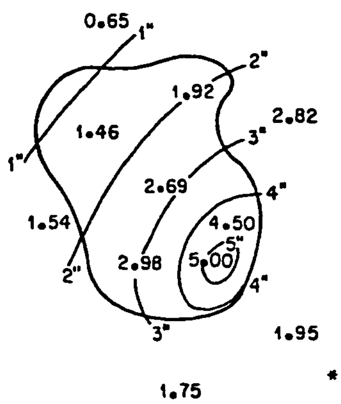
Thiessen method:

Observed precip. (in.)	Area* (sq mi)	Per cent total area	Weighted precipitation (in.) (col.1 x col.3)
0.65	7	1	0.01
1.46	120	19	0.28
1.92	109	18	0.35
2.69	120	19	0.51
1.54	20	3	0.05
2.98	92	15	0.45
5.00	82	13	0.65
4.50	76	12	0.54
	626	100	2.84

Average = 2.84 in.

*Area of corresponding polygon within basin boundary

(*b*)



Isohyetal method:

Isohyet (in.)	Area* enclosed (sq mi)	Net area (sq mi)	Avg. precip. (in.)	Precipitation volume (col.3 x col. 4)
5	13	13	5.3	69
4	90	77	4.6	354
3	206	116	3.5	406
2	402	196	2.5	490
1	595	193	1.5	290
<1	626	31	0.8	25
				1634

Average = 1634 ÷ 626 = 2.61 in.

*Within basin boundary

(*c*)

Fig. 3.2: Areal Average of Precipitation by
(a) Arithmetic Method,
(b) Theissen Method, and
(c) Isohytal Method
(Linsley, 1975).

The third question can be avoided, because once a network is installed, its continuation is often assured. The answers to the first and second questions are difficult, because the selection of sites for locating the networks depends on several factors such as the physical features of the sites; altitude, slope, and orientation; and the accessibility to the sites. At this junction, the scientific methods of network design can be applied.

There are a number of scientific methods of network design. Some of these are simple while others are more sophisticated. One of the simple methods which is applicable to individual basins rather than to a whole country is to use the systematic approach, so that the instruments would be installed at predetermined intervals over an area. These intervals are fixed in both horizontal and vertical planes, for example, set up one gauge per 23 KM^2 (Rodda, et al, 1976).

Several other methods of network design are of considerable interest; for example, the simulation approach by which a two-level network incorporating primary and secondary stations will be operated. Primary stations are those that will be operated continuously for a long time; secondary stations are only maintained long enough to establish a relationship with a primary station before the gauge is moved to another site and the process is repeated (Bras, 1976). Another and separate approach, which offers a useful way of determining the number and spacing of gauges in a network, is through the use of correlation analysis (Hutchinson, 1969). Correlation coefficients are determined between every pair of stations in a network, using the observations made at the sites, so that the decay in correlation with increasing gauge separation can be determined. In 1972, Stole assumed the decay function of the coefficient of correlation between two stations to be exponential. The relative efficiency was then observed from the following relationship (Stole, 1972):

$$n_r = [r(x,t)/\rho(t)]^2 \qquad (3.1)$$

Where:

n_r = the relative efficiency;

$r(x,t)$ = the correlation coefficient for intersection distance X at time t;

$\rho(t)$ = the correlation coefficient between two point locations for very dense network at time t.

Stephenson (Rodda, et al., 1976) suggested another approach to network design by using the monthly totals recorded in a network of "n" gauges, uniformly distributed, the coefficient of variation of the mean (CV_m) for each month can be employed in determining the adequacy of the network. Values of CV_m are calculated for the network using the monthly amounts expressed as a percentage of average annual rainfall. Then for 120 months, the cumulative frequency curve can be constructed from which the value (C') of CV_m exceeded by five percent will be determined. If C' is less than 10, the number of gauges is considered adequate. When C' is more than 10, then the number of gauges can be calculated from

$$N = (C'/10)^2 * n \quad (3.2)$$

Where:

N = Calculated number of gauges

C' = Coefficient of variation of the mean exceeded by 5 percent

n = Existing number of stations.

The method of isocorrelation can also be used in hydrologic network design (Hershfield, 1965). This method will correlate between one or more key stations and all other stations in the network; then, a line will be plotted connecting the points that have same correlation.

Yet another method, called regionalization approach, divides the hydrological area into square grids and relates hydrologic variables to physical parameters of the area. The forecasting of hydrologic data is made for ungaged locations (Solomon, et al., 1968).

The rational approach is another technique to network design. This technique develops a multiple linear regression based on the demographic, economic, meteorologic and basin characteristic factors

(Desi, Czelani and Rackoczi, 1965).

Decision theory is also introduced in hydrological network design. The purpose of this theory is to assess the network in terms of the impact of data on decisions, the more data collected, the less is the uncertainty in decision making (Hoffmann, 1974).

Another method that is used to select an optimum rain gage subset in a dense network is based on finding the number of gauges which yield the smallest standard error. Standard error is represented as follows (Bradsley, 1985):

$$\hat{\sigma}_{\hat{Y}} = [(1-R_M^2)S_s/(n-M)]^{1\,2} \qquad (3.3)$$

Where:

$\hat{\sigma}_{\hat{Y}}$ = Standard error of $\hat{Y}$ (i.e. $\hat{Y} = \sum_{k=1}^{M} V_k X_k$)

R_M^2 = Sample multiple correlation coefficient of

$$\hat{Y} = \sum_{k=1}^{M} V_k X_k$$

$S_s = \Sigma (Y - \overline{Y})$ = Sum of squares about mean for Y (i.e.

$$Y = \sum_{i=1}^{N} W_i X_i$$

n = Total number of ΔT's (T = time) containing non-zero of the complete network.

N = The number of gauges in the complete network.

M = The number of gauges that yield the smallest standard error.

Spline-surface fitting is another technique which is used to produce a contour map by interpolation between scattered point observations which avoids the drawback of uncontrolled oscillations arising when polynomial interpolation is used (Creutin, 1982; Lebel, 1987). The interpolation will be done to satisfy an optimal smoothness by finding the surface S(t) through minimizing the function (Creutin, 1982):

$$\int_{\Omega} [\nabla s(t)]^2 \, dt; \quad s(t) = \frac{\delta^2 S(t)}{\delta X^2} + 2\frac{\delta^2 S(t)}{\delta X \delta y} + \frac{\delta^2 S(t)}{\delta y^2}$$

$$S(t) = \alpha + \beta t + \sum_{i=1}^{N} \psi \, K(t^i, t)$$

$$K(t^i, t) = || \, t - t^i ||^2 \log || \, t - t^i \, ||^2 \qquad (3.4)$$

Where

α, β and φ = Coefficients obtained by solving the linear system (Creutin, 1982).

$S(t^i)$ = Measured rainfall at ith station among N (i = 1, ... N).

t^i = Station coordinate (X_i, Y_i)

Then, finding the optimum smooth line fitting between stations, a contour map can be plotted.

Another technique called Krigging has been used in the design of hydrological network. Krigging is a regionalization method which characterizes phenomena having variability with autocorrelated structure, such as rainfall which varies with time and space (Clark, 1984). The key to the mathematical algorithms of the Kriging system is the estimation of the variogram or semi-variogram, γ, which describes the expected difference in value between pairs of samples with a given relative orientation. Mathematically, the variogram is defined as (Clark, 1984; Creutin, 1982; Dingman, et al, 1988).

$$\gamma(h) = \frac{1}{2n} \sum_{i=1}^{n} [Z(X_i + h) - Z(X_i)]^2 \qquad (3.5)$$

Where:

n = Number of data points a distance "h" apart

h = Distance between sites

Z = Variable (i.e. rainfall) value at measured site.

Once a variogram is chosen, a minimization of the variance of the estimates subject to the constraint that the estimates be unbiased, i.e. $E[Z^*(t^\circ) - Z(t)] = 0$, defines the kriging system as follows (Creutin, 1982; Lebel, 1987):

$$\sum_{j=1}^{n} \lambda_j \gamma_{ij} + \sum_{\ell=1}^{K} \mu \; f_i^{\ell} = \gamma_{io} \quad i=1,\ldots.n$$

$$\sum_{j=1}^{n} \lambda_j f_j^{\ell} = f_o^{\ell} \qquad \hat{\ell} = 1,\ldots.,K \tag{3.6}$$

Where:

γ_{ij} = γ (h) where h is the distance between X_i and X_j

γ_j = Kriging coefficients

μ_ℓ = Lagrangian coefficients

f_i^ℓ = Monomials used in drift estimation

ℓ = Index on monomial number

i,j = Index on data point

n = Number of data points

K = Number of monomials used in the drift estimation.

Gandian's technique is another method that can be applied to the design of hydrological network. This method relies on the same basic principle as Kriging's. For a given area, the value at the ungaged point t° is estimated as a linear combination of n surrounding observed values (Creutin, 1982):

$$Z^*(t^\circ) = \sum_{i=1}^{n} \lambda_i \, Z\,(t^i) \tag{3.7}$$

Where:

$Z^*(t^o{}_i)$ = values at ungaged location

$Z(t^i)$ = values at surrounding gaged locations

n = surroundings number of stations

λ_i = weighing coefficient

The weighing coefficients are determined by minimizing the estimation variance:

$$E\,[(Z(t^\circ) - Z^*\,(t^\circ))^2] \tag{3.8}$$

which leads to Gandian's system:

$$\sum_{i=1}^{n} \lambda_i \, C(t^i, t^j) = C\,(t^j, t^\circ) \qquad j = 1,\ldots\ldots,n \tag{3.9}$$

where $C\,(t,\ t') = E\,[Z(t)Z(t')]$ is a covariance.

Most of the network design methods presented above can be applied for special cases. Some of them assume linear variation of rainfall between stations, others assume homogenous areas. However, for large areas where heterogeneity dominates, they will not be powerful, so other methods can be applied such as Shannon's information method which will be presented later. Also, the Fisher information technique which relies upon normality will be introduced and compared with Shannon's method through a case study.

Chapter 4

RAINFALL DATA ANALYSIS

4.1 Data Classification

Scientific data can be classified into two categories: experimental data and historical data. Experimental data are those which are obtained by running an experiment and can be obtained again if the same experiment is run in the same environment. On the other hand, historical data are those collected from natural phenomena which will be observed once and then will not occur again (Chow, 1964).

Since hydrological data such as rainfalls, floods, runoff, etc., are observed from natural hydrological phenomena, it will therefore be considered as historical data. In order to use these data for modeling or estimating a specific event based on its past record, statistics and probability will be applied. Statistics will deal with the computation of sampled data, and probability will deal with the measure of chance or likelihood based on the sampled data.

An important part of hydrological work is concerned with analysis of information. Analysis of hydrological observations should be done to provide ways to reduce and summarize observed data to determine the characteristics of the observed phenomena, and to make predictions concerning future behavior. Here, statistical and probability methods will be applied. They will be used to define the distribution of the variable or the variables over the range of occurrence in terms of frequency and probability.

In this study, rainfall data for selected stations in hydrological Area III will be used to produce their relative frequency distribution curves from which a fitted probability function will be selected.

4.2 Frequency Analysis and Distribution Fitting

Using daily rainfall data, the number of occurrences or the frequency will be plotted against selected intervals of rainfall to produce a frequency distribution. This distribution can also be produced in terms of relative frequency or probability, n/N where "n" is the number of frequencies in the selected interval and "N" is the total frequencies, against rainfall interval (from which frequency distribution can be fitted).

Then, theoretical probability distributions can be fitted by estimating the population moments (mean, variance, etc.) that is calculated from the sample data. Table 4.1 summarizes common distributions used to describe the behavior of some hydrological phenomena, but it should be emphasized that the theoretical distribution is not an exact representation of the natural process but just an approximation of the phenomena to be observed.

From hydrological Area III, some stations were selected

Table 4.1: Some Common Probability Density Functions (Husain, 1987).

Name	Probability Density Function	Expected Value, E(X)	Variance Var(X)
Normal	$f_N(x;\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(x-\mu)^2}{2\sigma^2}}$ $-\infty < x,\ \mu < \infty$ $0 < \sigma^2$	μ	σ^2
Log-normal	$f_{LN}(x;\mu_x,\sigma_x)$ $= \frac{1}{x\sigma_y\sqrt{2\pi}} e^{\frac{-(\ell nx-\mu_y)^2}{2\sigma_y^2}}$ $\sigma_y = \ell n\sqrt{(\mu_x^2+\sigma_x^2)/\mu_x^2}$ $\mu_y = \ell n\sqrt{\mu_x^4/(\mu_x^2+\sigma_x^2)}$	$e^{\mu_y+\sigma_y}$	$e^{2(\mu_y+\sigma_y)}$ $\cdot(e^{2\sigma_y}-1)$
Gamma	$f_G(x;a,\nu) = \frac{x^{\nu-1}e^{-x/a}a^{-\nu}}{\Gamma(\nu)}$ $0 < x,a,\nu$	νa	νa^2
Beta	$f_B(x;\alpha,\beta)$ $\frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} x^{\alpha-1}(1-x)^{\beta-1}$ $0 < x < 1$ $0 < \alpha, \beta$	$\frac{\alpha}{\alpha+\beta}$	$\frac{\alpha\beta}{(\alpha+\beta+1)(\alpha+\beta)^2}$
Extreme Value	$f_{EXT}(x)$ $= e^{-x} e^{-e^{-x}}$ $-\infty < x < \infty$	zero	one
Expo-nential	$f_{EXP}(x;\beta)$ $= \frac{1}{\beta} e^{-\frac{x}{\beta}}$	β	β^2

randomly to generate their relative frequency histograms, as shown in Figures 4.1 through 4.18. The plotted relative frequency of daily precipitation will resemble an exponential distirbution when rainfalls with small amounts of precipitation occur more frequently than larger raingfalls. However, gamma-distribution will describe the distribution of precipitation amounts more accurately than the exponential distribution, which is a special case of gamma-distribution; because of the greater flexibility obtained with the larger number of parameters (Richardson,1981).

The gamma distribution is described by:

$$f_G\ (x,a,\upsilon) = \frac{x^{\upsilon-1}\ e^{-x/a}\ a^{-\upsilon}}{\Gamma\ (\upsilon)} \qquad ;x,a,\upsilon,> 0$$

$$x \leq 0 \qquad (4.1)$$

Where :

x = Hydrological variable

a = Shape parameter

υ = Scale parameter

$\Gamma\ (\upsilon)$ = Gamma function = $\int_0^{\infty} x^{\upsilon-1}\ e^{-x}\ dx$.

The two parameters, a and υ are obtained by finding the mean and the variance of the raw data then substituting them in the following :

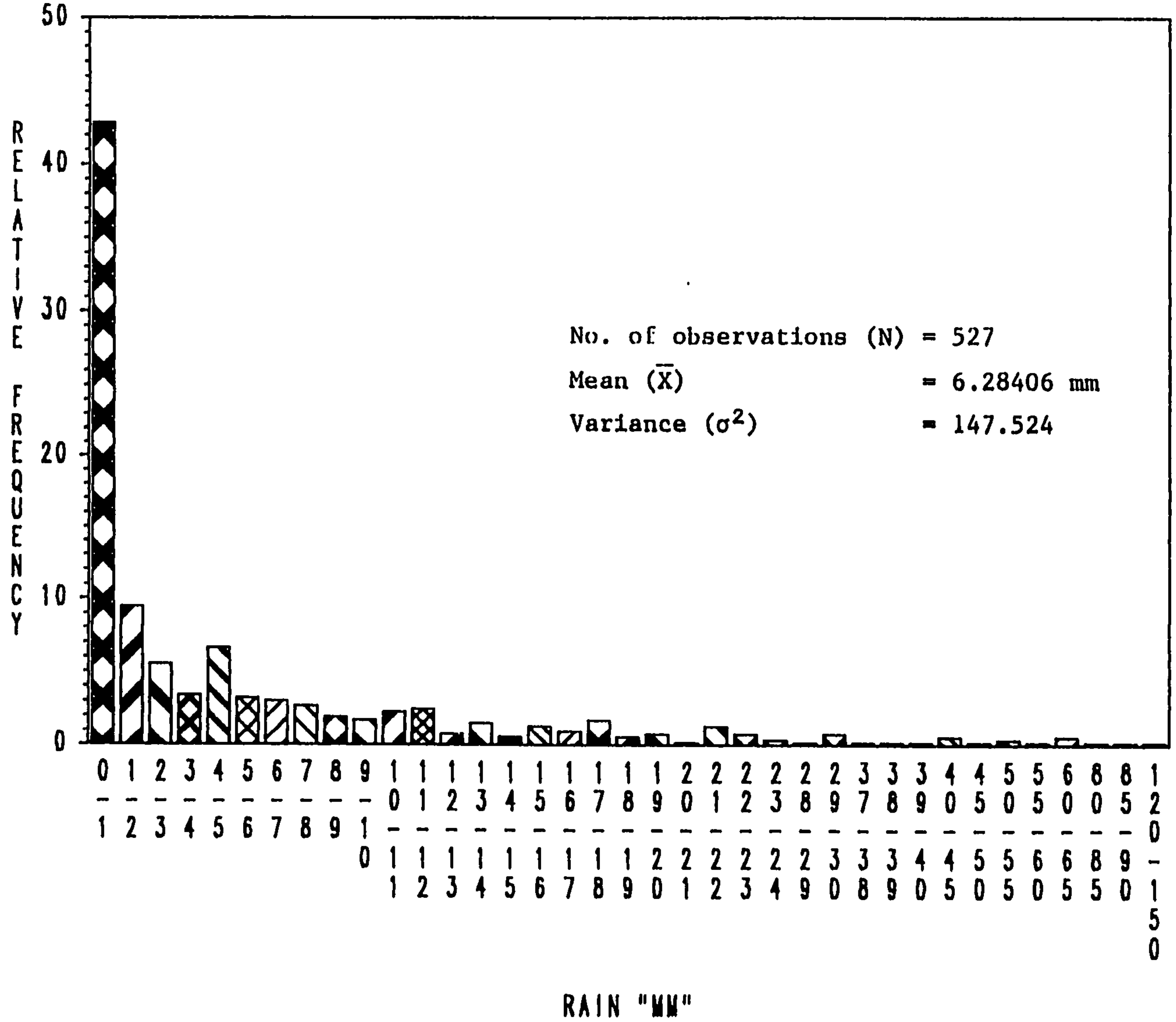


FIGURE 4.1 RELATIVE FREQUENCY HISTOGRAM OF STATION "A211" USING NON-ZERO DAILY RAINFALL DATA FROM 1966 TO 1984

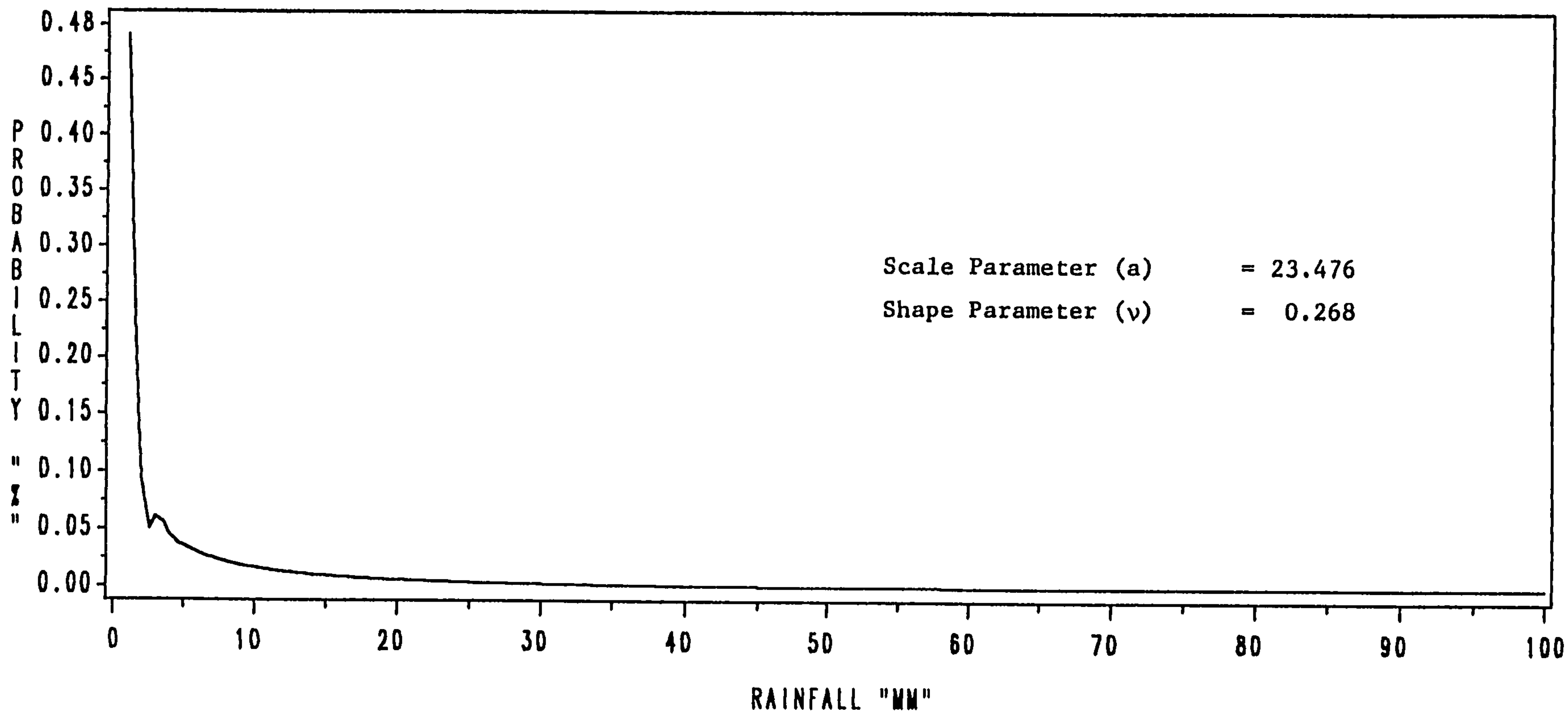


FIGURE 4.2 PROBABILITY OF RAINFALL ON STATION "A211" ASSUMING GAMMA-DISTRIBUTION

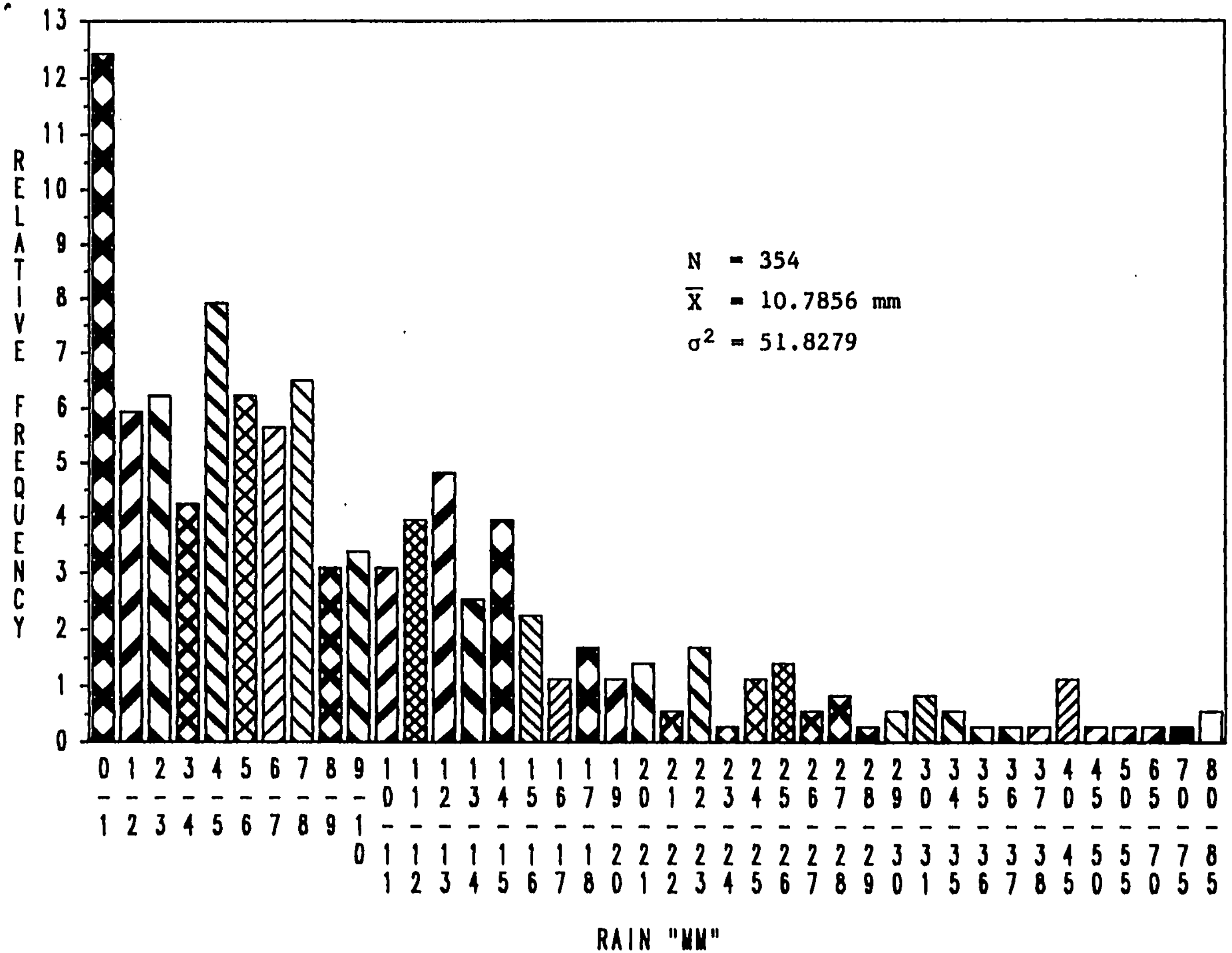


FIGURE 4.3 RELATIVE FREQUENCY HISTOGRAM OF STATION "N103" USING NON-ZERO DAILY RAINFALL DATA FROM 1966 TO 1984

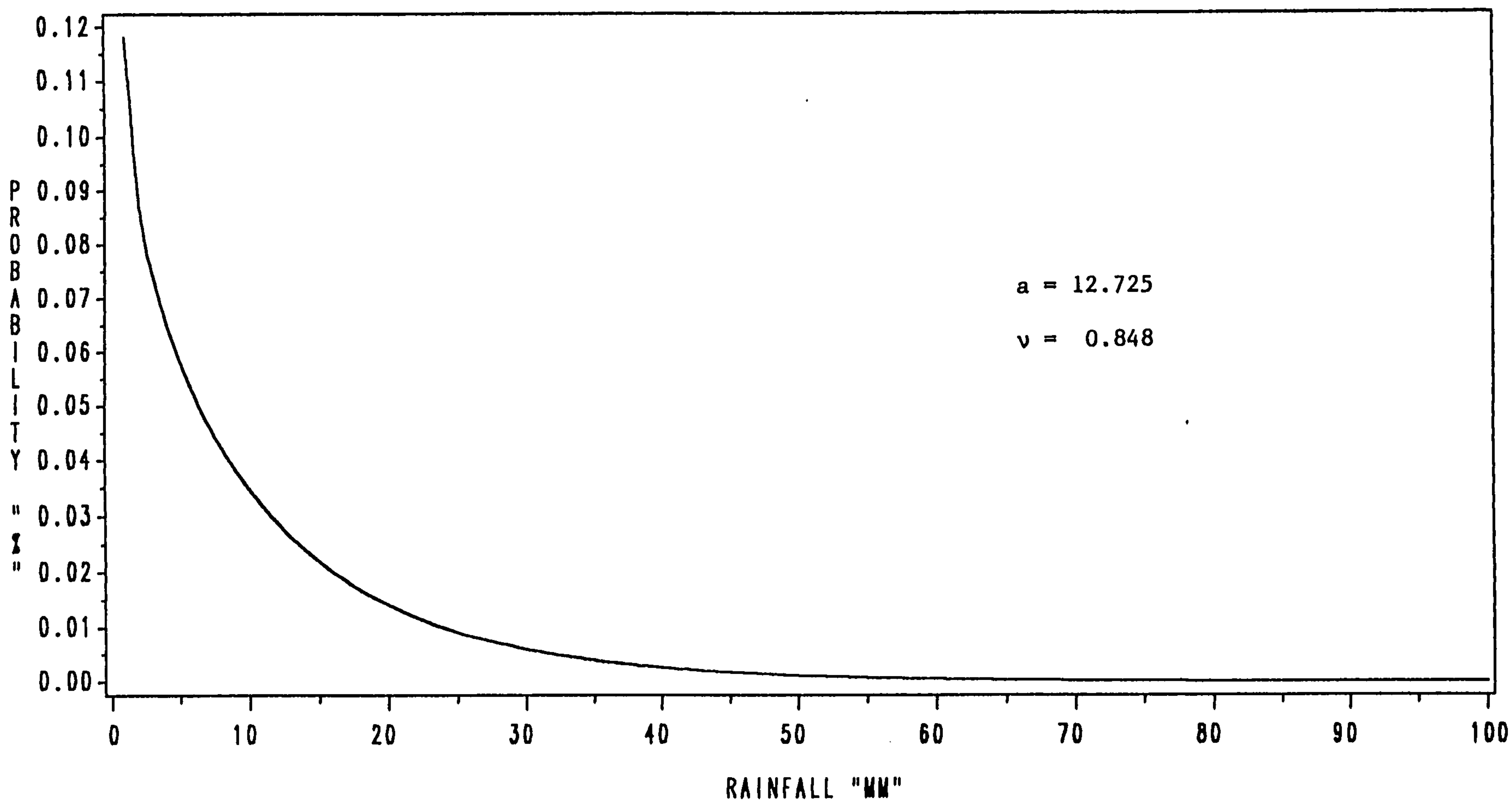


FIGURE 4.4 PROBABILITY OF RAINFALL ON STATION "N103" ASSUMING GAMMA-DISTRIBUTION

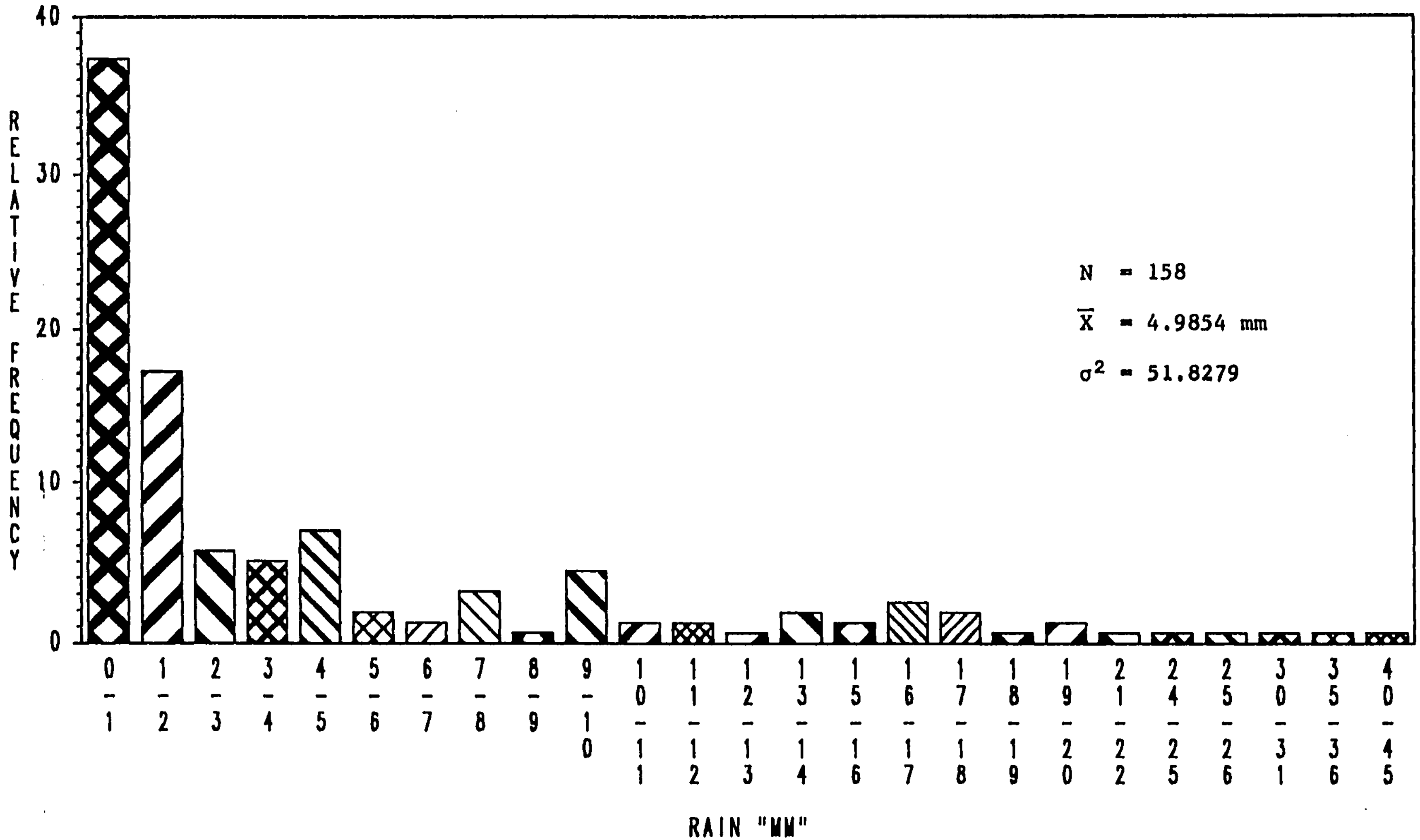


FIGURE 4.5 RELATIVE FREQUENCY HISTOGRAM OF STATION "N201" USING NON-ZERO DAILY RAINFALL DATA FROM 1966 TO 1984

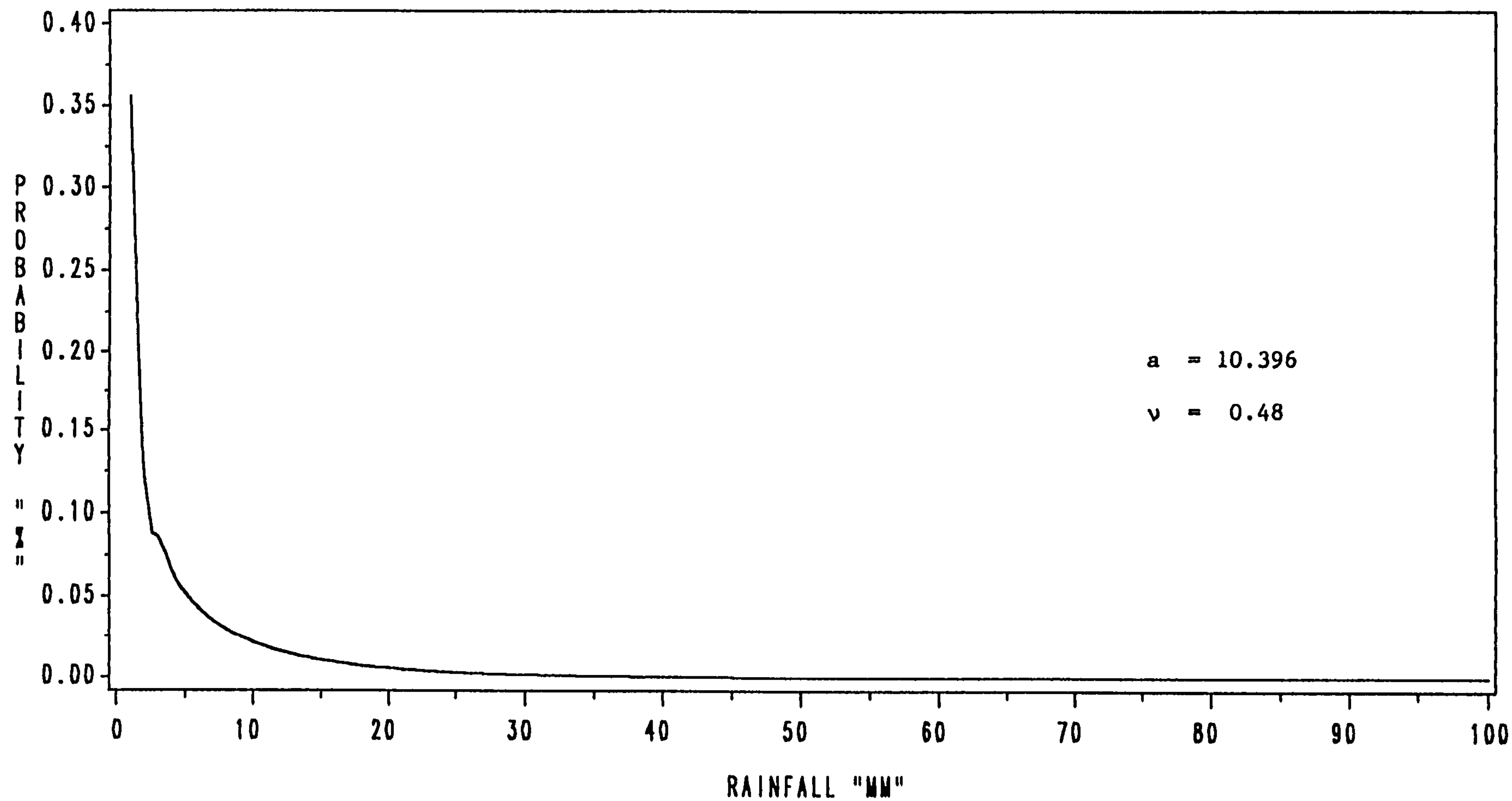


FIGURE 4.6 PROBABILITY OF RAINFALL ON STATION "N201" ASSUMING GAMMA-DISTRIBUTION

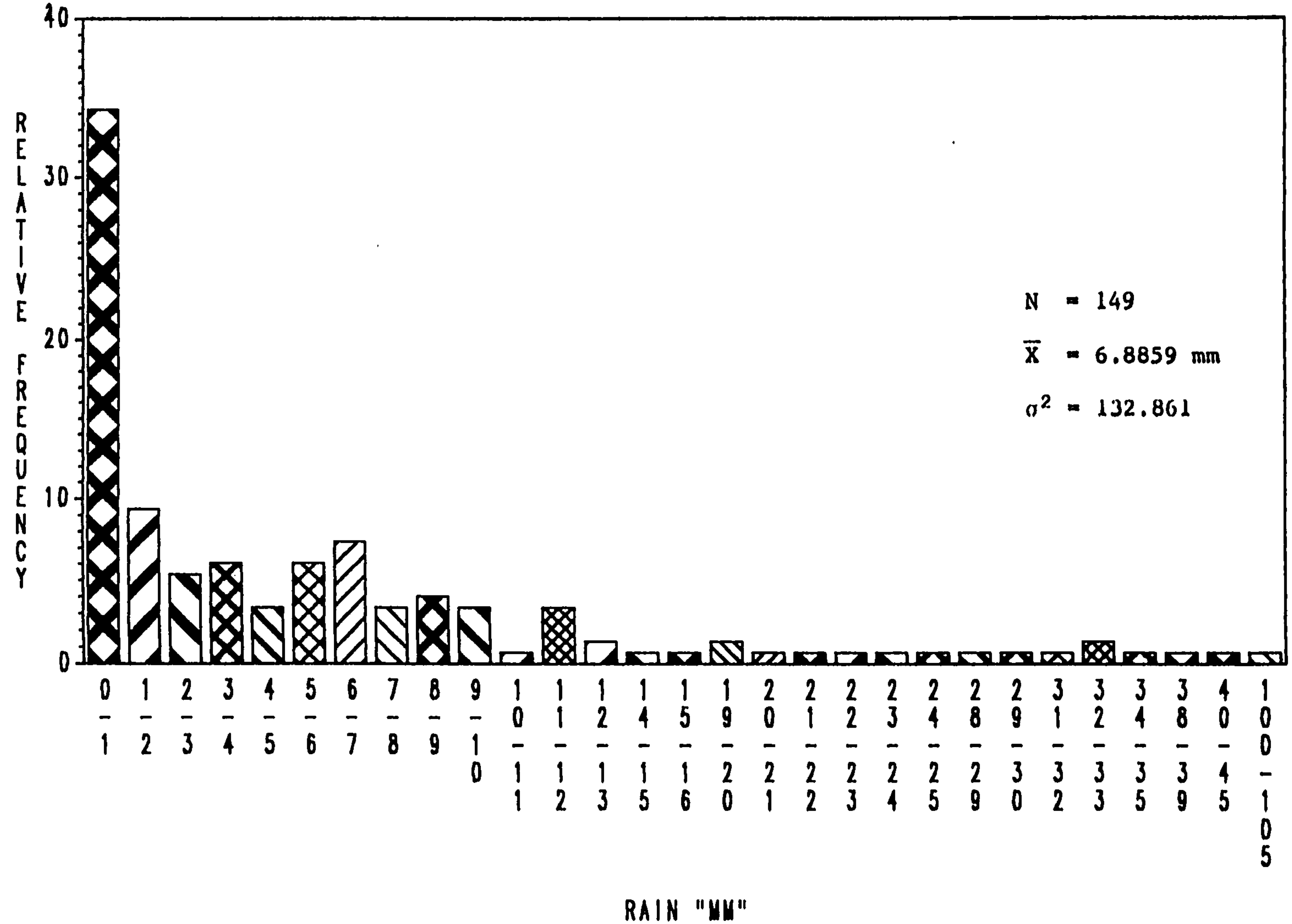


FIGURE 4.7 RELATIVE FREQUENCY HISTOGRAM OF STATION "B004" USING NON-ZERO DAILY RAINFALL DATA FROM 1966 TO 1984

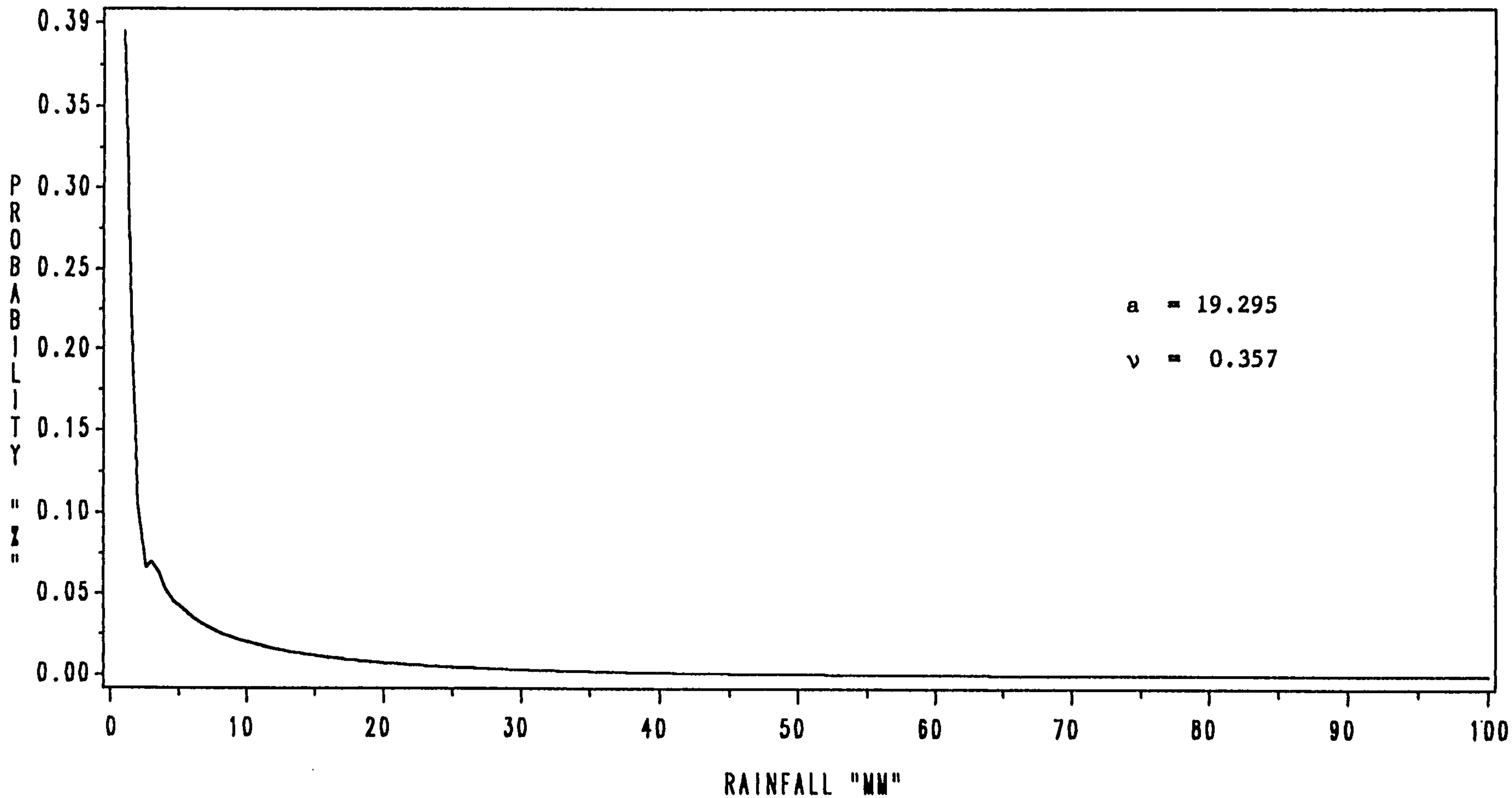


FIGURE 4.8 PROBABILITY OF RAINFALL ON STATION "B004" ASSUMING GAMMA–DISTRIBUTION

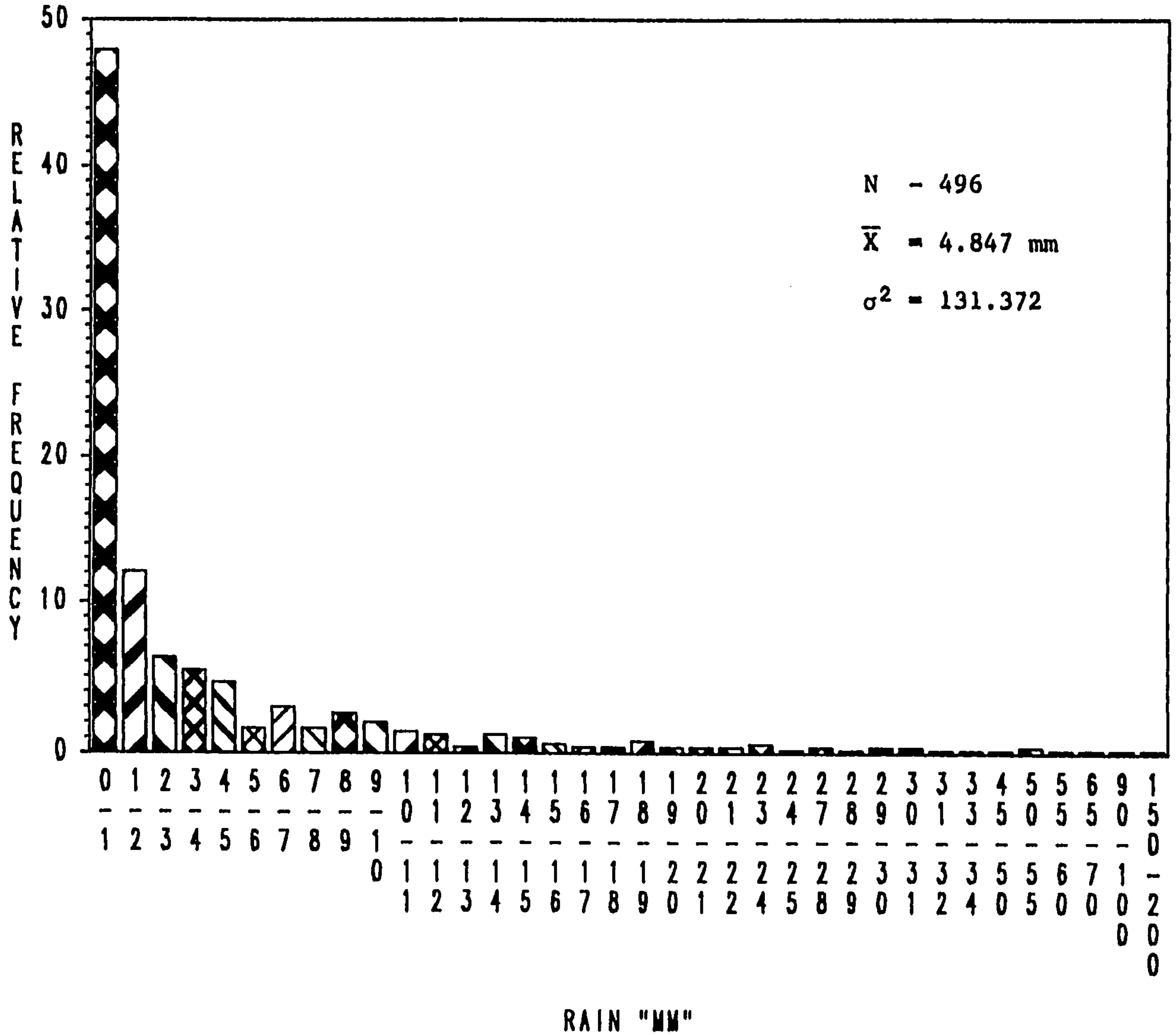


FIGURE 4.9 RELATIVE FREQUENCY HISTOGRAM OF STATION "A213" USING NON-ZERO DAILY RAINFALL DATA FROM 1966 TO 1984

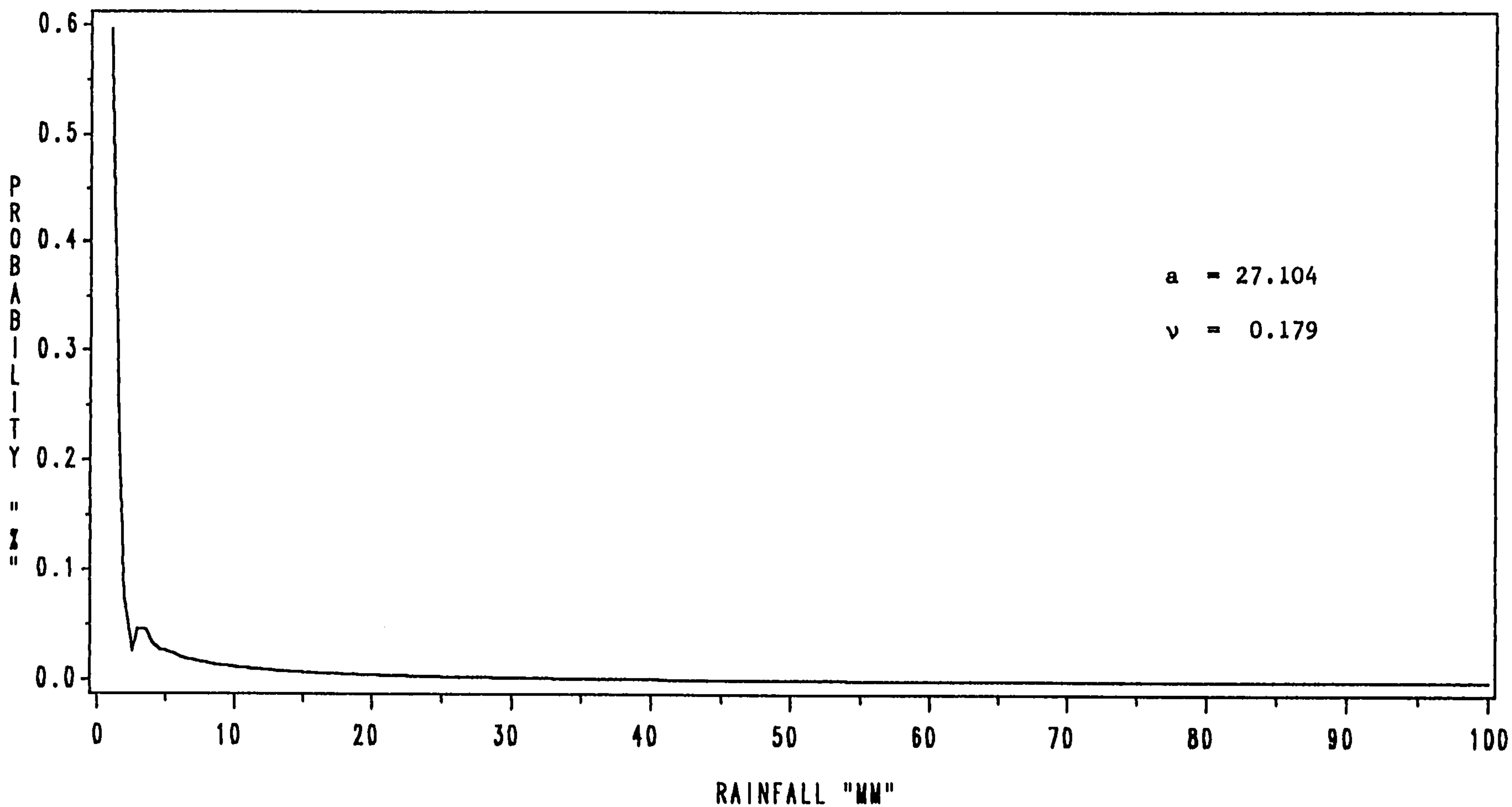


FIGURE 4.10 PROBABILITY OF RAINFALL ON STATION "A213" ASSUMING GAMMA–DISTRIBUTION

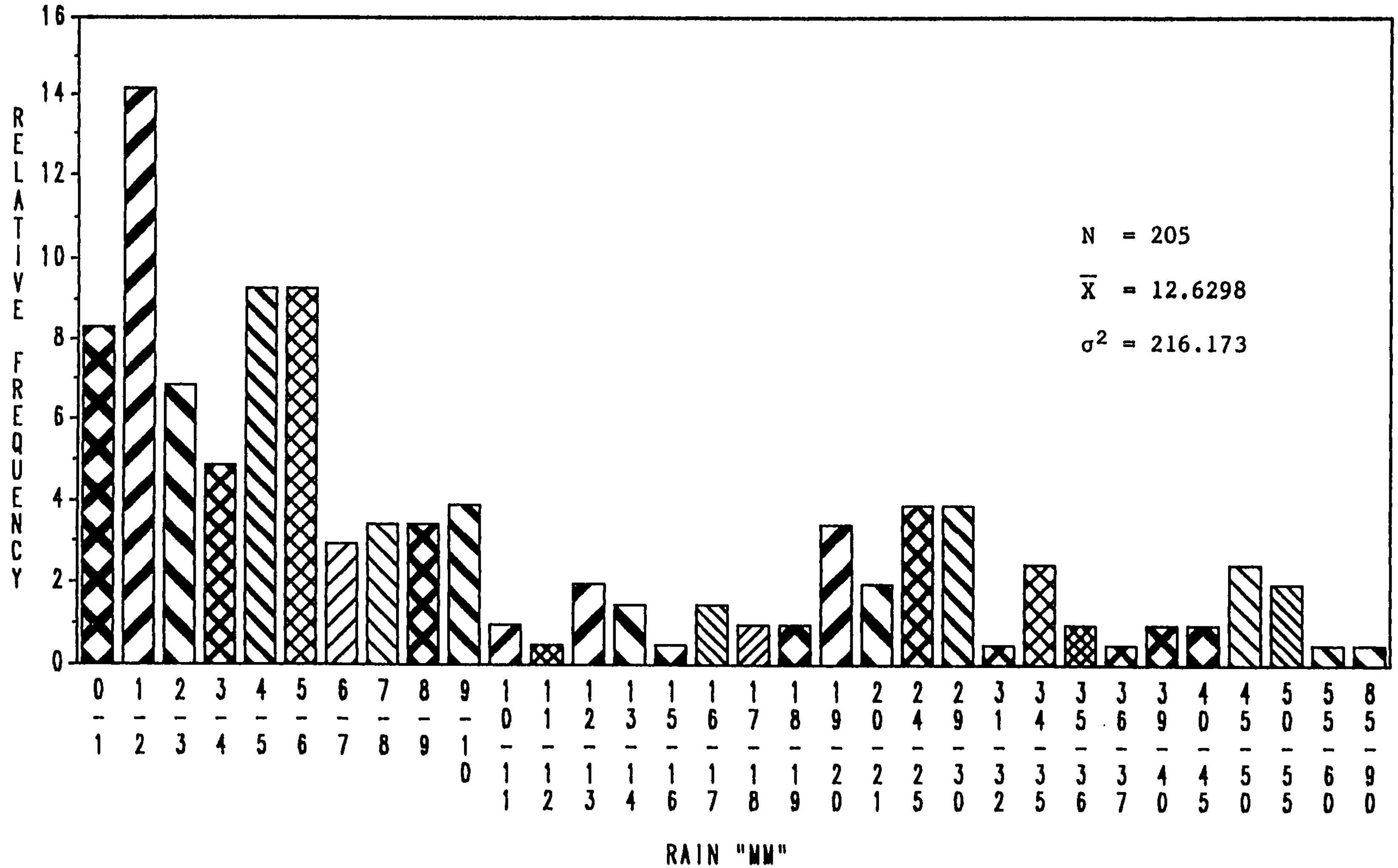


FIGURE 4.11 RELATIVE FREQUENCY HISTOGRAM OF
STATION "A110"
USING NON-ZERO DAILY RAINFALL DATA
FROM 1966 TO 1984

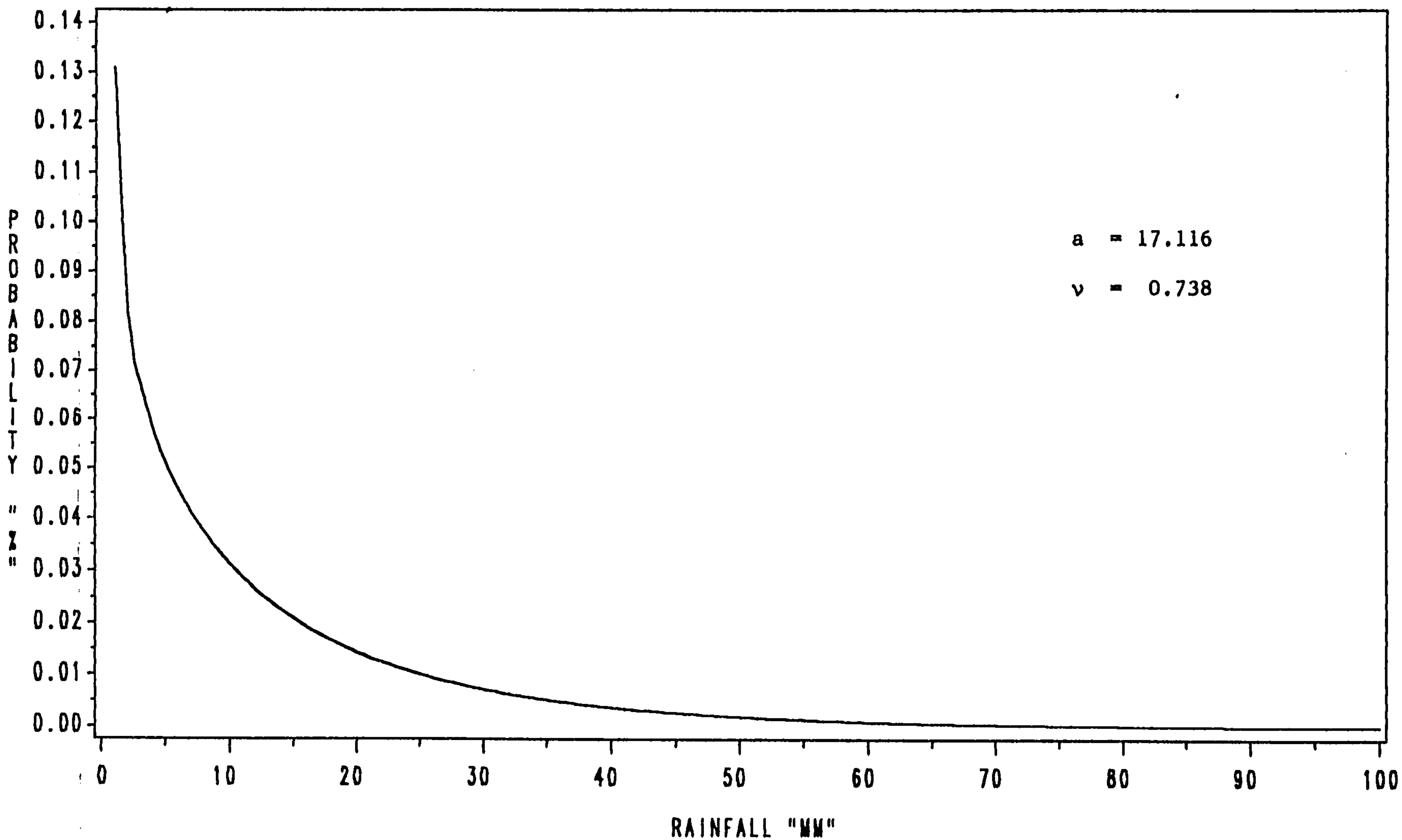


FIGURE 4.12 PROBABILITY OF RAINFALL ON STATION "A110" ASSUMING GAMMA-DISTRIBUTION

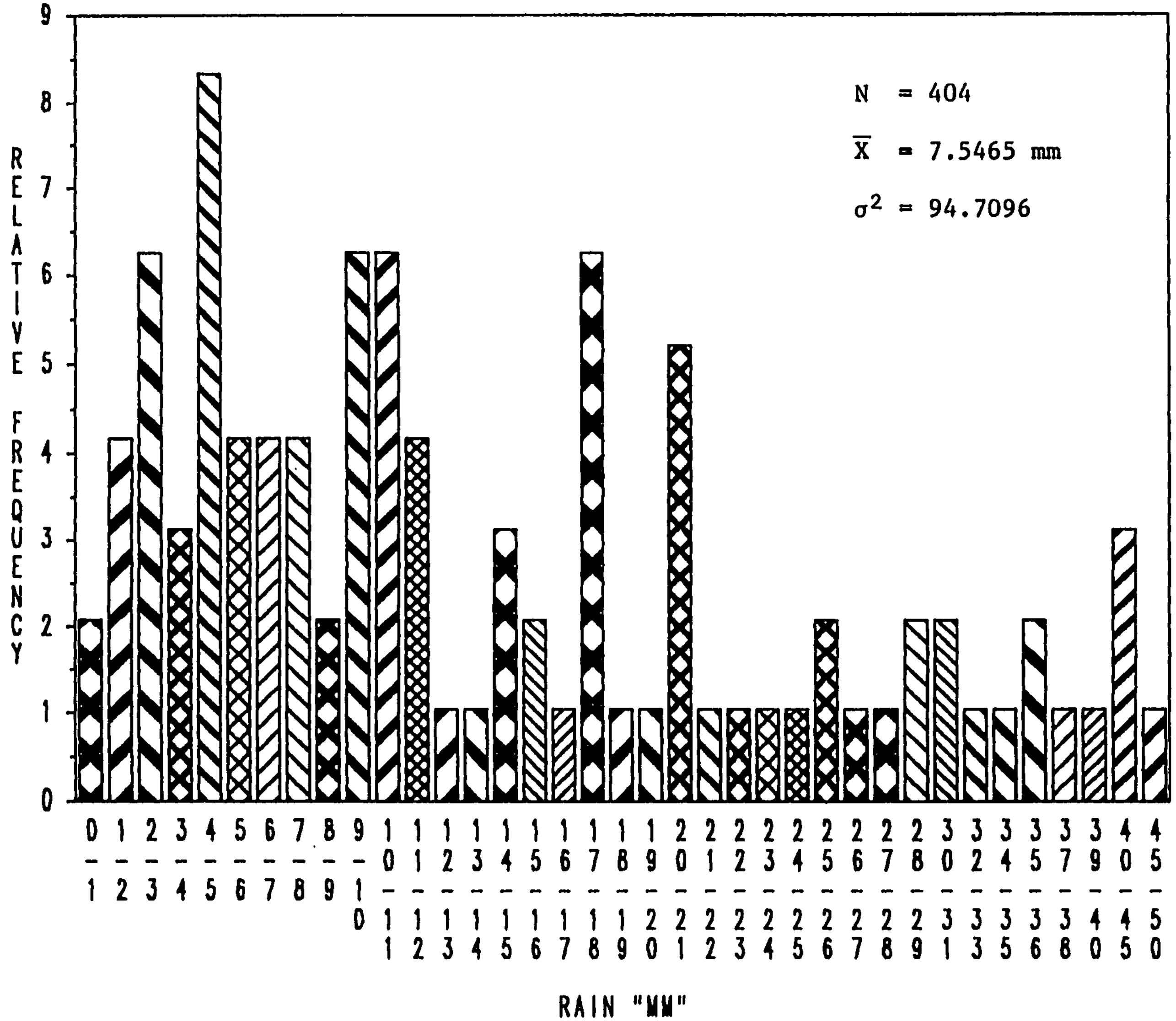


FIGURE 4.13 RELATIVE FREQUENCY HISTOGRAM OF
STATION "A105"
USING NON-ZERO DAILY RAINFALL DATA
FROM 1966 TO 1984

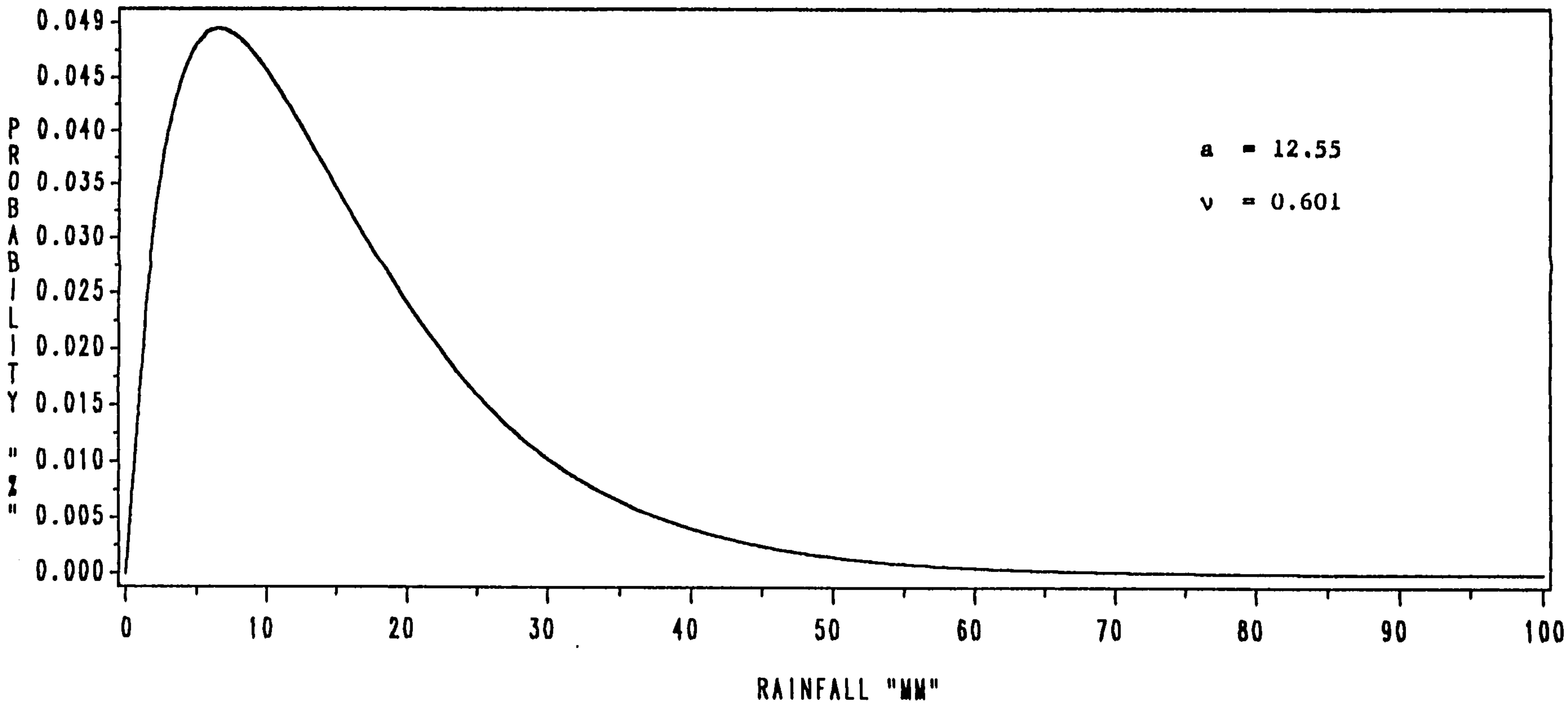


FIGURE 4.14 PROBABILITY OF RAINFALL ON STATION "A105" ASSUMING GAMMA–DISTRIBUTION

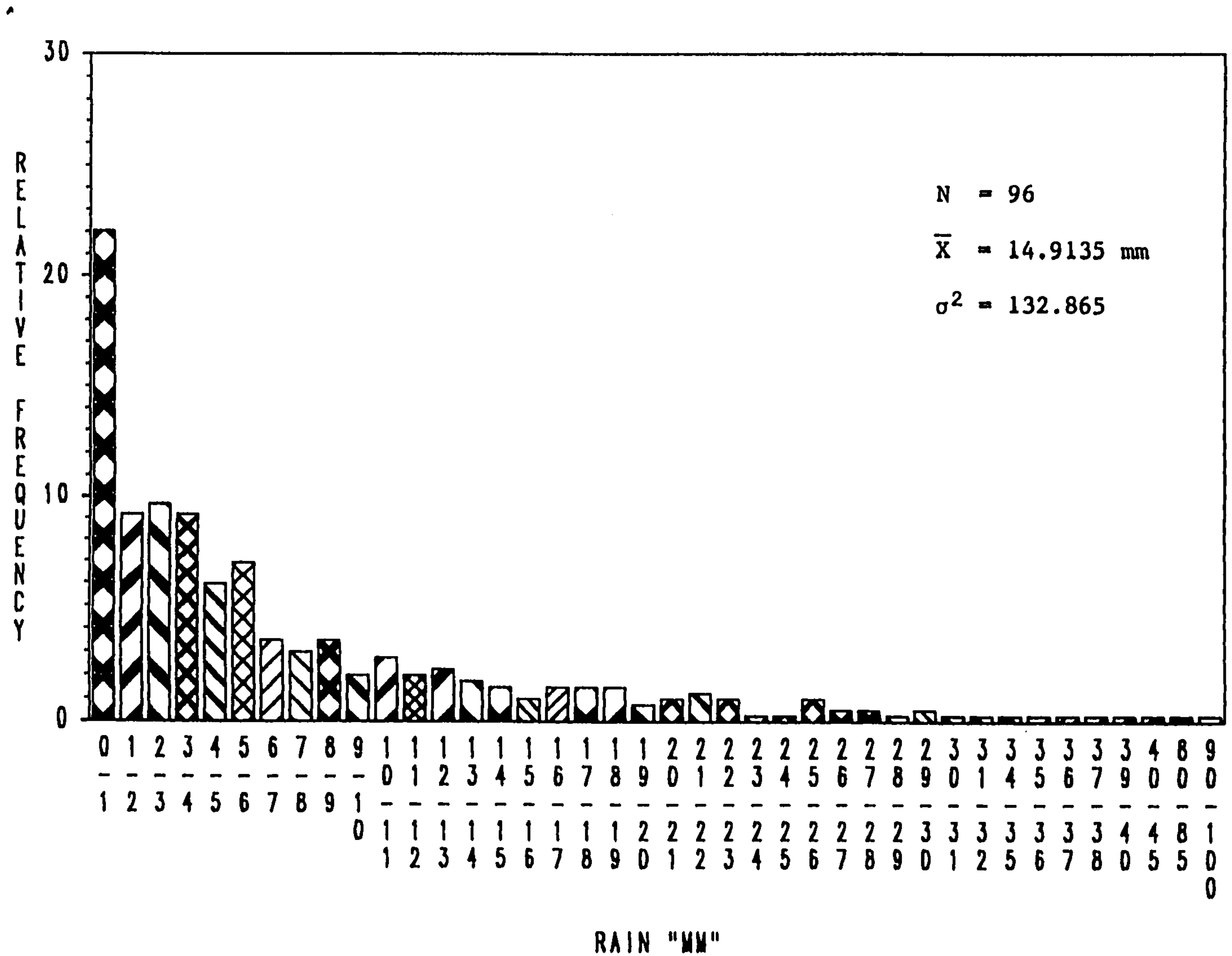


FIGURE 4.15 RELATIVE FREQUENCY HISTOGRAM OF STATION "A108" USING NON-ZERO DAILY RAINFALL DATA FROM 1966 TO 1984

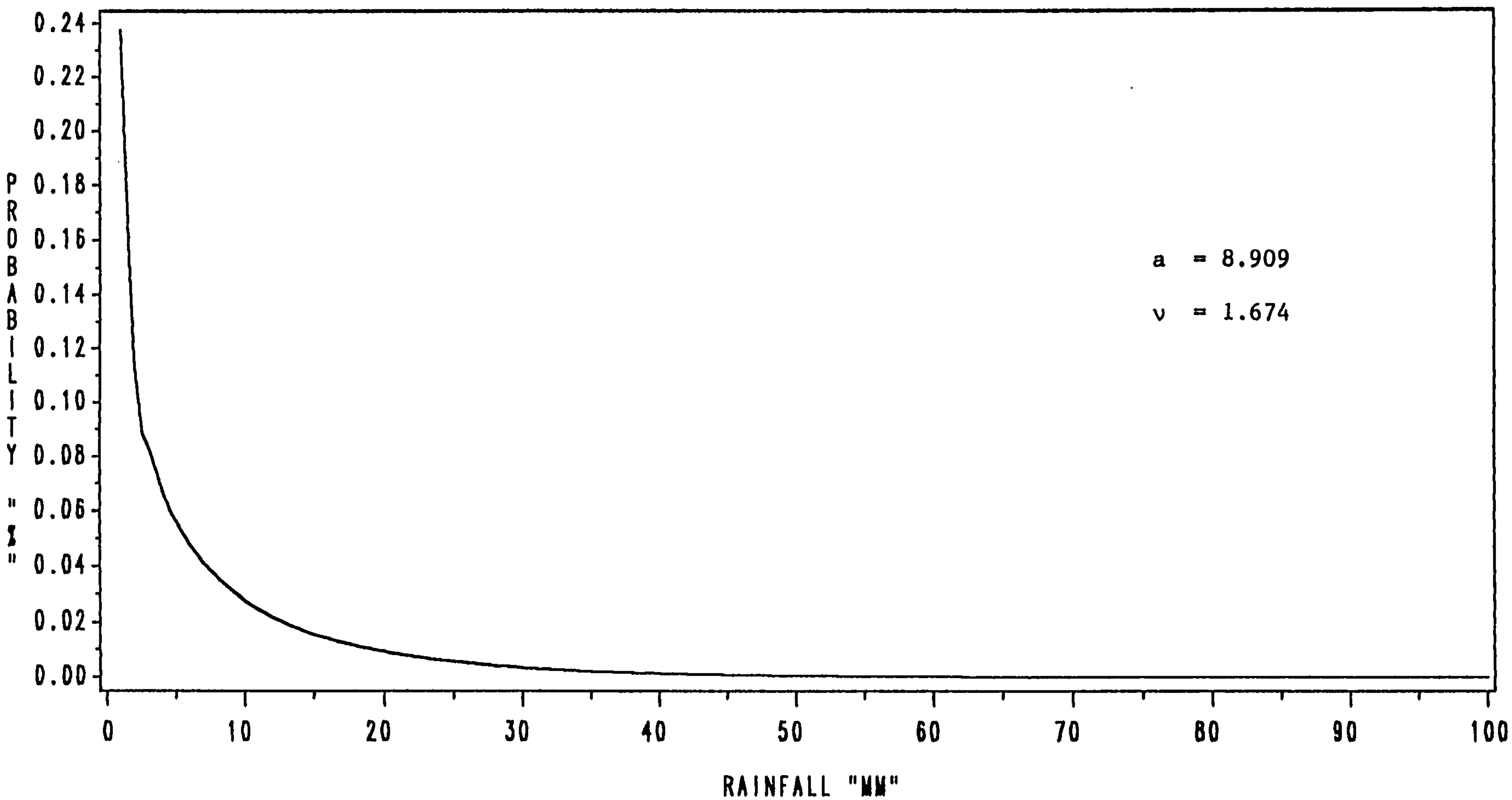


FIGURE 4.16 PROBABILITY OF RAINFALL ON STATION "A108" ASSUMING GAMMA-DISTRIBUTION

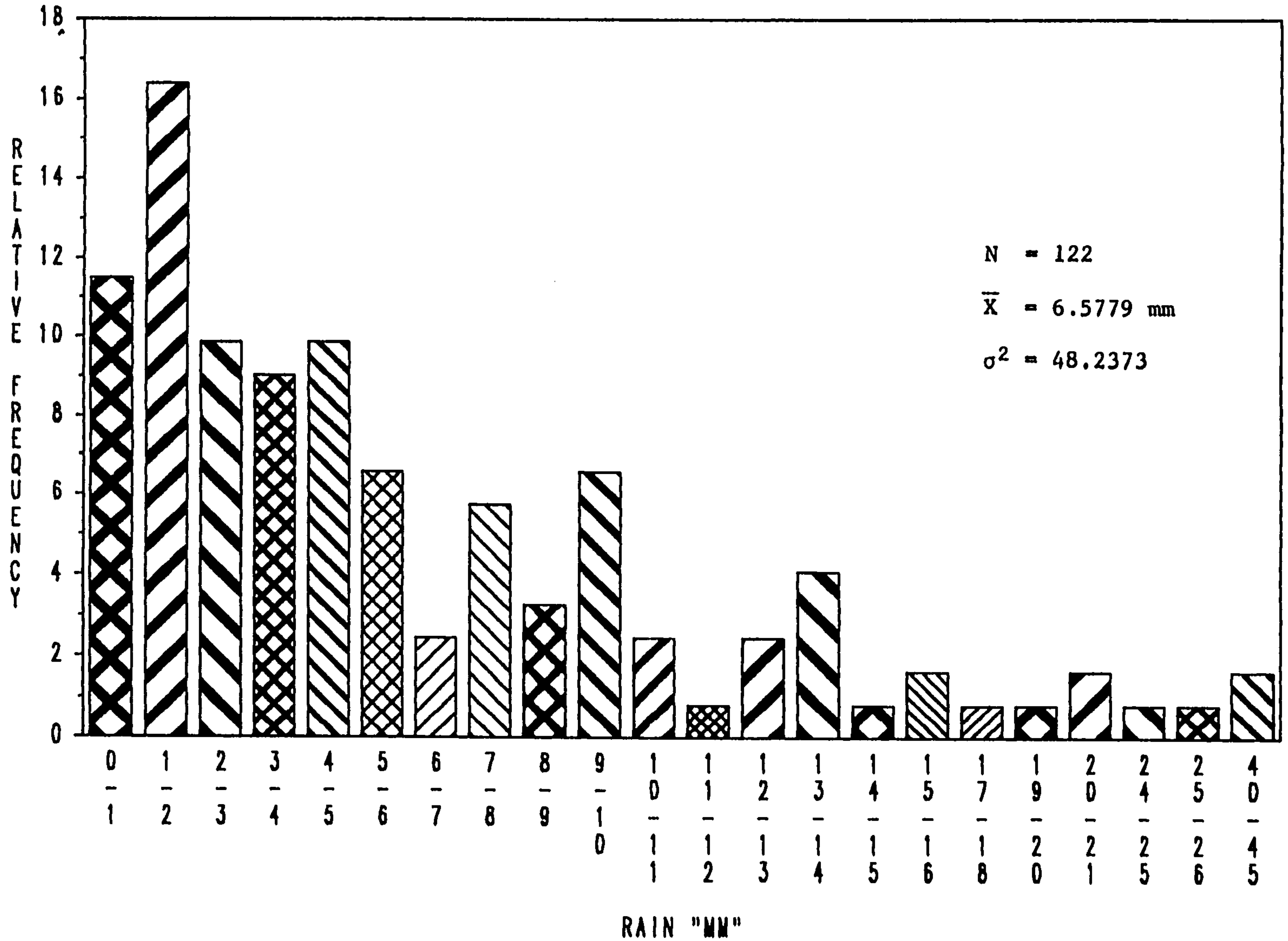


FIGURE 4.17 RELATIVE FREQUENCY HISTOGRAM OF STATION "B209" USING NON-ZERO DAILY RAINFALL DATA FROM 1966 TO 1984

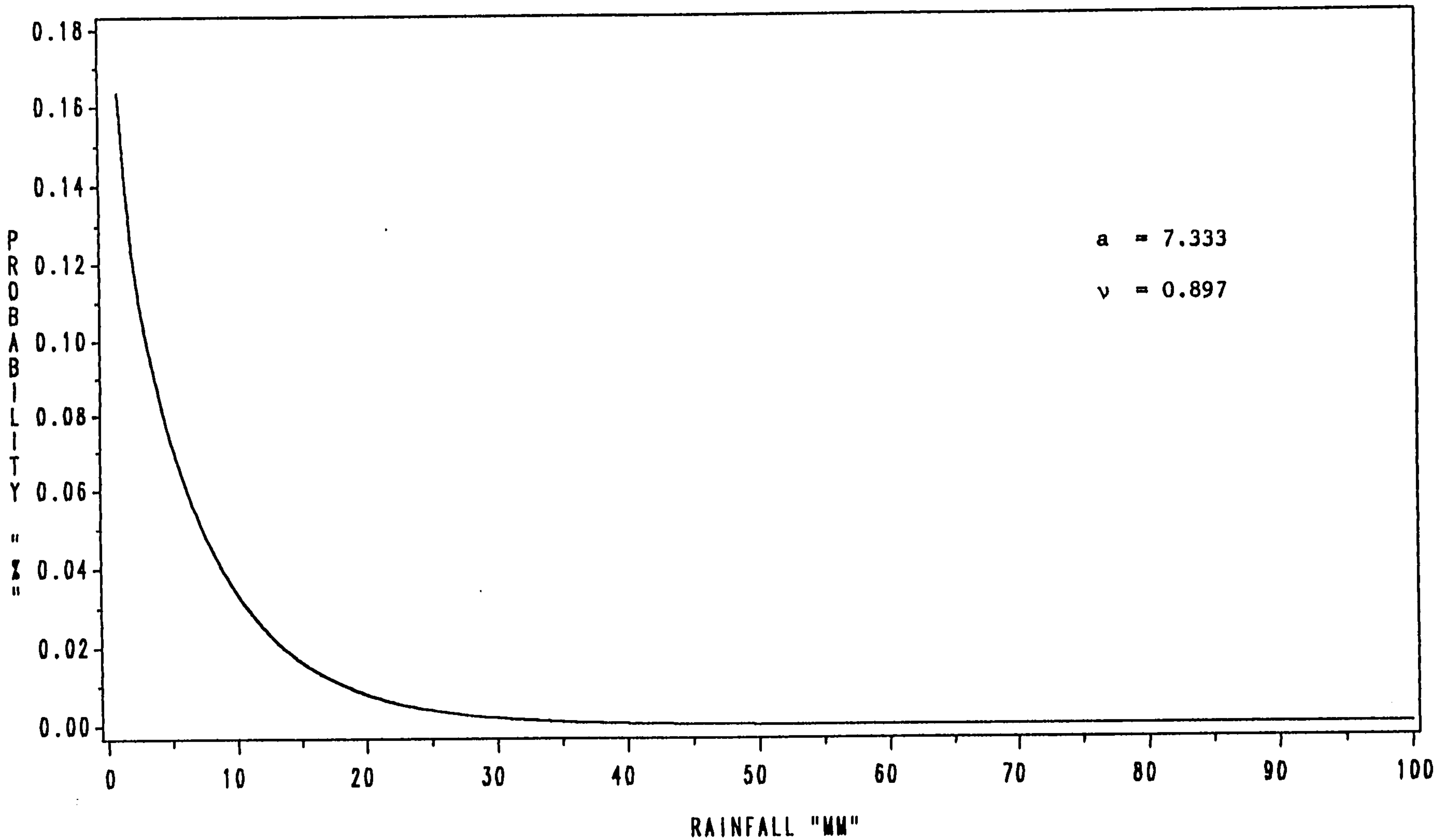


FIGURE 4.18 PROBABILITY OF RAINFALL ON STATION "B209" ASSUMING GAMMA-DISTRIBUTION

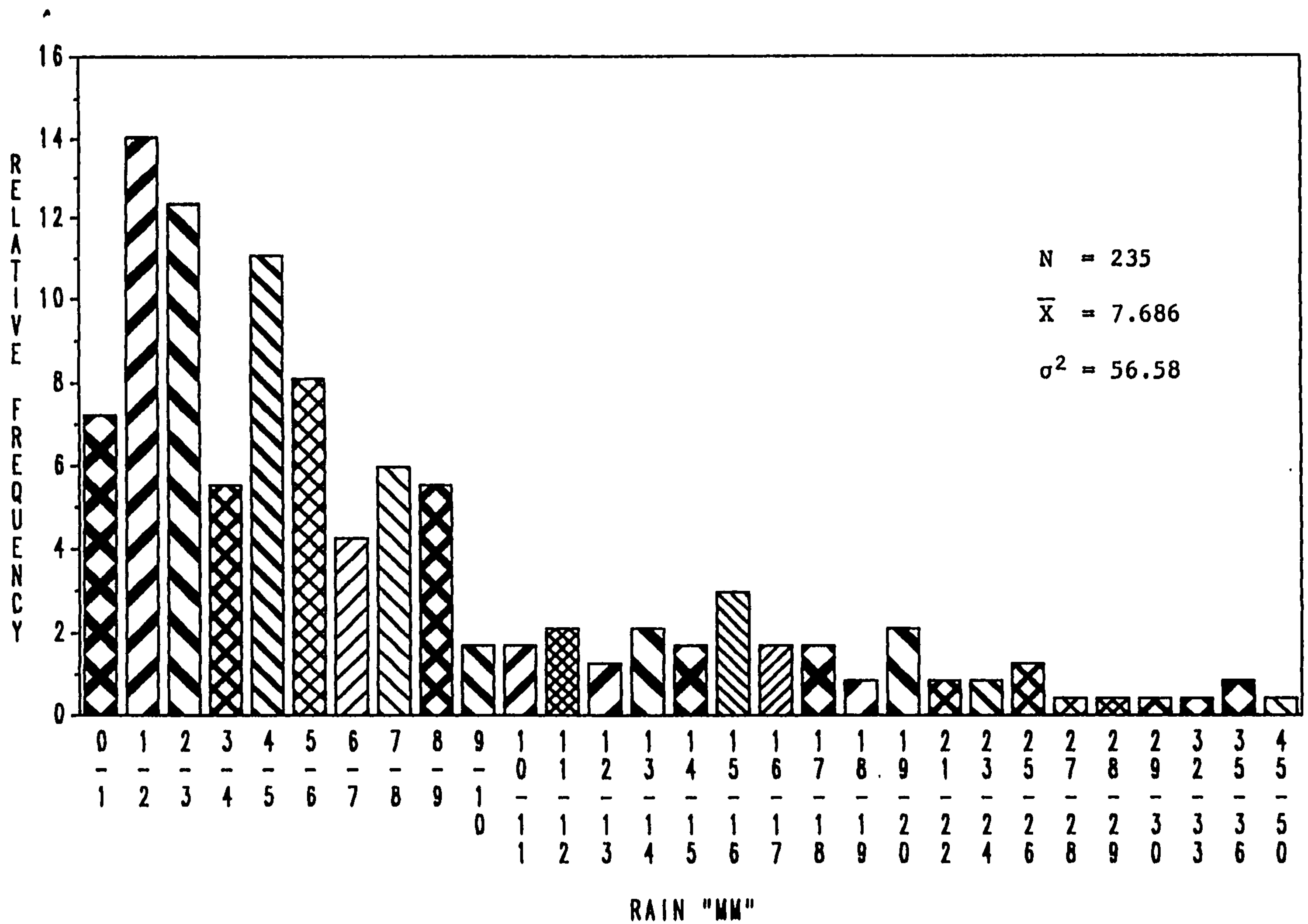


FIGURE 4.19 RELATIVE FREQUENCY HISTOGRAM OF STATION "TA112" USING NON-ZERO DAILY RAINFALL DATA FROM 1966 TO 1984

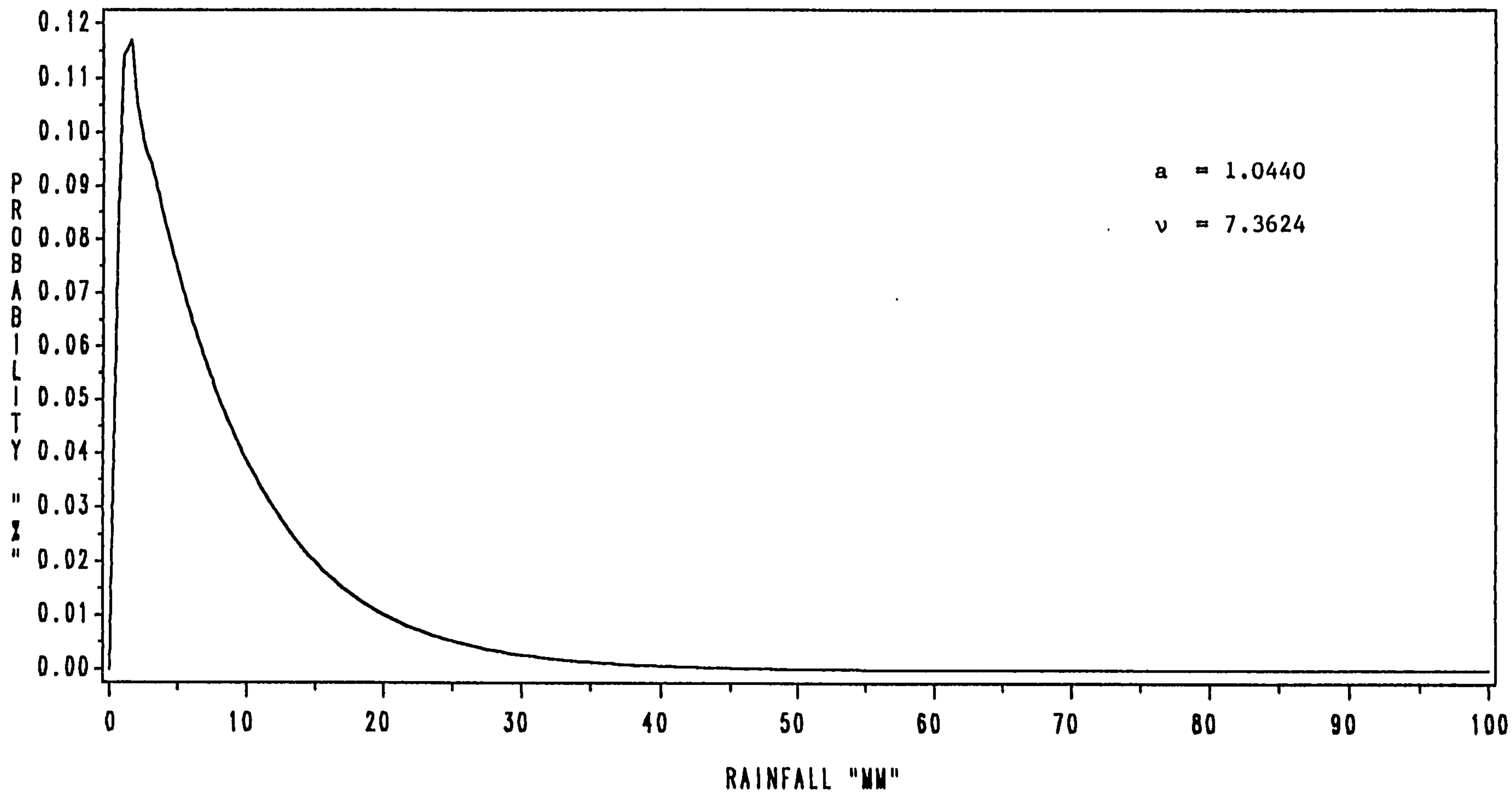


FIGURE 4.20 PROBABILITY OF RAINFALL ON STATION "TA112" ASSUMING GAMMA-DISTRIBUTION

$$\upsilon = \frac{(\text{Mean})^2}{\text{Variance}} \tag{4.2}$$

$$a = \frac{\text{Variance}}{\text{Mean}} \tag{4.3}$$

The exponential distribution is a gamma-distribution with $\upsilon = 1.$ or

$$f_{exp}(x;a)=a\ e^{-ax} \quad x \geq 0\ ,\ a > 0. \tag{4.4}$$

Chi-square test (goodness of fit) was also performed to examine the fitted distribution. This test proved that the selected distribution, gamma-distribution is accepted. Appendix A shows samples of chi-square test of some selected stations. Therefore, gamma-distribution will be used in analysis undertaken in this study as the best fitted distribution of rainfall data. Figures 4-1 through 4.18 show relative frequency histograms and the corresponding gamma-distribution curves for each of the selected stations respectively.

Chapter 5

SHANNON'S INFORMATION MEASURE

5.1 Historical Background

Shannon's information theory is a measure of uncertainty associated with the occurrence of events (Husain and Khan, 1983). This concept was developed by Shannon in 1948 to be applied in the field of communications (Shannon and Weaver, 1949). Since 1949, Shannon's information theory has been successfully applied in various areas of science and technology other than communications engineering such as economics, thermodynamics, hydrology, statistical mechanics, reservoir engineering, turbulence, structural reliability, and landscape evolution (Singh, Rajagopal and Singh, K., 1986).

In hydrology, this methodology has previously been applied in network design. For example, it has been applied in the design of hydrological networks (Caselton and Husain, 1980; Husain, 1987), meteorological networks (Ukayli, Husain and Khan, 1982; Husain and Ukayli, 1986), and air quality monitoring networks (Husain and Khan, 1983).

5.2 Hydrological Network and Communication System

The communication system can be represented schematically as shown in Figure 5.1 as information encoder, transmitter, receiver and decoder. When a source sends a message, it will be encoded by a transmitter into a signal which will be transmitted on the communication channel, then the receiver will change the received signals and change it back into a message source. During this process of information transmission, distortion sometimes occurs causing errors in transmission. All of these changes in transmitted signals are called noise (Husain and Ukayli, 1986; Caselton and Husain, 1980).

The analogy between a hydrological network transmitting information and the communication system described above is explained in the following paragraphs.

The hydrology of a region served by a network is represented in Figure 5.2 by the magnitude of hydrologic events occurring successively in time at each of a large number of point locations dispersed throughout the region. This set of event magnitudes may be considered to form the hydrologic information or message source. The objective of the hydrological stations, which occupy only a small number of point locations, is to act collectively as a transmitter for the hydrological data. The measurements of a number of hydrological variables are encoded, which will represent the hydrological variabilities throughout the region. These values will be recorded and then transmitted to the data base, where the magnitudes of the hydrological events at the ungauged points are subsequently reconstituted (decoded) using the network station measurements and some form of

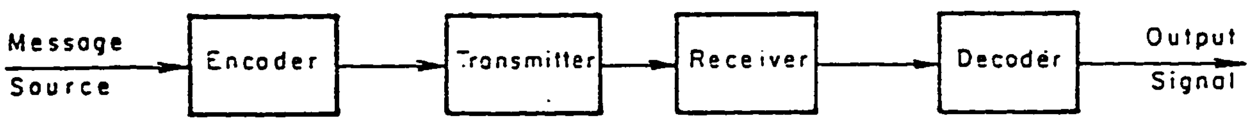


Fig. 5.1: Conventional Representation of Communication System (Shannon, 1949).

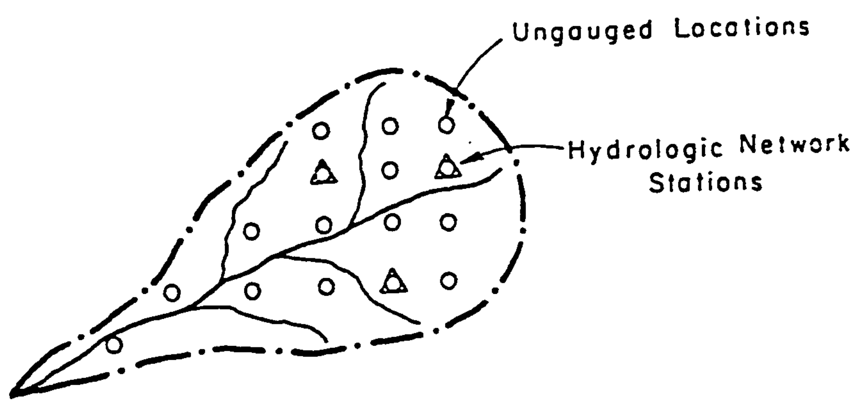


Fig. 5.2: Grid Point Representation of Communication System (Caselton, 1980).

interpolation or spatial estimation model. The complete output signal will be represented by the combined network station measurements and the reconstituted values for ungauged locations (Ukayli, Husain and Khan, 1982; Caselton and Husain, 1980). The hydrological network as a communication system can be represented as shown in Figure 5.3 (Caselton and Husain, 1980).

In order to fully estimate the hydrological events of a specific area, a station must be installed at every point location of interest in the region. However, this behavior is not logical due to many reasons such as budget constraints. Therefore, one must select an acceptable number of stations (network) that most closely represents the hydrological events occurring in the area. Then, the performance of this hydrological network can be evaluated by measuring the values of reduction of uncertainty of the information transmitted between the input message and output signals. Even though errors will be included in the output signals, one should try to minimize measuring uncertainty by increasing the existing number of stations or changing the orientation of the network, i.e., changing the station locations (Caselton and Husain, 1980).

5.3 Shannon's Information Methodology

The measure of uncertainty associated with the occurrence of event is defined by Shannon as an entropy. For a hydrological variable X (e.g. rainfall) measured at a station with events

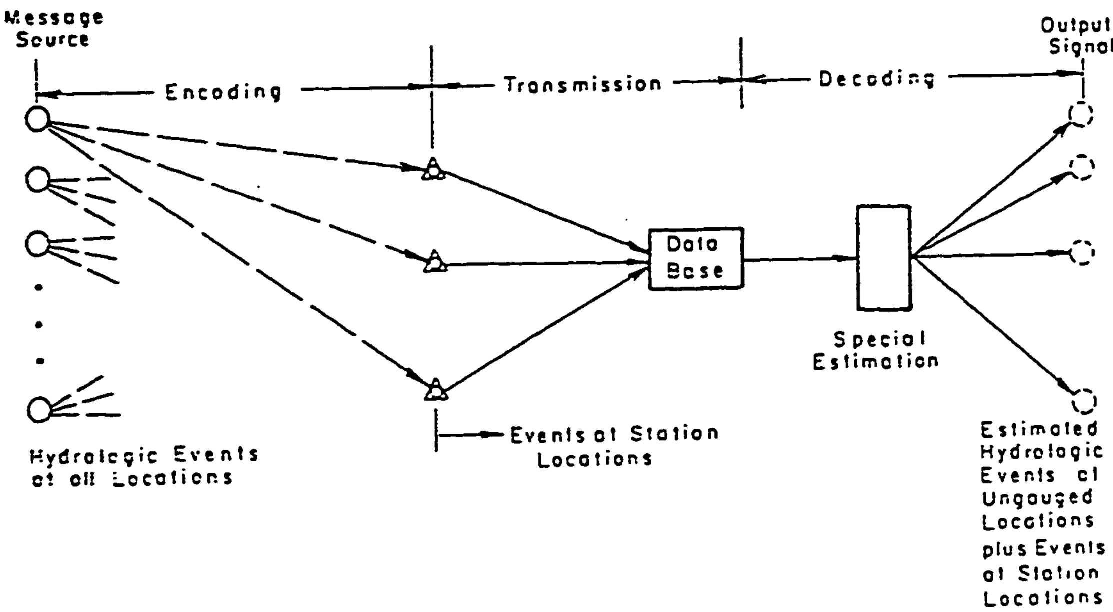


Fig. 5.3: Hydrologic Network as Communication System (Caselton, 1980).

$(x_1, x_2, \ldots X_n)$, the entropy is formulated as (Husain and Caselton, 1980; Chapman, 1986):

$$H(X) = -\sum_{i=1}^{N} P(X_i) \log_2 P(X_i) \quad (5.1a)$$

where $P(X_i)$ is the probability of the outcome X_i. The units of entropy depend on the base of algorithm in eqn. (5.1a). It will be "bits" for base 2 and "decibel" for base 10. For computational convenience, a natural logarithm is considered for entropy computation throughout this study with units of measurement "nats" (Chapman, 1986). For continuous distribution the entropy was calculated as follows:

$$H(X_i) = -\int_0^{\infty} f(X_i:\mu_1,\mu_2,\mu_3,\ldots,\mu_l) \ln f(X_i:\mu_1,\mu_2,\mu_3,\ldots,\mu_\ell)\, dX_i \quad (5.1b)$$

in which $f(X_i:\mu_1,\mu_2,\mu_3,\ldots,\mu_\ell)$ is the probability density function of hydrologic variable X_i and is fitted by a continuous distribution with parameters $(\mu_1,\mu_2,\ldots,\mu_\ell)$.

The concept of entropy can be generalized to more than one station measuring the same variable, (e.g. rainfall). For example, when there are "m" stations in a region with variables $(X_1, X_2, \ldots X_m)$, then the joint entropy will be:

$$H(X_1, X_2, \ldots X_m) = -\sum_{i=1}^{m} P(x_i^1, x_i^2, \ldots x_i^m) \log P(x_i^1, x_i^2, \ldots x_i^m) \tag{5.2}$$

where $(X_1, X_2, \ldots X_m)$ are the measured hydrologic variable at "m" stations, and $P(x_i^1, x_i^2, \ldots x_i^m)$ is the joint probability of occurance of the ith event at "m" stations.

Chapter 4 shows that the hydrological variable (rainfall) will follow a gamma-distribution. The entropy of this continuous distribution function using eqn. (5.1b) is:

$$H(X) = -\int_0^\infty f_G\,(x;\upsilon,a)\ \ln f_G(X;\upsilon,a)\ dx \tag{5.3}$$

The entropy of gamma-distribution function has been simplified to (Husain, 1987):

$$H(X) = -(\upsilon - 1)\ \Psi\ (\upsilon) + \ln \Gamma(\upsilon) + \upsilon + \ln a \tag{5.4}$$

where $\Psi(\upsilon)$ is the digamma function defined by (Chapman, 1986):

$$\Psi(\upsilon) = \frac{d}{d\upsilon} \ln(\upsilon). \tag{5.5}$$

There are various forms of bivariate gamma distribution but due to limitations in their derivations, their application is very limited (Mardia, 1960). For example, the following form

$$F_G(x,y;a,p,q) = \frac{a^{(P+q)}}{\Gamma(P)\,\Gamma(q)}\, x^{P-1}\, e^{-ay}\, (y-x)^{q-1} \tag{5.6}$$

$$y > x > 0$$

$$a,\ P,\ q > 0$$

which defines bivariate gamma distribution, assuming that one variable should be greater than the other. However, this is not the case when dealing with rainfall data where precipitation at one station is not always greater than the precipitation on the other station. To resolve this complexities, gamma-distribution values will be transformed to normalized variates z and w as follows:

$$\frac{1}{\sqrt{2\pi}} \int_{-\infty}^{z} e^{-\frac{1}{2}t^2}\, dt = \int_{0}^{x} f(t;\ \upsilon_x,\ a_x)\, dt \tag{5.7a}$$

$$\frac{1}{\sqrt{2\pi}} \int_{-\infty}^{w} e^{-\frac{1}{2}t^2}\, dt = \int_{0}^{y} f(t;\ \upsilon_y,\ a_y)\, dt \tag{5.7b}$$

where x and y are the gamma-distribution variables with parameters (υ, a), whereas z and w are the normalized variables of x and y with mean of zero and variance of one (Husain, 1989). Shannons (1949) shows that the information transmitted by variable x about y, or y about x is:

$$T(x;y) = T(y;x) = -\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} f_n(z,w) \ln \frac{f_n(z,w)}{f_n(z) f_n(w)}\, dzdw \tag{5.8}$$

where

$f_n(z,w)$ = normal probability function of normalized variates z and w, transformed from $f_G(x,y;\ \upsilon_x, a_x, \upsilon_y, a_y)$

$f(z)$ = normal probability function of normalized variate z and transformed from $f_G(x;\ \upsilon_x, a_x)$.

$f(w)$ = normal probability function of normalized variate w and transformed from $f_G(y;\ \upsilon_y, a_y)$.

If ρ_{zw} is the correlation coefficient between z and w, then Equation (5.8) can be simplified to (Husain, 1987; Husain, 1989):

$$T(x;y) = T(y;x) = -\frac{1}{2}\ln(1 - \rho_{zw}^2). \qquad (5.9)$$

In hydrologic network optimization the objective is to retain a station or a number of stations from a dense network so that maximum information will be transmitted by the retained station or stations about the region (Husain and Caselton, 1980; Husain, 1987). For a single station to be retained from a dense network with "m" stations, the objective function is:

$$\text{Max } T(X_1, X_2, \ldots X_m; X_L) = \text{Max} \sum_{i=1}^{m} T(X_i; X_L)$$

$$= H(X_L) + \sum_{i=1}^{m-1} T(X_i;X_L) \qquad (i \neq L)$$

$$(i=1,2,\ldots m)$$

(5.10)

where

$T(X_1,X_2, \ldots X_m,X_L)$ is the total information transmitted by station X_L about the region, and $T(X_i,X_L)$ is the information transmitted by station "L" about individual station "i" and equal to $H(X_i) + H(X_L) - H(X_i,X_L)$. Similarly, to retain a group of stations from an existing dense network, the objective function is as follows:

$$\text{Max } T(X_1,X_2, \ldots X_m; X_K,X_L, \ldots X_S)$$

$$= \text{Max } \sum_{i=1}^{m} T(X_i,X_K,X_L, \ldots X_S)$$

$$= \text{Max} \left[H(X_K) + H(X_L) + \ldots H(X_s) + \sum_{i=1}^{m-s} \sum_{j=1}^{s} T(X_i;X_j) \right]$$

(5.11)

where (K,L,...,S) are the set of stations to be selected from "m" stations existing in a dense network. All possible stations combinations will be tried to calculate the transmitted information, for example, selecting a set of "n" stations from a dense network of "m" stations the possible combinations will be

$$\binom{m}{n} = \frac{m!}{n!(m-n)!}$$

where m! (m factional) = m (m-1)(m-2)...., from those combinations stations that give maximum information will be retained (Caselton and Husain, 1980).

Shannon's information theory can also be applied for hydrological network expansion using the data of the existing network to improve its adequacy. To show how this technique can be applied, it is better to explain it on a small scale. For this purpose. select three stations (i, j, K), as shown in Figure 5.4, measuring hydrological variable (e.g. rainfall) X_i, X_j and X_K respectively. Then, the entropy of each variable between each pair of them will be (Husain and Ukayli, 1986; Husain, 1989):

$$H(X_i) = T(X_i;X_j) + H(X_i,X_j) - H(X_j) \qquad (5.12a)$$

$$H(X_j) = T(X_i;X_j) + H(X_i,X_j) - H(X_i) \qquad (5.12b)$$

$$H(X_i) = T(X_i;X_K) + H(X_i,X_K) - H(X_K) \qquad (5.12c)$$

$$H(X_K) = T(X_i;X_K) + H(X_i,X_K) - H(X_i) \qquad (5.12d)$$

$$H(X_j) = T(X_j;X_K) + H(X_j,X_K) - H(X_K) \qquad (5.12e)$$

$$H(X_K) = T(X_j;X_K) + H(X_j,X_K) - H(X_j) \qquad (5.12f)$$

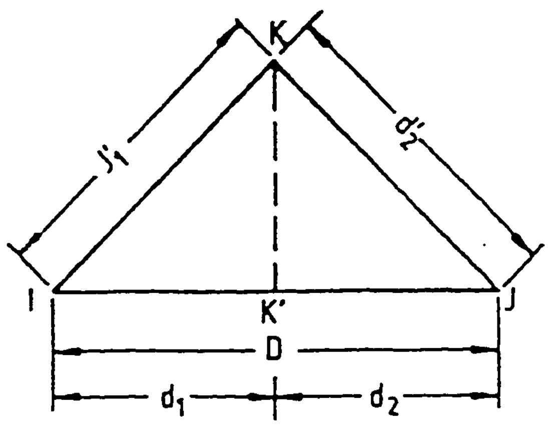


Fig. 5.4: Triangular Element Formed by Joining Three Hydrological Stations (i, j and k) Measuring Hydrological Variables X_i, X_j and X_k, respectively (Husain, 1989).

The above equations show that for any pair of stations on the same line such, as (i,j), a common information $T(X_i;X_j)$ between them will exist. Also, net information $H(X_i,X_j) - H(X_j)$ at i will exist which depends on the distance between the station pair and will be greatest at the station locations. The relationship between the three stations and the entropy as well as the transmitted information is shown schematically in Figure 5.5 (Husain and Ukayli, 1986).

Ukayli (1982) describes the variation of the net information for pair of stations, shown in Figure 5.5, to behave exponentially as:

$$Y_i = C \; e^{-bd_i/(D-d_i)} \qquad (5.13)$$

where

Y_i = net information at a distance d_i from station "i".

C = net information at station location

b = coefficient of the exponential decay curve

D = distance between pair of stations.

To find the total interpolated information at any point, exponential decay coefficients of any point lying between two stations should be computed. For example, total interpolated information at location K lying between stations i and j, as shown in Figure 5.5 is

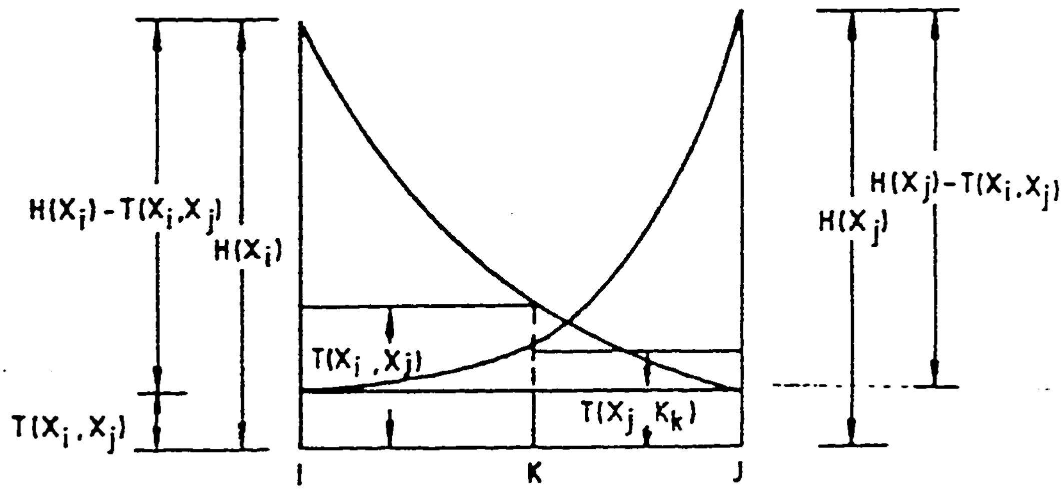


Fig. 5.5: Schematic Diagram Entropy, Information Transmission and Decay Curve (Husain, 1989).

computed using

$$Y_i = T\,(X_i;X_k) - T\,(X_i;X_j) \tag{5.14}$$

Therefore,

$$T(X_i;X_k) - T(X_i;X_j) = [H(X_i)-T(X_i;X_j)]\, e^{-b(D-d_2)/d_2} \tag{5.15}$$

from which the coefficient "b" (originally from i to j) will be

$$b = [d_2/(D-d_2)]\,[H(X_i) - T(X_i;X_j)\,]/\,[\,T(X_i,X_k) - T\,(X_i;X_j)\,] \tag{5.16}$$

Also, the exponential decay coefficient from j to i will be determined as before which equals:

$$b' = [d_1/(D-d_1)]\,[H(X_i) - T(X_i;X_j)\,]/\,[\,T(X_i,X_k) - T\,(X_i;X_j)\,] \tag{5.17}$$

Then, using the previous relationships, the total interpolated information at any point (X_L) joining line i-j can be interpolated as:

$$H(X_L) = T(X_i,X_j) + [H(X_i)-T(X_i,X_j)]\, e^{-b\left[d_L/(D-d_L)\right]}$$

$$+ [H(X_j)-T(X_i,X_j)]\, e^{-b'\left[(D-d_L)/d_L\right]} \tag{5.18}$$

Shannon's information measure is capable of selecting the optimum locations without the assumptions of normality and linearity.

Also, it takes into account the variation of space and time. Multi-purpose networks can also be designed using this technique because it is not restricted to one variable, but it can use a number of different types of variables simultaneously in the design. Events for unguaged locations can be estimated using this method by taking the combinations of three station sites and interpolating the information between each pair of them at any point on the line joining them. This can be used to produce contour maps showing the high and low information zones.

5.4 Analysis

To illustrate the applicability of the network design methodology developed by Shannon, rainfall data on a daily basis for the existing stations in hydrological Area III of the Kingdom of Saudi Arabia (from installation date of the station until year 1984) were obtained from the Ministry of Agriculture and Water Resources through publication issues (MAW, 1984). The station locations and topography of the area are shown in Table 2.1 and Figure 2.3 respectively. The analysis will cover the following:

A. hydrological network reduction, and

B. hydrological network expansion.

5.4.1 Hydrological Network Reduction

The objective of network reduction is to obtain maximum information transmitted by a minimum number of select stations from an existing network. This analysis will be focused on dense networks. For this purpose, the hydrological area were divided into an an imaginary six dense zones, as shown in Figure 5.6, based on how close the stations are to each other and also on ease of computations. Because of the need to evaluate all possible combinations of "n" stations from "m" stations, the computational time may grow rapidly as "m" becomes large. To avoid this combinational problem, the number of stations in each imaginary dense zone is assumed to be less than 10.

Concurrent rainfall data will be processed for each zone, i.e., when existing station on that zone receives rain, rainfall for the rest of the stations will be considered. Using eqns. (4.2) and (4.3) the rainfall data, mean and variance for each station, are computed. From this, scale and shape parameters are calculated. Entropy is found at each station by substituting these parameters into eqn. (5.4) which is equivalent to information transmitted by the station since

$$T(X_i;X_j) = H(X_i) + H(X_j) - H(X_i;X_j) \quad \text{when } i \neq j$$

$$= H(X_i) \quad \text{when } i = j.$$

After the gamma-distribution is fitted and the parameters (shape and scale) are computed, they will be transformed to normal

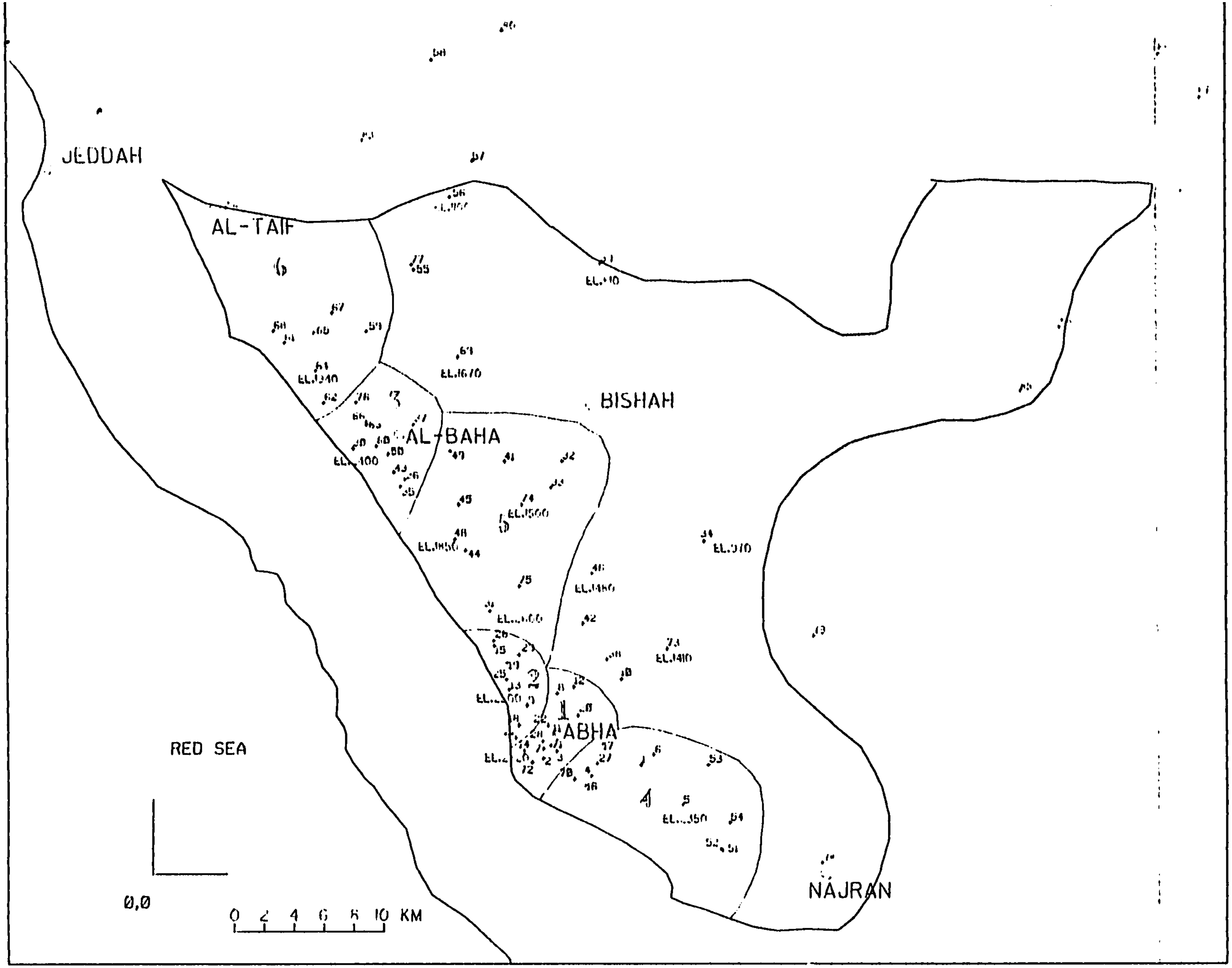


Figure 5.6: Map Showing Zones for Hydrological Network Reduction.

variables using eqn. (5.7). The transmitted information $T(X_i, X_j)$ when $i \neq j$, will be computed by finding the correlation between any pair of stations and substituting in eqn. (5.9). Finally, optimum stations to be retained can be selected using the objective function described by eqns. (5.10) and (5.11).

The information matrix as well as the optimum information and stations retained for each dense zone existing in hydrological Area III are shown respectively in Tables 5.1 through 5.12. Appendix B shows sample output of Zone No. 5 of all station combinations with their corresponding transmitted information.

Optimum information transmitted by the retained stations will be plotted against the optimal station combination for each zone separately. The obtained curves should follow those curves shown in Figure 5.7 where curve "b" indicates homogeneous conditions at all locations meaning that one station can represent the concerned area, curve "c" indicates that events at each network location are independent of one another. In other words, the area is heterogeneous and curve "a" indicates that the existing network does not represent the area fully. Therefore more stations are needed to improve the adequacy of the existing network.

For each zone, the optimum information transmitted versus the optimum station combination is plotted in Figures 5.8 to 5.13. For Zone No. 1, the slope of information transmission curve reaches con-

Table 5.1: Shannon's Information Matrix (Gamma Distribution) of Zone # 1.

No.	1	2	3	4	5	6	7	8	9	10
Station ID	A118	A001	A003	A106	A216	A112	A201	A107	A113	A128

	1	2	3	4	5	6	7	8	9	10
1	0.3320	0.1528	0.1029	0.0525	0.0070	0.1201	0.0742	0.0068	0.0540	0.0040
2	0.1528	0.4817	0.3830	0.1225	0.1105	0.2070	0.1794	0.0486	0.0354	0.0151
3	0.1029	0.3830	0.6596	0.0773	0.0588	0.1898	0.1593	0.0553	0.0158	0.0457
4	0.0525	0.1225	0.0773	0.5136	0.0937	0.1824	0.0864	0.0208	0.0214	0.0245
5	0.0070	0.1105	0.0588	0.0937	0.6238	0.1841	0.0695	0.0010	0.0168	0.0026
6	0.1201	0.2070	0.1898	0.1824	0.1841	1.3191	0.1625	0.0374	0.0585	0.0040
7	0.0742	0.1794	0.1593	0.0864	0.0695	0.1625	0.4976	0.0328	0.0215	0.0018
8	0.0068	0.0486	0.0553	0.0208	0.0010	0.0374	0.0328	0.4772	0.0468	0.1067
9	0.0540	0.0354	0.0158	0.0214	0.0168	0.0585	0.0215	0.0468	1.1011	0.0271
10	0.0040	0.0151	0.0457	0.0245	0.0026	0.0040	0.0018	0.1067	0.0271	0.9505

Table 5.2: Optimum Information and Stations Retained in Zone # 1.

Optimum Station Combination	Optimum Station No.Retained	Optimum Information Transmitted	Relative Information Trans. (%)	Marginal Information Trans. (%)
1	6	2.4648	35.4	
2	6,9	3.5400	50.9	15.46
3	6,9,10	4.5233	65.0	14.14
4	3,6,9,10	5.1177	73.6	8.55
5	3,5,6,9,10	5.5574	79.9	6.32

Table 5.3: Shannon's Information Matrix of Zone # 2.

No.	1	2	3	4	5	6	7
Stat-tion ID	A124	A108	A117	A206	A217	A120	A211

	1	2	3	4	5	6	7
1	1.7374	0.0039	0.1816	0.0101	0.0074	0.0933	0.0381
2	0.0039	1.8396	0.0652	0.0784	0.0186	0.0572	0.0238
3	0.1816	0.0652	2.0871	0.0443	0.0186	0.0482	0.1027
4	0.0101	0.0784	0.0443	1.9117	0.0129	0.0369	0.0317
5	0.0074	0.0186	0.0186	0.0129	2.0367	0.0008	0.0386
6	0.0933	0.0572	0.0482	0.0369	0.0008	1.5988	0.2013
7	0.0381	0.0238	0.1027	0.0317	0.0386	0.2013	1.8778

Table 5.4: Optimum Information and Stations Retained in Zone # 2.

Optimum Station Combination	Optimum Station No.Retained	Optimum Information Transmitted	Relative Information Trans. (%)	Marginal Information Trans. (%)
1	3	2.5478	19.5	
2	3,5	4.5659	34.9	15.42
3	3,5,7	6.4940	49.6	14.73
4	3,4,5,7	8.2215	62.8	13.20
5	2,3,4,5,7	9.9917	76.3	13.52

Table 5.5: Shannon's Information Matrix of Zone # 3.

No.	1	2	3	4	5	6	7
Station ID	B003	B101	B212	TA219	B001	B103	TA237

	1	2	3	4	5	6	7
1	1.9478	0.2065	0.1834	0.1768	0.1276	0.0012	0.0893
2	0.2065	1.9144	0.2056	0.0990	0.0261	0.0444	0.0082
3	0.1834	0.2056	1.9847	0.0885	0.1126	0.0176	0.0557
4	0.1768	0.0990	0.0885	0.0992	1.9066	0.0107	0.1292
5	0.1276	0.0261	0.1126	0.0992	1.9066	0.0107	0.1292
6	0.0012	0.0444	0.0176	0.0077	0.0107	1.9849	0.0057
7	0.8935	0.0082	0.0557	0.1160	0.1292	0.0057	1.3198

Table 5.6: Optimum Information and Stations Retained in Zone # 3.

Optimum Station Combination	Optimum Station No.Retained	Optimum Information Transmitted	Relative Information Trans. (%)	Marginal Information Trans. (%)
1	1	2.7326	21.1	
2	1,6	4.7163	36.4	15.29
3	1,3,6	6.5175	50.2	13.88
4	1,3,5,6	8.3365	64.3	14.02
5	1,2,3,5,6	10.0444	77.4	13.17

Table 5.7: Shannon's Information Matrix of Zone # 4.

No.	1	2	3	4	5	6	7	8	9
Station ID	A004	A105	A123	A213	A103	A121	N103	N203	A104

	1	2	3	4	5	6	7	8	9
1	2.1168	0.0061	0.0291	0.1085	0.0521	0.0832	0.0103	0.0221	0.0222
2	0.0061	2.2420	0.0516	0.0004	0.0654	0.0054	0.0068	0.0929	0.0002
3	0.0291	0.0516	2.1815	0.0043	0.0013	0.0260	0.0076	0.0045	0.0025
4	0.1085	0.0004	0.0043	1.9757	0.0407	0.0333	0.0628	0.0958	0.0314
5	0.0521	0.0654	0.0013	0.0407	2.1480	0.0488	0.0013	0.0339	0.0209
6	0.0832	0.0054	0.0260	0.0333	0.0488	2.1440	0.0374	0.0161	0.0228
7	0.0103	0.0086	0.0076	0.0628	0.0013	0.0374	2.2860	0.2641	0.0317
8	0.0221	0.0929	0.0045	0.0958	0.0339	0.0161	0.2641	1.8604	0.0032
9	0.0222	0.0002	0.0025	0.0314	0.0209	0.0228	0.0317	0.0032	2.5639

Table 5.8: Optimum Information and Stations Retained in Zone # 4.

Optimum Station Combination	Optimum Station No.Retained	Optimum Information Transmitted	Relative Information Trans. (%)	Marginal Information Trans. (%)
1	7	2.7099	13.9	
2	7,9	5.2735	27.0	13.13
3	2,7,9	7.5954	38.9	11.90
4	1,2,7,9	9.7816	50.1	11.27
5	1,2,3,7,9	11.9114	61.0	10.92

Table 5.9: Shannon's Information Matrix of Zone # 5.

No.	1	2	3	4	5	6	7	8
Station ID	B002	B216	B221	B217	B222	B114	B004	B005

	1	2	3	4	5	6	7	8
1	1.3851	0.0673	0.1388	0.1067	0.0030	0.0634	0.0757	0.1002
2	0.0673	1.4050	0.1554	0.0722	0.0042	0.0180	0.0332	0.1088
3	0.1388	0.1554	1.5378	0.0922	0.0364	0.0529	0.0954	0.1681
4	0.1067	0.0722	0.0922	1.1433	0.0741	0.0973	0.0723	0.0501
5	0.0030	0.0042	0.0364	0.0741	1.4783	0.1273	0.1773	0.0942
6	0.0634	0.0180	0.0529	0.0973	0.1273	1.5326	0.0970	0.1418
7	0.0757	0.0332	0.0954	0.0723	0.1773	0.0970	1.4327	0.2738
8	0.1002	0.1125	0.1681	0.0501	0.0942	0.1418	0.2738	1.5227

Table 5.10: Optimum Information and Stations Retained in Zone # 5.

Optimum Station Combination	Optimum Station No.Retained	Optimum Information Transmitted	Relative Information Trans. (%)	Marginal Information Trans. (%)
1	8	2.4597	21.5	
2	3,8	3.9568	34.6	13.09
3	3,6,8	5.3857	47.1	12.49
4	3,5,6,8	6.6402	58.1	10.97
5	1,3,5,6,8	7.8959	69.0	10.98

Table 5.11: Shannon's Information Matrix of Zone # 6.

No.	1	2	3	4	5	6
Stat-tion ID	TA229	TA235	TA215	TA228	TA236	TA238

	1	2	3	4	5	6
1	1.5845	0.0949	0.0344	0.0891	0.0610	0.2015
2	0.0949	1.3895	0.0273	0.2177	0.1086	0.0648
3	0.0344	0.0273	1.5301	0.0081	0.0716	0.0051
4	0.0891	0.2177	0.0081	1.4997	0.0445	0.0399
5	0.0610	0.1086	0.0716	0.0445	1.4819	0.0352
6	0.2015	0.0648	0.0051	0.0399	0.0352	2.1177

Table 5.12: Optimum Information and Stations Retained in Zone # 6.

Optimum Station Combination	Optimum Station No.Retained	Optimum Information Transmitted	Relative Information Trans. (%)	Marginal Information Trans. (%)
1	6	2.4641	25.7	
2	4,6	4.0892	42.6	16.92
3	3,4,6	5.6382	58.7	16.13
4	1,3,4,6	7.0212	73.1	14.40
5	1,3,4,5,6	8.4316	87.8	14.69

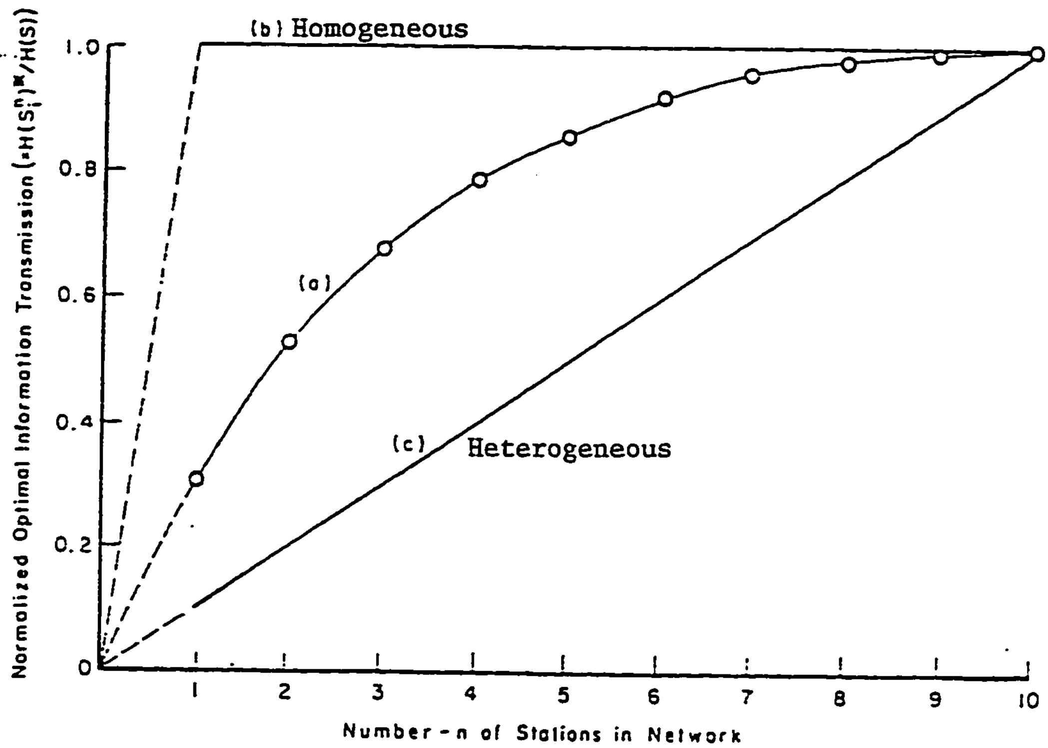


Fig. 5.7: Information Transmission by Optimal Networks (Caselton, 1980).

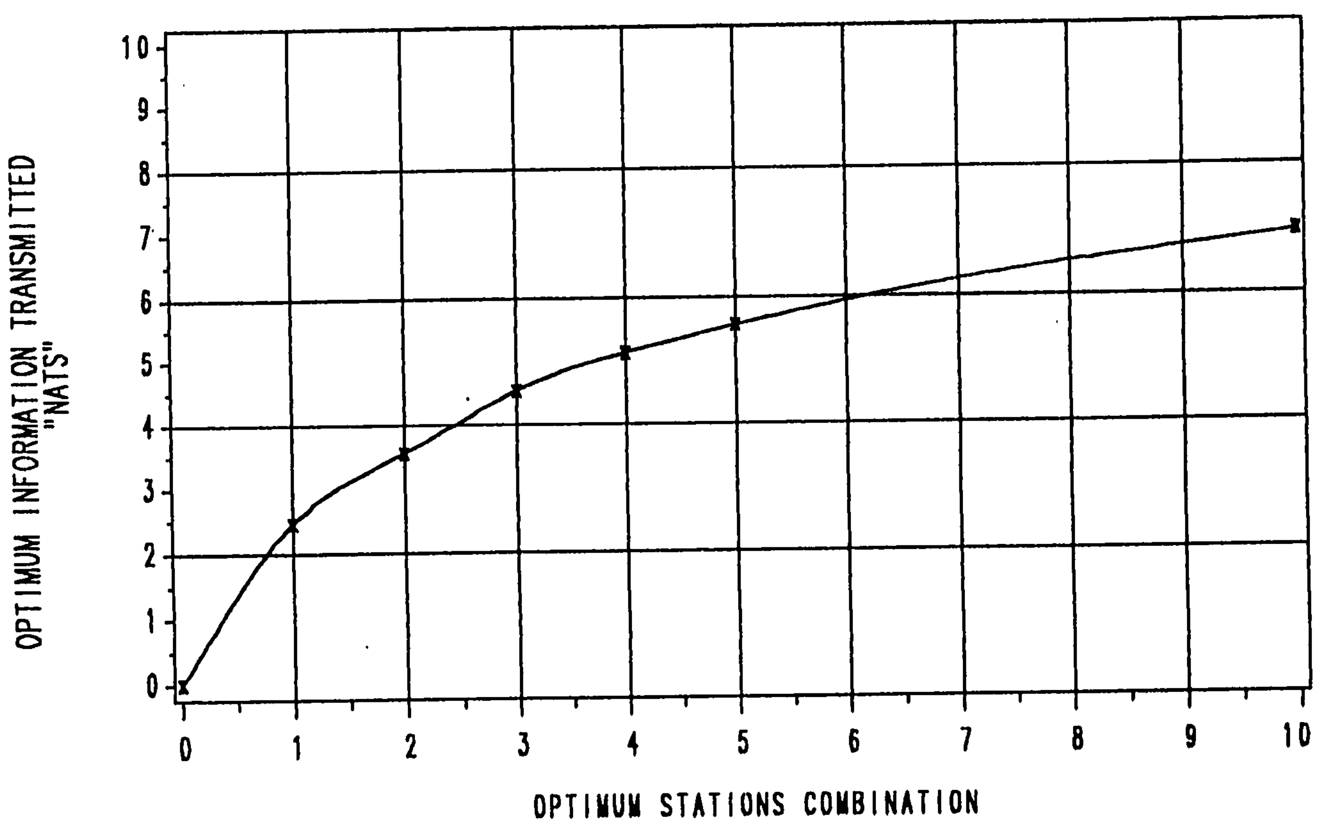


FIGURE 5.8 OPTIMUM INFORMATION AND STATIONS RETAINED IN ZONE#1 USING SHANNON'S INFORMATION MEASURE (A118 , A001 , A003 , A106 , A121 , A112 A201 , A107 , A113 , A128)

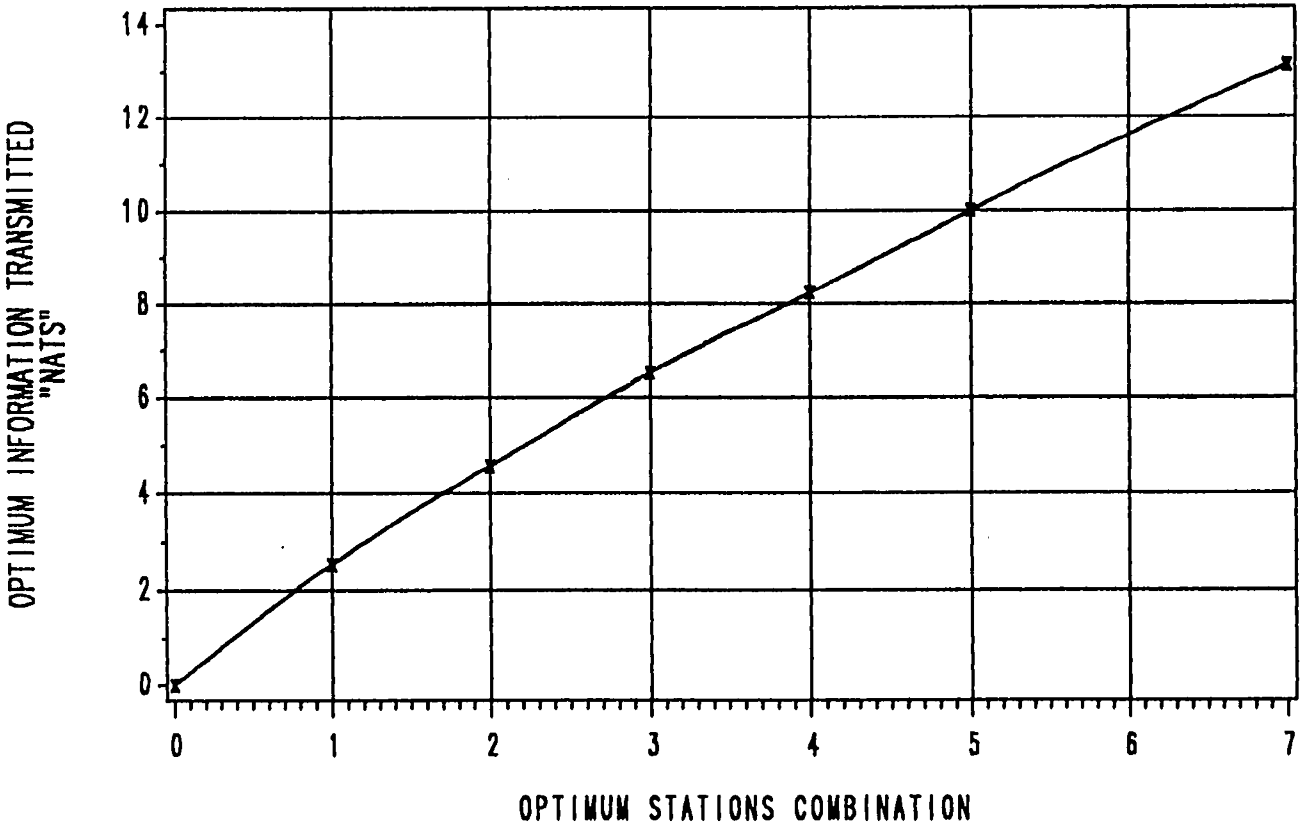


FIGURE 5.9 OPTIMUM INFORMATION AND STATIONS RETAINED IN ZONE#2 USING SHANNON'S INFORMATION MEASURE (A124 , A108 , A117 , A206 , A217 A120 , A211)

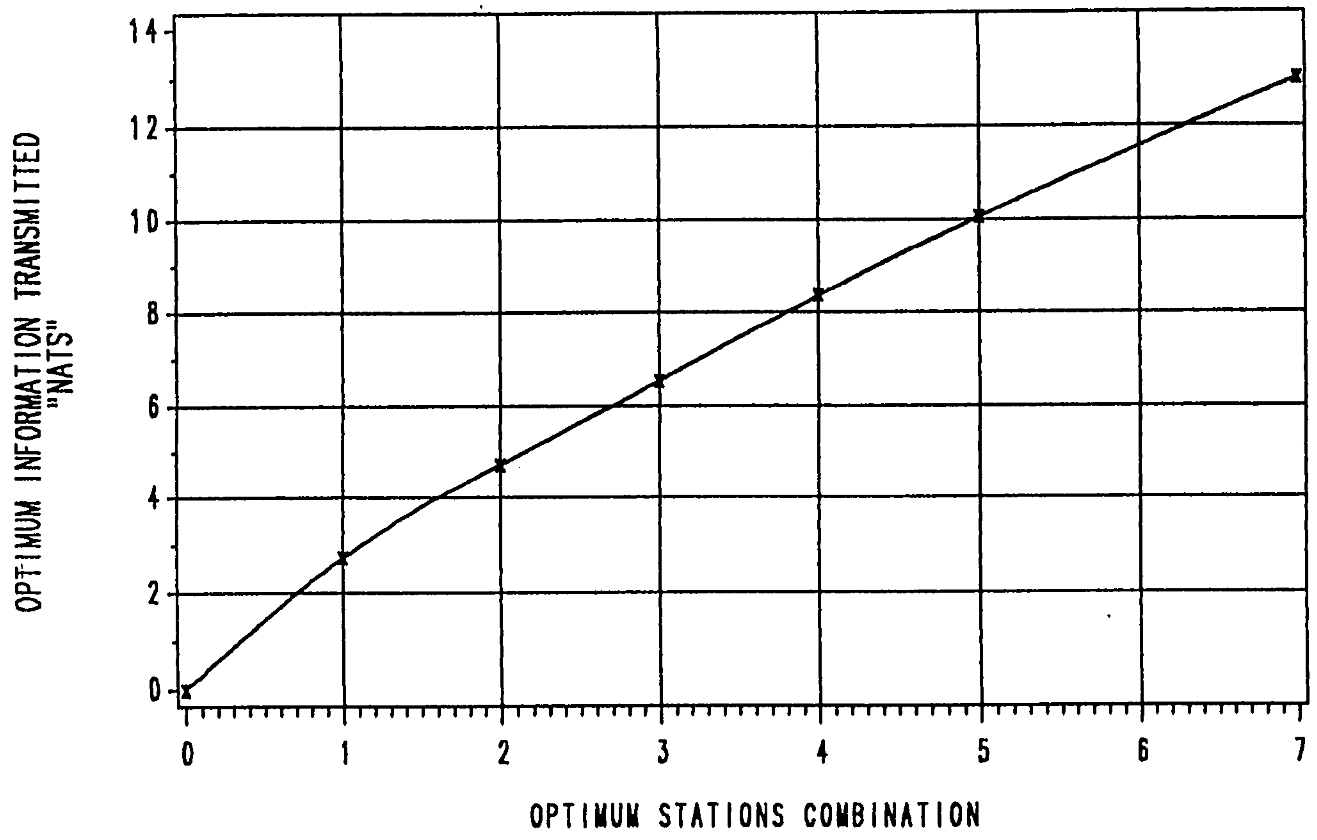


FIGURE 5.10 OPTIMUM INFORMATION AND STATIONS RETAINED IN ZONE#3 USING SHANNON'S INFORMATION MEASURE (B003 , B101 , B212 , TA219 , B001 B103 , TA237)

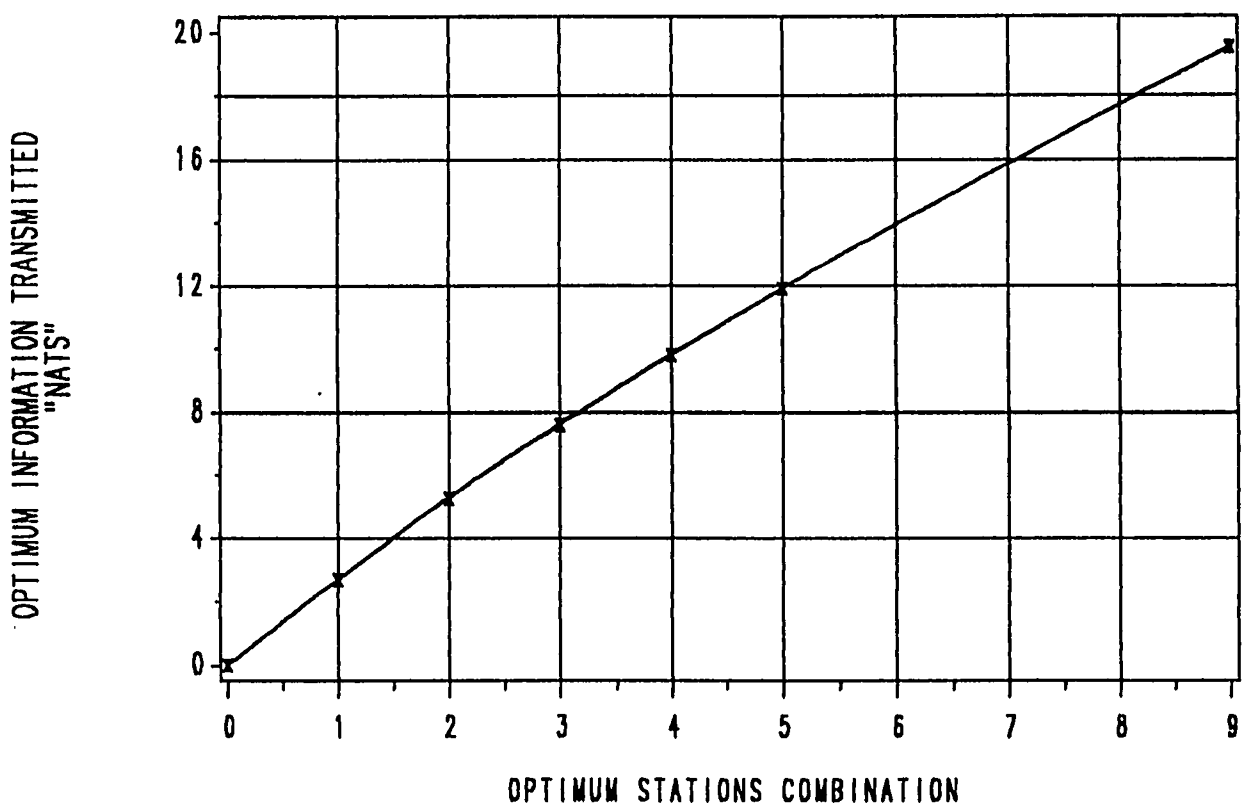


FIGURE 5.11 OPTIMUM INFORMATION AND STATIONS RETAINED IN ZONE#4 USING SHANNON'S INFORMATION MEASURE (A004 , A105 , A123 , A213 , A103 A121 , N103 , N203 , A104)

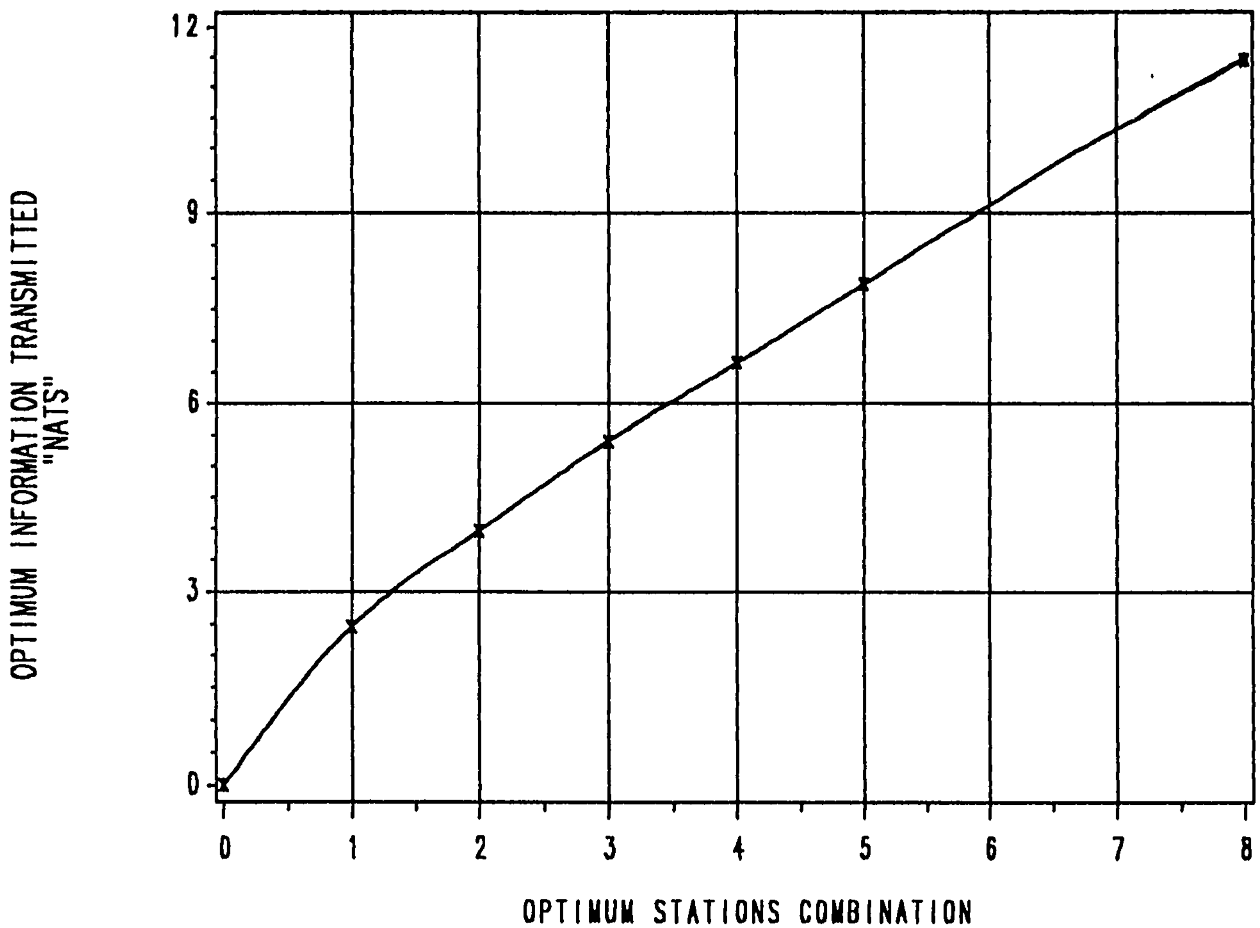


FIGURE 5.12 OPTIMUM INFORMATION AND STATIONS RETAINED IN ZONE#5 USING SHANNON'S INFORMATION MEASURE (B002 , B216 , B217 , B222 , B114 , B004 , B005)

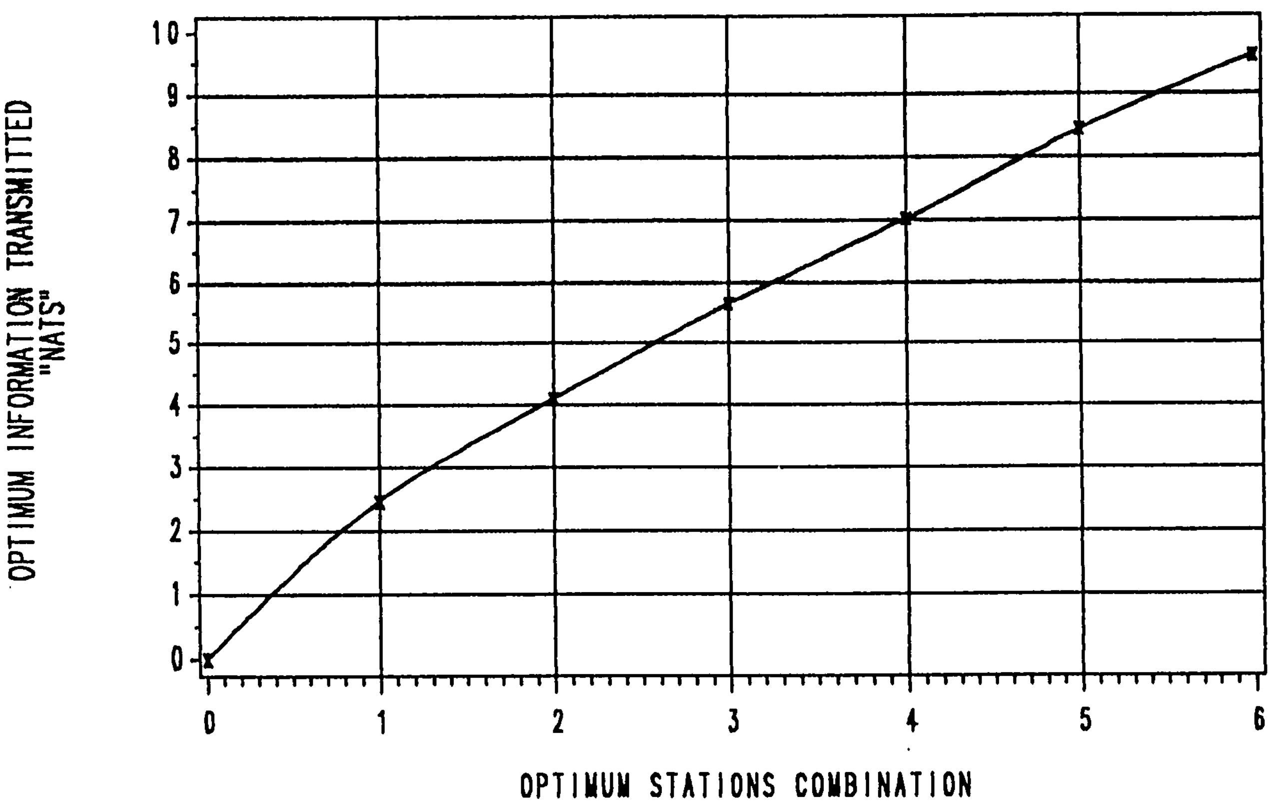


FIGURE 5.13 OPTIMUM INFORMATION AND STATIONS RETAINED IN ZONE#6 USING SHANNON'S INFORMATION MEASURE (TA229 , TA235 , TA215 , TA228 , TA236 , TA238)

stant value when the number of stations equals to 5, which means that those stations can represent Zone 1. On the other hand, the other zone's five stations are not enough to represent them. Even more, Zones 4 and 5, with the existing stations, are not enough to represent the rainfall distribution over them because the curve of the information transmitted by each of them give no indication of being straight, i.e., slope equal to zero , and their relative transmitted information is low. Therefore, hydrologic network expansion should be performed to locate sites where stations can be installed so an acceptable picture of areal rainfall distribution can be achieved. Network expansion will be done on the following part.

5.4.2 Hydrological Network Expansion

Hydrological Area III was divided into five areas for the purpose of network expansion. This division was based on how stations are located and where station distribution is low, especially in the northeast and southeast of hydrological Area III. For this purpose, the very close rainfall stations existing in neighboring areas were included to observe their effects upon rainfall distribution. The boundaries of the five areas as well as those stations from neighboring areas are shown in Figure 5.14. Hydrological network expansion will include the following:

* representation of study area into triplets,
* information computation at each local station and information interpolation contouring, and
* recommendations for additional station sites.

Each area will be divided into a number of feasible triplets, so information transmitted will be computed between the line joining any pair of stations for various points. Tables 5.13 to 5.17 list the sets of feasible triplets for each of the five areas.

For each triangle the entropy was computed at each station locations using eqn. (5.4), with the information transmission derived in eqn. (5.8). These values were then substituted in eqns. (5.16) and (5.17) to calculate the exponential decay coefficient b and b'.

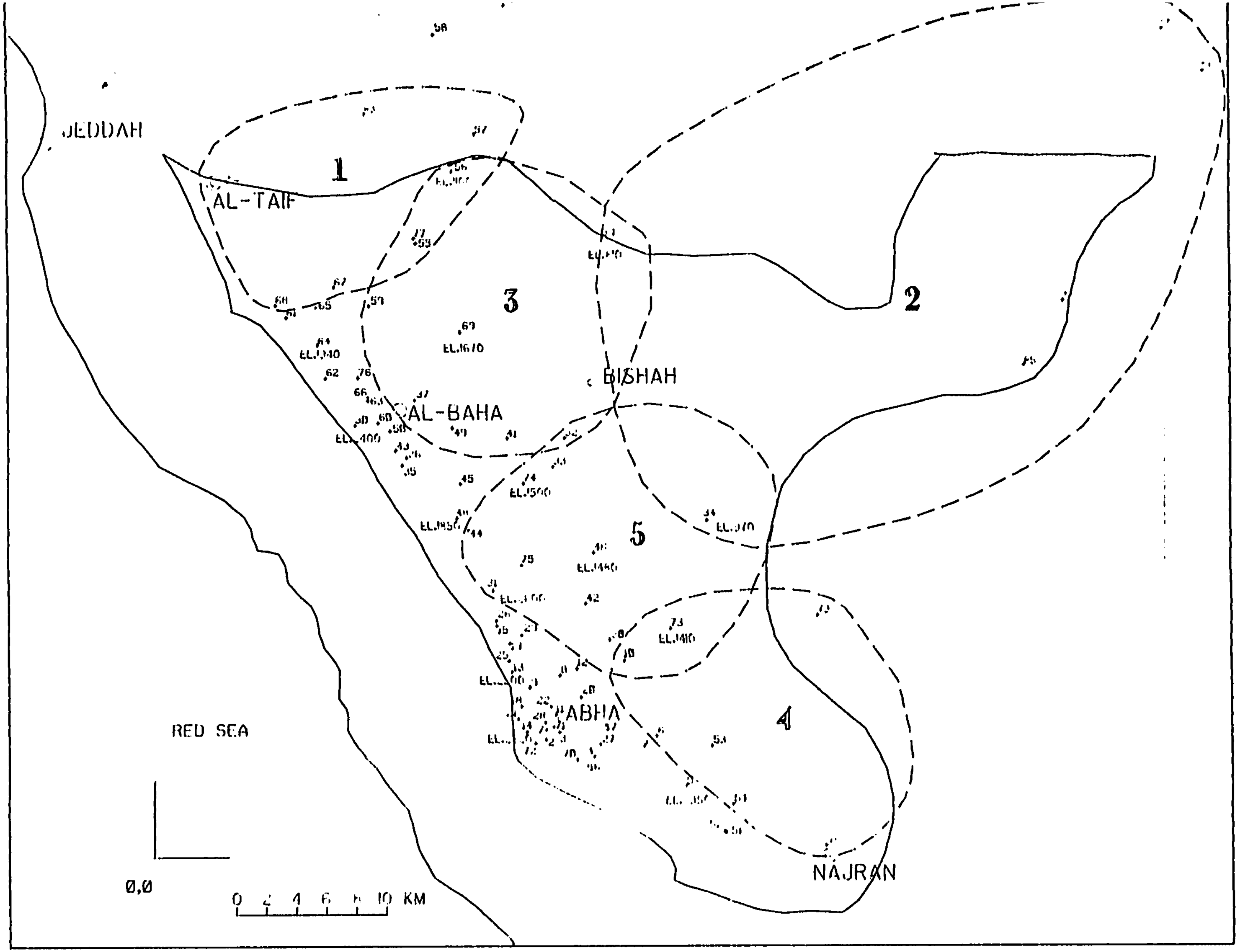


Figure 5.14: Map Showing Areas for Hydrological Network Expansion.

Table 5.13: Sets of Feasible Triplets in Area # 1

Number	Stations Sets		
1	TA203	TA239	TA238
2	TA203	TA238	TA005
3	TA203	TA005	TA111
4	TA203	TA111	TA112
5	TA239	TA239	TA005
6	TA239	TA005	TA111
7	TA005	TA112	TA112

Table 5.14: Sets of Feasible Triplets in Area # 2

Number	Stations Sets		
1	B111	R003	SU201
2	B111	R003	B113
3	B111	SU201	SU001
4	B111	SU001	B113
5	R003	SU201	SU001
6	R003	SU201	B113
7	SU201	SU001	B113

Table 5.15: Sets of Feasible Triplets in Area # 3

Number	Stations Sets		
1	B111	TA005	TA215
2	B111	TA005	TA247
3	B111	TA005	TA111
4	B111	TA215	B103
5	B111	TA247	B103
6	B111	TA247	B222
7	B111	TA247	TA111
8	B111	B103	B222
9	B111	B222	B114
10	B111	B114	B004
11	TA005	TA215	TA247
12	TA247	B222	B114
13	TA247	B114	B004

Table 5.16: Sets of Feasible Triplets in Area # 4

Number	Stations Sets		
1	A110	B209	N201
2	A110	B209	A105
3	A110	N201	A105
4	A110	N201	N001
5	A110	A105	N001
6	B209	N201	A105
7	B209	N201	N001
8	B209	A105	N001
9	N201	A105	N001

Table 5.17: Sets of Feasible Triplets in Area # 5

Number	Stations Sets		
1	B004	B005	B113
2	B004	B005	B216
3	B004	B005	B219
4	B004	B113	B219
5	B005	B216	B002
6	B005	B002	B219
7	B005	B002	B208
8	B005	B219	B208
9	B113	B219	B208
10	B113	B002	B219
11	B113	B219	B110
12	B113	B219	B209
13	B113	B208	B110
14	B113	B110	A110
15	B113	A110	A209
16	B216	B002	B219
17	B216	B002	B208
18	B002	B208	B110
19	B219	B208	B209
20	B219	B110	A110
21	B219	B110	A209
22	B208	B110	A110

Then substituting those coefficients into eqn. (5.18), the interpolated information at various points of the line segments forming triplets was estimated.

Finally, the interpolated transmitted information values were used to produce contour maps as shown in Figures 5.15 to 5.19 for area No. 1 to 5 respectively.

The interpolated information values with the information transmitted by each station were used to draw contour maps. The contour map for Area I is shown in Figure 5.15. It consists of one loop with information ranging from 49 to 154 nats. The map shows relative homogeneity, but there is high variation between minimum and maximum transmitted information which indicates that one station at the middle where the transmitted information is low, can be added to reduce this variation. Actually, there are two stations which have not been included in the analysis of information for this area due to poor record. They are TA113 and TA123. Station TA113 was cancelled due to proximity to station TA005. The other station TA123 is a new station located near station TA203.

The interpolated transmitted information values of rainfall in Area 2 Figure 5.16 shows high homogeneity. The information values in this area varies between 88 and 127 nats showing low variations compared to Area 1. This is due to the nature of this part of hydrological Area III where topography is flat and the amount of rain fall is low compared to Area 1.

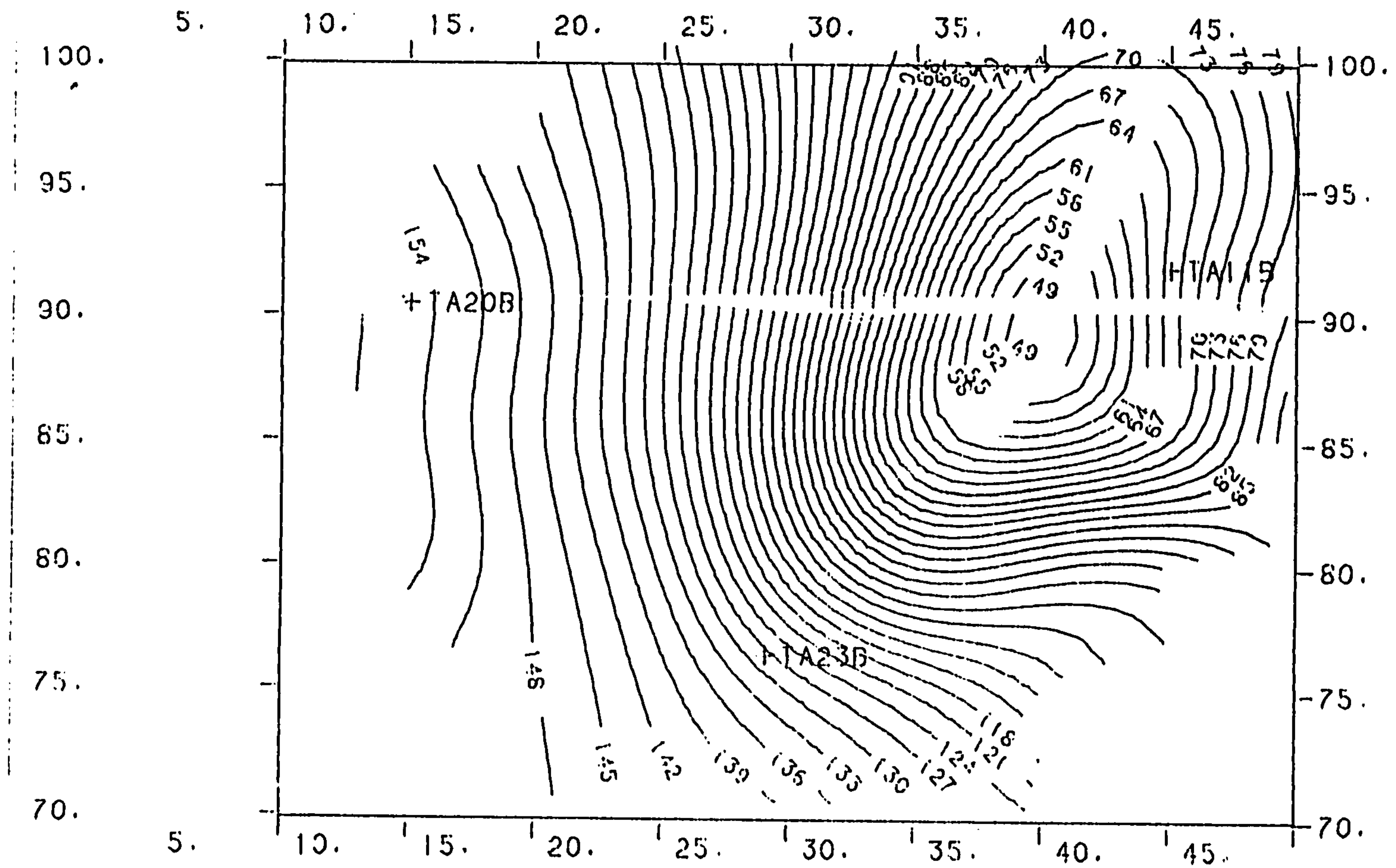


Figure 5.15: Map Showing Contours of the Information Transmitted in Area # I (Values = Nats x 100).

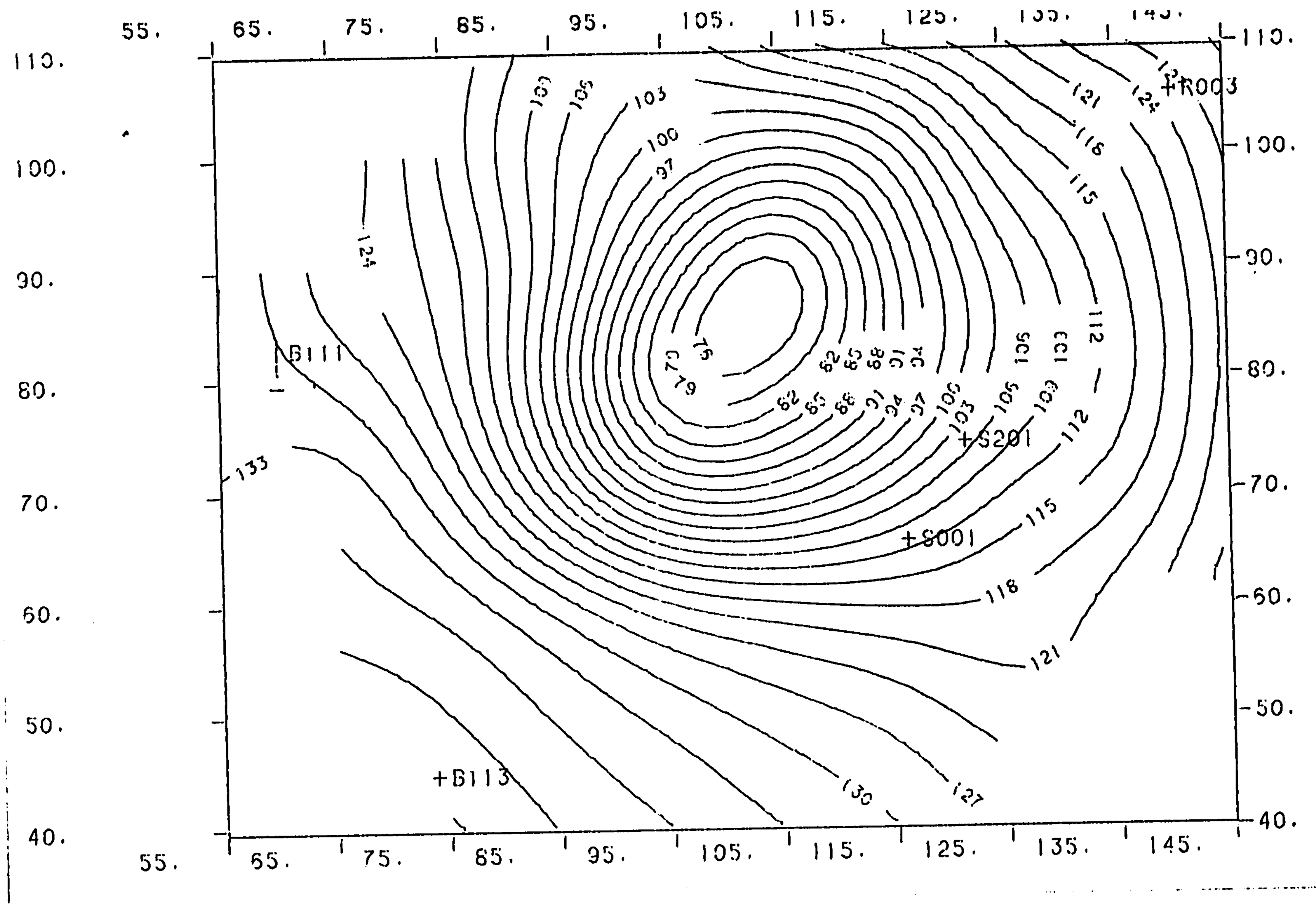


Figure 5.16: Map Showing Contours of the Information Transmitted in Area # 2 (Values = Nats x 100).

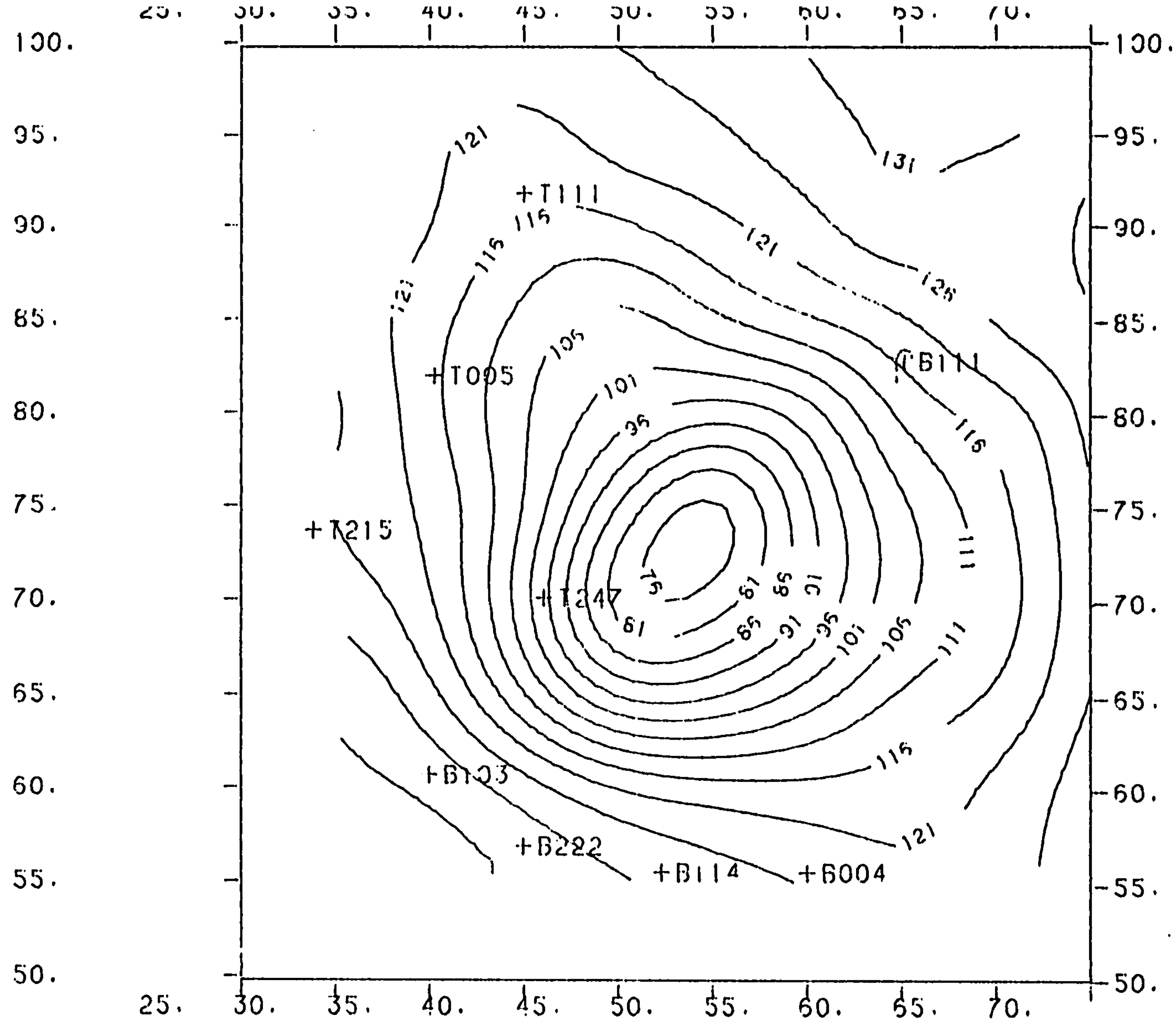


Figure 5.17: Map Showing Contours of the Information Transmitted in Area # 3 (Values = Nats x 100).

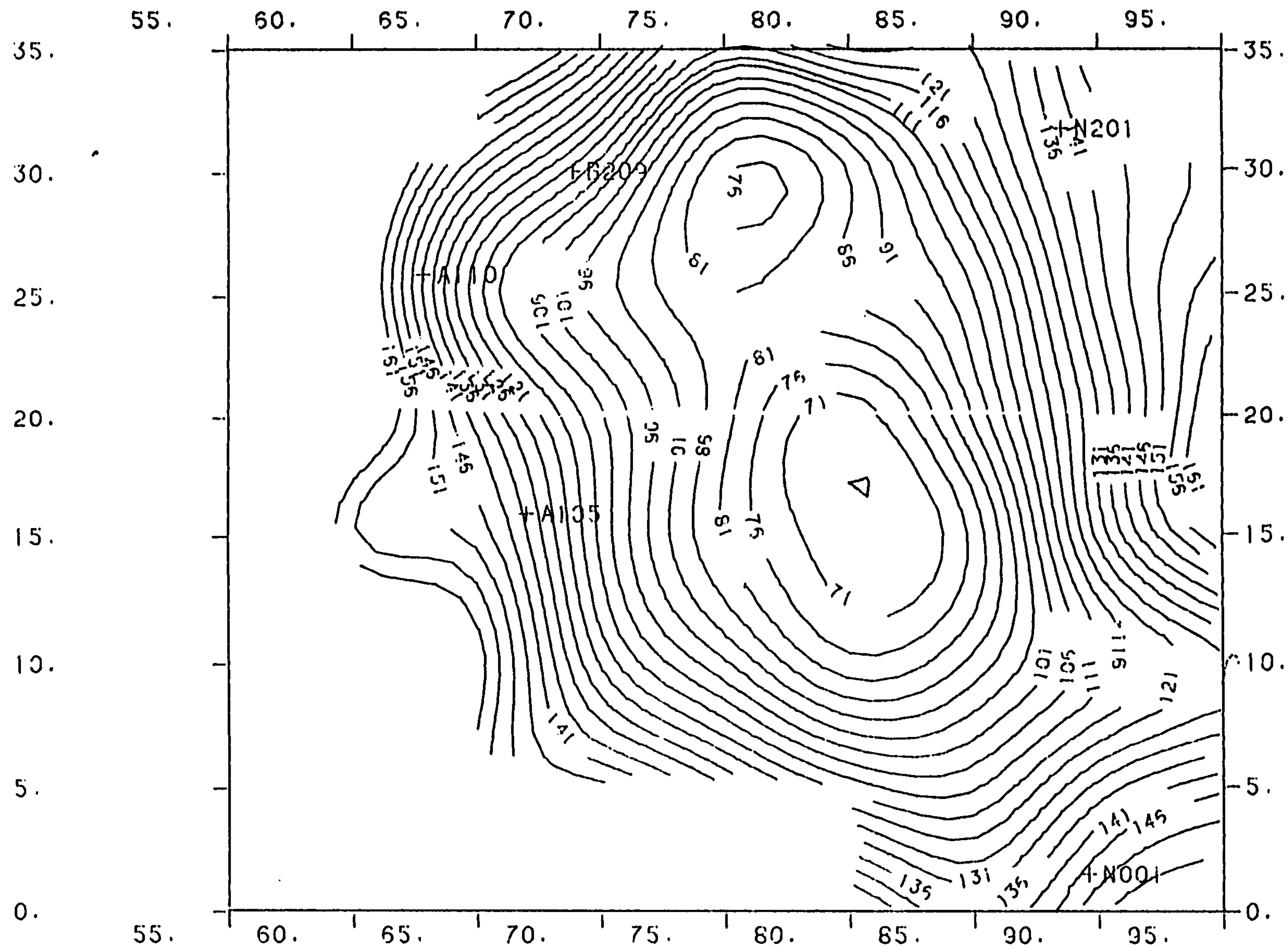


Figure 5.18: Map Showing Contours of the Information Transmitted in Area # 4 (Values = Nats x 100).

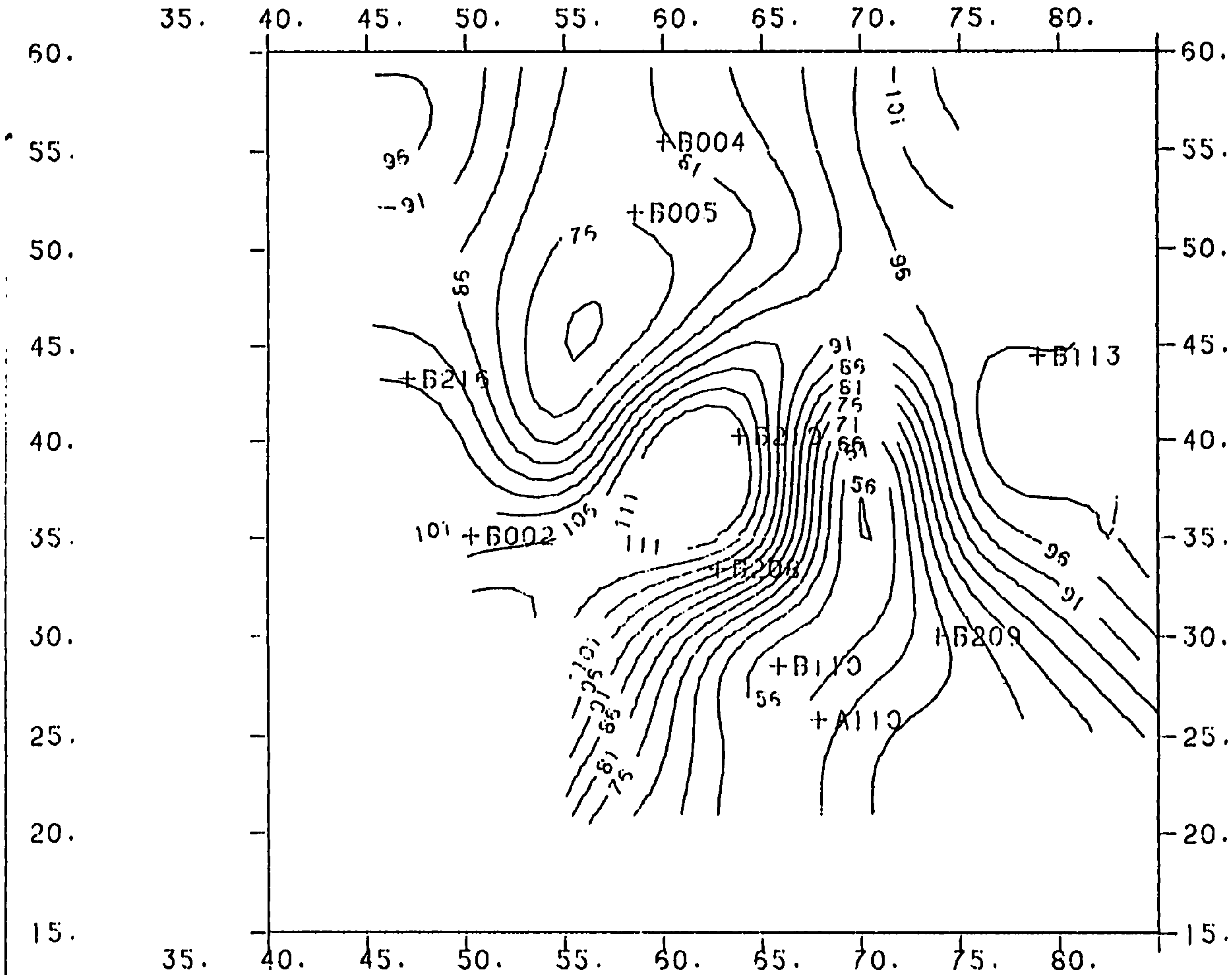


Figure 5.19: Map Showing Contours of the Information Transmitted in Area # 5 (Values = Nats x 100).

Figure 5.17 shows the interpolated transmitted information of rainfall in Area 3. This figure consists of one loop which is the same as Areas 1 and 2 with information varying from 76 to 126 nats. However, the homogeneity is lower than those shown in the previous areas indicating that more stations are needed to improve the homogeneity of the area.

The interpolated information values of rainfall in Areas 4 and 5 show high heterogeneity, as shown in Figures 5.18 and 5.19 respectively. There are two contour loops in Area 4 with high information values varying from 71 to 161 nats; whereas for area 5, there are three contour loops having information values ranging from 56 to 111 nats. To resolve the variability in the measured rainfall in both regions, a dense network is needed for an accurate areal estimation of rainfall.

In each area, a proposed station number and site location are identified. However, it should be noted that it is a difficult task to identify station sites and number because it depends on several factors such as the accessibility to site locations and budget constraints.

Chapter 6

FISHER'S INFORMATION MEASURE

6.1 Background

In 1925, Fisher derived a statistical relationship to measure the information content in a given set of data. For a random variable X with n independent events, Fisher information content with respect to a population parameter α is as follows (Husain and Khan, 1983):

$$I_f = n \int f_x (x;\alpha) \left[\frac{\delta \ln f_x(X;\alpha)}{\delta \alpha} \right]^2 dx \qquad (6.1)$$

where

$f_x(x,\alpha)$ = Probability density function of X (p.d.f.).

If $\hat{\alpha}$ is the estimate of α, and considering $\hat{\alpha}$ as a single observation taken from the sample distribution $f_A(\hat{\alpha},\alpha)$, then the information content about $\hat{\alpha}$ is (Husain and Khan, 1983):

$$I_f(\hat{\alpha}) = \int f_A(\hat{\alpha};\alpha) \left[\frac{\delta \ln f_A(\hat{\alpha};\alpha)}{\delta \alpha} \right]^2 d\hat{\alpha} \qquad (6.2)$$

For a large data distributed normally, the population parameter of $\hat{\alpha}$ can be specified by mean $\overline{X}$ and variance σ^2. Hence, the p.d.f. of $f_A(\hat{\alpha})$ with bias in the mean value β is (Husain and Khan, 1983):

$$f_A(\hat{a}) = (2\pi\sigma^2)^{-1/2} \exp\left[-\frac{(\hat{a} - (\alpha + \beta))^2}{2\sigma^2}\right] \tag{6.3}$$

Combining Equations 6.2 and 6.3, we get

$$I_f = \frac{(1+\delta\beta / \delta X)^2}{\sigma^2} \tag{6.4}$$

If β is assumed to be zero, Equation 6.4 will become

$$I_f = \frac{1}{\sigma^2} \tag{6.5}$$

Equation 6.5 is the basis of Fisher's information measure which can be stated as follows: the information content in a sequence of observations as the reciprocal of the variance of the estimates of the parameter of interest (Husain and Caselton, 1980).

Fisher's information measure has been recently introduced to the field of network design. For example, it has been applied in the design of hydrological networks (Husain and Caselton, 1980) and air monitoring network design (Husain and Khan, 1983).

To use Fisher's information measure in hydrological network design, consider two hydrological variables X_i and X_j. After collecting N_1 concurrent observations, the data collection scheme for variable X_i is discontinued but extended to N_2 additional measurements on X_j. Based on the concurrent N_1 observations, a linear regression, with X_i as dependent variable and X_j as independent variable is carried out yielding the linear model (Husain and Caselton, 1980; Husain and Khan, 1983):

$$\hat{X}_{i,k} = a + b\,(X_{j,k} - \overline{X}_j) \qquad (6.6)$$

where

a,b = Regression coefficients.

$\overline{X}_j$ = Mean of X based on N_1 observations.

Using eqn. (6.6), N_2 estimates of X_j based on the N_2 additional observations of X_i are obtained. If $\overline{X}_i$ and $\hat{X}_i$ are the estimates of the mean of X_i based on N_1 observation and N_2 regression estimates, respectively, then the weighted estimate of the mean of $X_i,\hat{X}_i$ is (Husain and Khan, 1983):

$$\hat{X}_i = (N_1\,\overline{X}_i + N_2\,\hat{\overline{X}}_i/(N_i + N_2) \qquad (6.7)$$

where:

$$\overline{X}_i = \sum_{k=1}^{N_1} X_{i,k} \,/\, N_1$$

$$\hat{\bar{X}}_i = \sum_{k=N_1+1}^{N_1+N_2} \hat{X}_{i,k} / N_2$$

Based on the normality assumptions of X_i and X_j, the variance of $\hat{X}_i$, denoted by σ^2_m, is derived as follows (Husain and Caselton, 1980):

$$\sigma^2_m = \frac{\sigma^2_{X_i}}{N_1} \left[1 - \frac{N_2}{N_1+N_2} \left\{ \rho^2_{ij} - (1-\rho^2_{ij}) / (N_1-3) \right\} \right] \quad (6.8)$$

Where:

$\sigma_{X_i}^2/N_1$ = The variance of the estimates of the mean for the random sequence of X_i with N_1 observations

σ^2_{ij} = Correlation coefficient between X_i and X_j based on ons N_1 concurrent observations.

For an unbiased estimate when $E(\hat{\bar{X}}_i) = \bar{X}_i$, the information content of X_i and X_j, which is shown in eqn. (6.5) as the reciprocal of the variance, and here as the reciprocal of the variance of the estimates of the mean, is defined as (Husain and Khan, 1983):

$$I_f(X_i;X_j) = \left[1 - \frac{N_2}{N_1+N_2} \left\{ \rho_{ij}^2 - \left(\frac{1-\rho_{ij}^2}{N_1-3} \right) \right\} \right]^{-1} \quad \text{for } i \neq j$$

$$= 1 \qquad \text{for all } i = j \qquad (6.9)$$

Fisher's information measure is one of the methods that can be used in the design of hydrological network because it is able to take into account the variation of space and time and it can be used for multivariate cases where estimation at a point location is based on data from a number of station locations. Unfortunately, Fisher's information measure is not powerful in hydrological network design because it relies upon linearity, assumes linear variation of precipitation between stations; and normality assumptions in its derivation (Husain and Caselton, 1980).

6.2 Analysis

Daily rainfall data as described in the analysis of hydrological network reduction using Shannon's information measure will be used in this section to illustrate the applicability of Fisher's information measure. Also, the objective function as well as zones to be studied will be the same as before.

6.2.1 Hydrological Network Reduction

For each dense zone shown in Figure 5.6, the correlation coefficients for all possible combinations will be computed. Then, by knowing the total concurrent observations for each station separately, and using eqn. (6.9), the information transmitted of all possible combinations in each zone will be computed.

Applying the objective function with its two constraints, optimum station combination can be selected. The objective function Z, which is to be maximized is:

$$Z = \max \sum_{i,j=1}^{m} I_f\,(x_i ; x_j)\;\delta_{i,j} \tag{6.10}$$

where

Z = Objective function

$\delta_{i,j}$ = decision variable = 0 if station i=j to be discounted or information can't be transferred from j to i.

1 if the information is transferred from j to i.

The constraints to be considered are (Husain and Caselton, 1980; Husain and Khan, 1983):

(a) Information transferability constraint: which indicates that information from only one station j can be transferred to another station i.

$$\sum_{j=1}^{m} \delta_{i,j} = 1 \tag{6.11}$$

(b) Budgetary constraints: if the maximum number of stations that can be retained due to budgetary constraints is n, then

$$\sum_{l=1}^{m} \delta_{i,j} = n \qquad (6.12)$$

Fisher's information transmission matrix and the selected optimum stations with their corresponding information transmission for all zones are listed in Tables 6.1 to 6.12. Appendix C shows sample output for Zone 5 showing all station combinations with their transmitted information.

The optimal information transmission for Zone 1 shown in Table 6.2 is higher than the other regions; however, marginal information gain by retaining an additional station is low compared to other zones. This is due to the high number of stations existing in that zone. On the other hand, Zones 2, 3, 4 and 5 have high information transmission and low marginal information compared to Zone 6 where more stations are needed to solve its heterogeneity.

Fisher's information measure retains more than one alternative of station combinations because it depends on the correlation coefficient between stations. Those stations with the same correlation will be retained with different combinations as shown in the tables.

Graphs showing optimum information transmitted using Fisher's technique versus optimum station combinations are shown in Figures

Table 6.1: Fisher's Information Matrix of Zone # 1.

No.	1	2	3	4	5	6	7	8	9	10
Station ID	A118	A001	A003	A106	A216	A112	A201	A107	A113	A128

	1	2	3	4	5	6	7	8	9	10
1	1.0000	0.6763	0.6428	0.6754	0.5491	0.6036	0.5826	0.5364	0.5608	0.5383
2	0.6763	1.0000	0.8400	0.7050	0.6011	0.6240	0.5944	0.5440	0.5485	0.5640
3	0.6428	0.8400	1.0000	0.6655	0.6051	0.6017	0.5684	0.5436	0.5381	0.5595
4	0.6754	0.7050	0.6655	1.0000	0.6044	0.6118	0.5992	0.5518	0.5553	0.5489
5	0.5491	0.6011	0.6051	0.6044	1.0000	0.5227	0.5527	0.5050	0.5181	0.5217
6	0.6036	0.6240	0.6017	0.6118	0.5227	1.0000	0.5463	0.5285	0.5240	0.5274
7	0.5826	0.5944	0.5684	0.5992	0.5527	0.5463	1.0000	0.5405	0.5516	0.5362
8	0.5364	0.5440	0.5436	0.5518	0.5050	0.5285	0.5405	1.0000	0.5634	0.5375
9	0.5608	0.5485	0.5381	0.5553	0.5181	0.5240	0.5516	0.5634	1.0000	0.5601
10	0.5383	0.5640	0.5595	0.5489	0.5217	0.5274	0.5362	0.5357	0.5601	1.0000

Table 6.2: Optimum Information and Stations Retained in Zone # 1.

Optimum Station Combination	Optimum Station No. Retained	Optimum Information Transmitted	Relative Information Trans. (%)	Marginal Information Tans. (%)
1	2	6.6973	66.9	
2	2,8 2,9	7.1681	71.7	4.71
3	2,8,9	7.6047	76.0	4.37
4	2,8,9,10	8.0406	80.4	4.36
5	2,7,8,9,10	8.4463	84.5	4.06

Table 6.3: Fisher's Information Matrix of Zone # 2.

No.	1	2	3	4	5	6	7
Station ID	A124	A108	A117	A206	A217	A120	A211

	1	2	3	4	5	6	7
1	1.0000	0.5206	0.6041	0.5272	0.5169	0.5320	0.5637
2	0.5206	1.0000	0.5353	0.6310	0.5144	0.5418	0.5169
3	0.6041	0.5353	1.0000	0.5595	0.5234	0.5489	0.5672
4	0.5272	0.6310	0.5595	1.0000	0.5110	0.5382	0.5683
5	0.5169	0.5145	0.5234	0.5110	1.0000	0.5000	0.5474
6	0.5320	0.5418	0.5489	0.5382	0.5000	1.0000	0.5581
7	0.5637	0.5169	0.5672	0.5683	0.5474	0.5581	1.0000

Table 6.4: Optimum Information and Stations Retained in Zone # 2.

Optimum Station Combination	Optimum Station No.Retained	Optimum Information Transmitted	Relative Information Trans. (%)	Marginal Information Tans. (%)
1	3	4.3384	62.0	
2	3,4	4.8757	69.7	7.69
3	3,4,5	5.3523	76.5	6.81
4	1,4,5,6 3,4,5,6	5.8034	82.9	6.45
5	1,2,5,6,7 1,4,5,6,7 2,3,4,6,7 3,4,5,6,7	6.2351	89.1	6.17

Table 6.5: Fisher's Information Matrix of Zone # 3.

No.	1	2	3	4	5	6	7
Station ID	B003	B101	B212	TA219	B001	B103	TA237

	1	2	3	4	5	6	7
1	1.0000	0.5959	0.5783	0.5752	0.6002	0.5205	0.5941
2	0.5959	1.0000	0.5643	0.5617	0.5677	0.5204	0.5684
3	0.5783	0.5643	1.0000	0.5205	0.5758	0.5028	0.5477
4	0.5752	0.5617	0.5205	1.0000	0.5653	0.5116	0.6266
5	0.6002	0.5677	0.5758	0.5653	1.0000	0.5050	0.6207
6	0.5205	0.5204	0.5028	0.5116	0.5050	1.0000	0.5136
7	0.5941	0.5684	0.5477	0.6266	0.6207	0.5136	1.0000

Table 6.6: Optimum Information and Stations Retained in Zone # 3.

Optimum Station Combination	Optimum Station No.Retained	Optimum Information Transmitted	Relative Information Trans. (%)	Marginal Information Tans. (%)
1	7	4.4771	63.9	
2	6,7	4.9575	70.8	6.95
3	1,6,7	5.4215	77.5	6.63
4	1,3,4,6	5.8227	83.2	5.73
5	1,2,3,4,6	6.2268	88.9	5.77

Table 6.7: Fisher's Information Matrix of Zone # 4.

No.	1	2	3	4	5	6	7	8	9
Stat-tion ID	A004	A105	A123	A213	A103	A121	N103	N203	A104

	1	2	3	4	5	6	7	8	9
1	1.0000	0.5373	0.6066	0.6555	0.7174	0.5995	0.5498	0.5386	0.5650
2	0.5373	1.0000	0.5345	0.5295	0.5255	0.5108	0.5206	0.5096	0.5691
3	0.6066	0.5345	1.0000	0.5764	0.5755	0.5516	0.5252	0.5238	0.5723
4	0.6555	0.5295	0.5764	1.0000	0.6639	0.5518	0.5203	0.5326	0.5368
5	0.7174	0.5255	0.5755	0.6639	1.0000	0.5971	0.5249	0.5275	0.5459
6	0.5995	0.5108	0.5516	0.5518	0.5971	1.0000	0.5497	0.5295	0.5685
7	0.5498	0.5206	0.5252	0.5203	0.5249	0.5497	1.0000	0.6135	0.5732
8	0.5386	0.5096	0.5238	0.5326	0.5275	0.5295	0.6135	1.0000	0.5275
9	0.5650	0.5691	0.5723	0.5368	0.5459	0.5685	0.5732	0.5275	1.0000

Table 6.8: Optimum Information and Stations Retained in Zone # 4.

Optimum Station Combination	Optimum Station No.Retained	Optimum Information Transmitted	Relative Information Trans. (%)	Marginal Information Tans. (%)
1	1	5.7697	64.1	
2	1,7	6.3030	70.0	5.93
3	1,2,7	6.7657	75.2	5.14
4	1,2,7,9 1,2,8,9	7.1925	79.9	4.74
5	1,2,6,7,9 1,2,6,8,9	7.5930	84.4	4.45

Table 6.9: Fisher's Information Matrix of Zone # 5.

No.	1	2	3	4	5	6	7	8
Station ID	B002	B216	B221	B217	B222	B114	b004	B005

	1	2	3	4	5	6	7	8
1	1.0000	0.5848	0.6261	0.6153	0.5215	0.5439	0.5237	0.5875
2	0.5848	1.0000	0.6372	0.5300	0.5238	0.5395	0.5231	0.5740
3	0.6261	0.6372	1.0000	0.5555	0.5621	0.5646	0.5453	0.6402
4	0.6153	0.5300	0.5555	1.0000	0.5394	0.5231	0.5166	0.5593
5	0.5215	0.5238	0.5621	0.5394	1.0000	0.5542	0.5523	0.5927
6	0.5439	0.5395	0.5646	0.5231	0.5542	1.0000	0.5329	0.6317
7	0.5237	0.5231	0.5453	0.5166	0.5523	0.5329	1.0000	0.5731
8	0.5875	0.5740	0.6402	0.5593	0.5927	0.6317	0.5731	1.0000

Table 6.10: Optimum Information and Stations Retained in Zone # 5.

Optimum Station Combination	Optimum Station No.Retained	Optimum Information Transmitted	Relative Information Trans. (%)	Marginal Information Tans. (%)
1	8	5.1585	64.5	
2	1,8	5.6377	70.5	5.99
3	1,7,8	6.0647	75.8	5.34
4	3,4,5,7	6.4680	80.9	5.04
5	3,4,5,6,7	6.9034	86.3	5.44

Table 6.11: Fisher's Information Matrix of Zone # 6.

No.	1	2	3	4	5	6
Station ID	TA229	TA235	TA215	TA228	TA236	TA238

	1	2	3	4	5	6
1	1.0000	0.5212	0.5827	0.5517	0.6184	0.5679
2	0.5212	1.0000	0.5221	0.5532	0.5365	0.5254
3	0.5827	0.5221	1.0000	0.5296	0.5913	0.5316
4	0.5517	0.5532	0.5296	1.0000	0.5537	0.5319
5	0.6184	0.5365	0.5913	0.5537	1.0000	0.5493
6	0.5679	0.5254	0.5316	0.5319	0.5493	1.0000

Table 6.12: Optimum Information and Stations Retained in Zone # 6.

Optimum Station Combination	Optimum Station No.Retained	Optimum Information Transmitted	Relative Information Trans. (%)	Marginal Information Trans. (%)
1	5	3.8492	64.2	
2	1,2 1,4	4.3223	72.0	7.89
3	1,2,4	4.7691	79.5	7.45
4	2,4,5,6	5.2097	86.8	7.34
5	1,2,3,4,6 2,3,4,5,6	5.6184	93.6	6.81

6.1 through 6.6. As these figures reveal, the marginal information transmitted after retaining two stations are very low with slopes close to zero. Similar behavior is existed in all other curves due to the linearity assumption that Fisher's information measure relies upon.

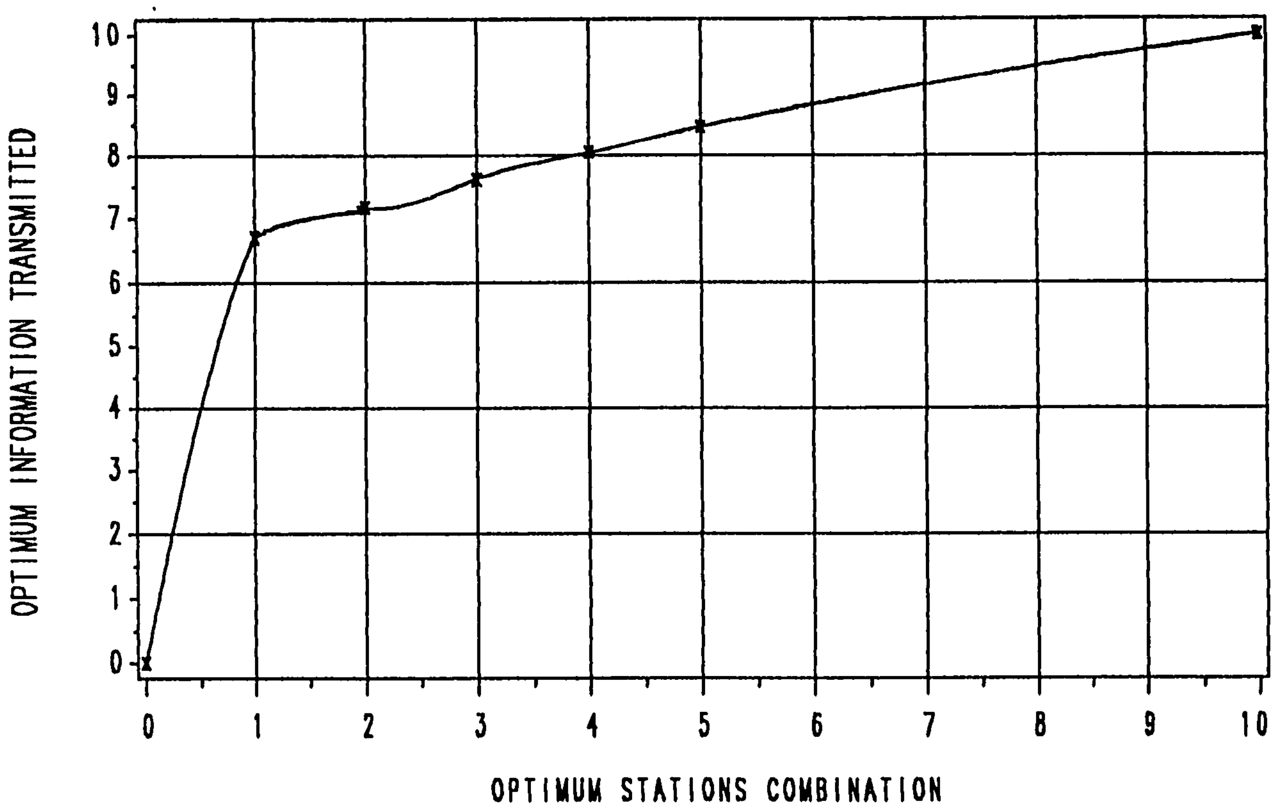


FIGURE 6.1 OPTIMUM INFORMATION AND STATIONS RETAINED IN ZONE#1 USING FISHER'S INFORMATION MEASURE (A118 , A210 , A001 , A003 , A106 , A112 A201 , A107 , A113 , A128)

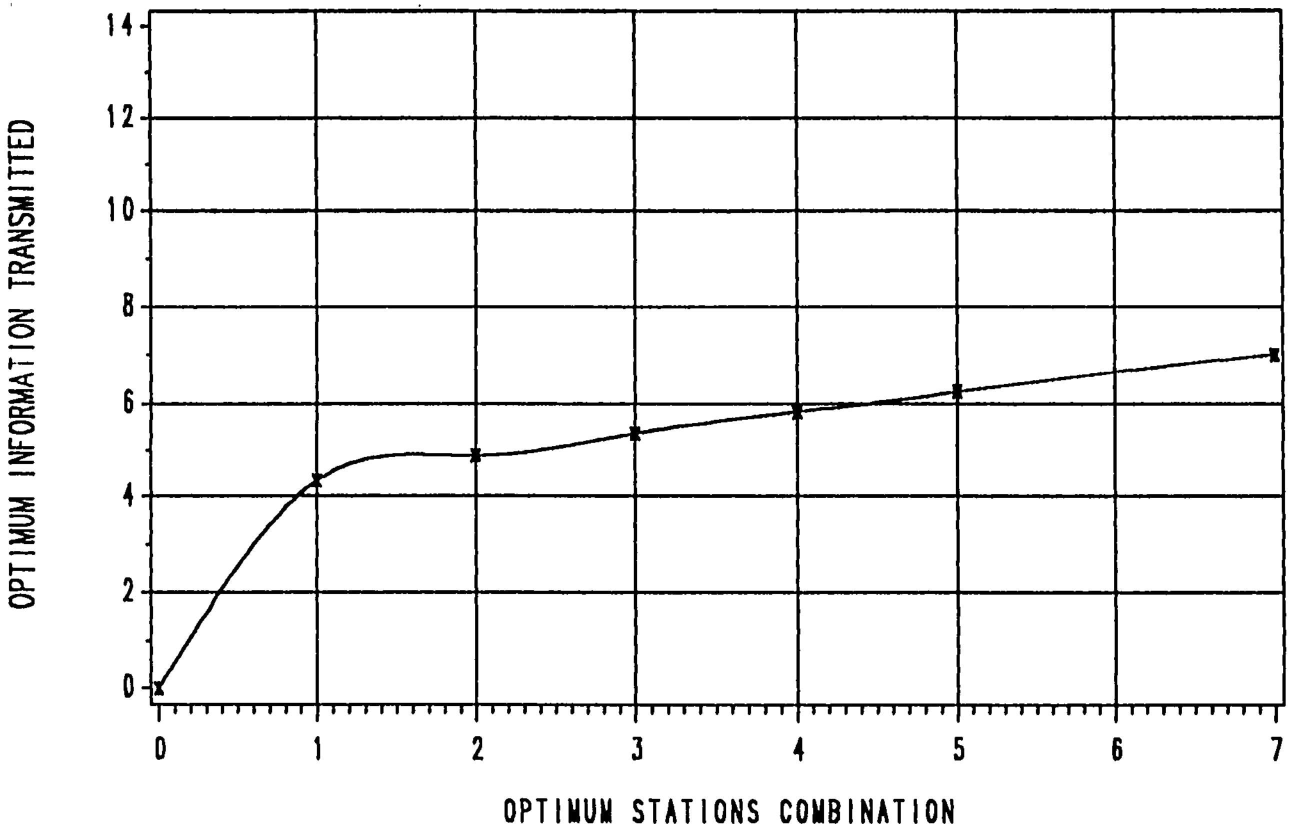


FIGURE 6.2 OPTIMUM INFORMATION AND STATIONS RETAINED IN ZONE#2 USING FISHER'S INFORMATION MEASURE (A124 , A108 , A117 , A206 , A217 A120 , A211)

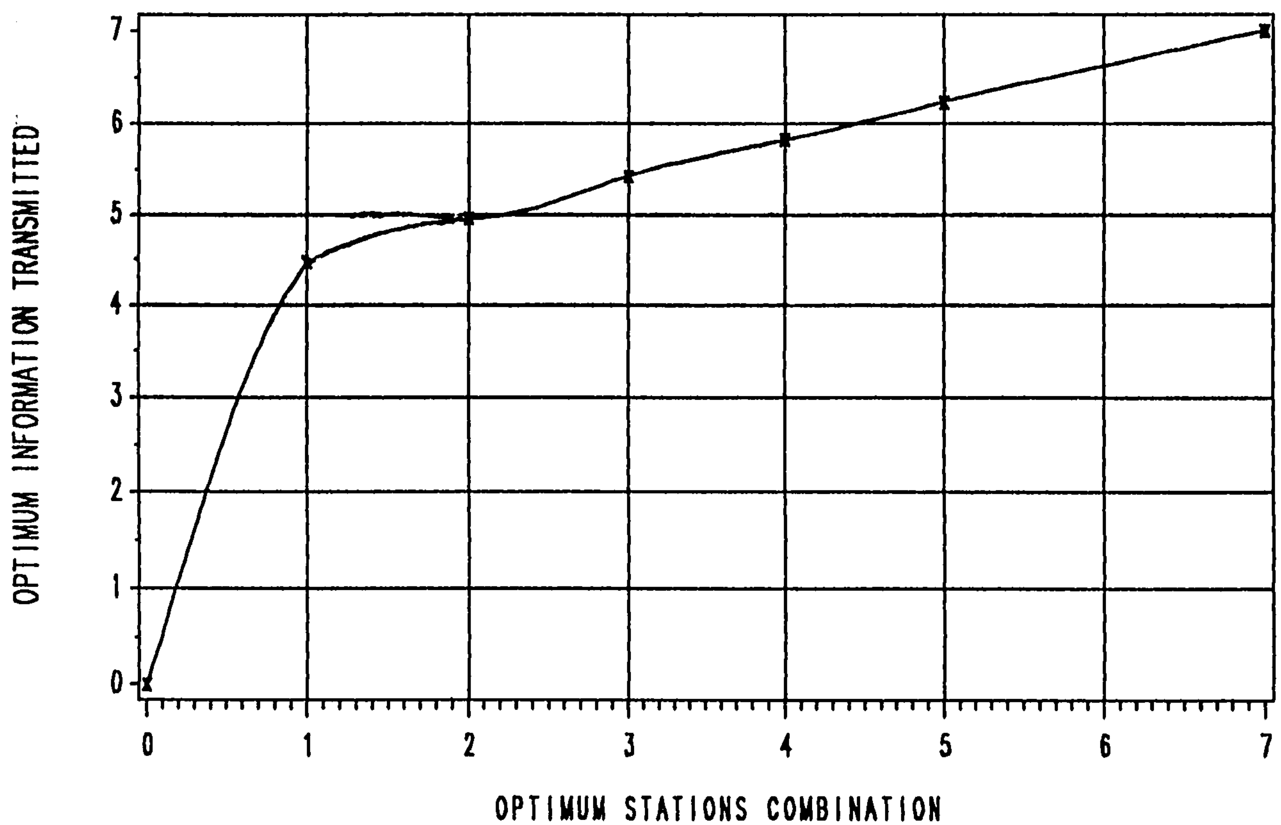


FIGURE 6.3 OPTIMUM INFORMATION AND STATIONS RETAINED IN ZONE#3 USING FISHIR'S INFORMATION MEASURE (B003 , B101 , B212 , TA219 , B001 B103 , TA237)

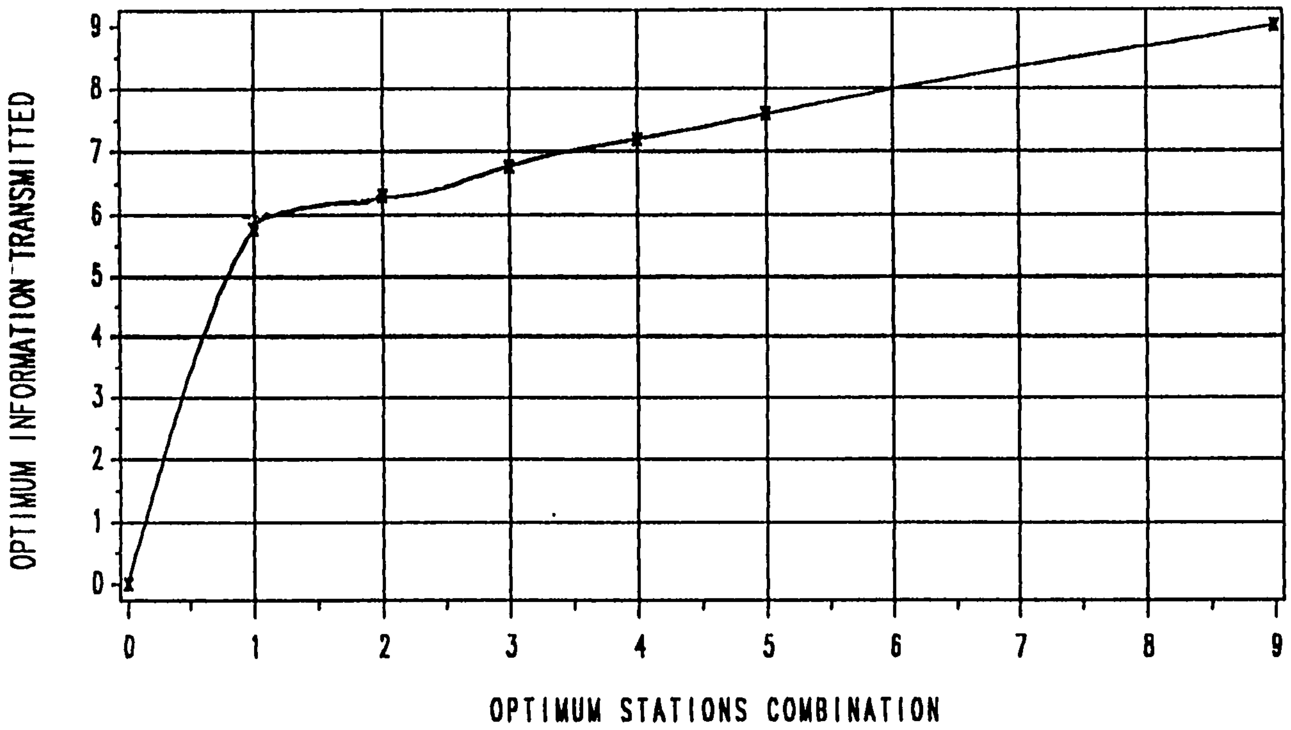


FIGURE 6.4 OPTIMUM INFORMATION AND STATIONS RETAINED IN ZONE#4 USING FISHER'S INFORMATION MEASURE (A004 , A105 , A123 , A213 , A103 A121 , N103 , N203 , A104)

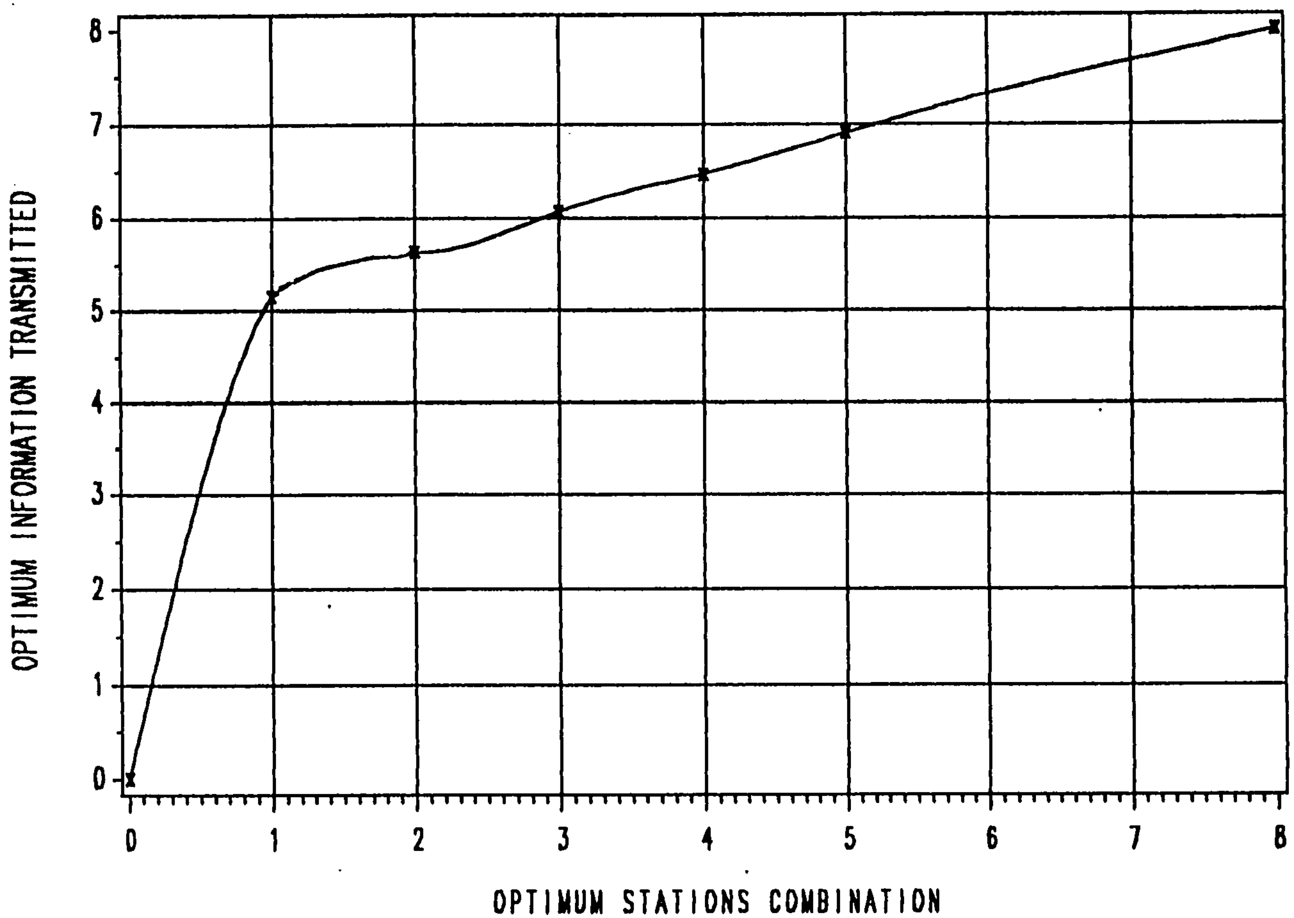


FIGURE 6.5 OPTIMUM INFORMATION AND STATIONS RETAINED IN ZONE#5 USING FISHER'S INFORMATION MEASURE (B002 , B216 , B217 , B222 , B114 , B004 , B005)

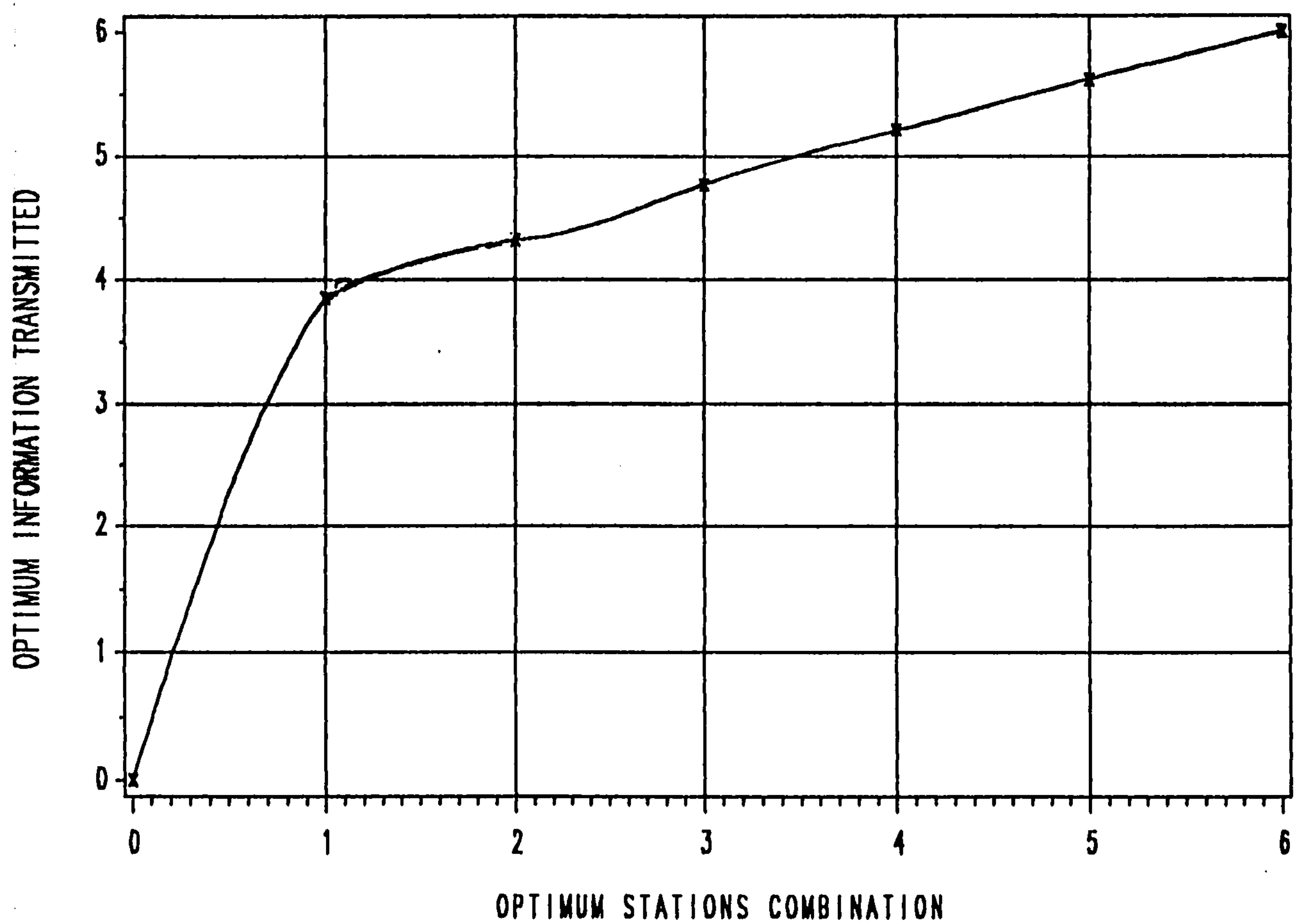


FIGURE 6.6 OPTIMUM INFORMATION AND STATIONS RETAINED IN ZONE#6 USING FISHER'S INFORMATION MEASURE (TA229 , TA235 , TA215 , TA228 , TA236 , TA238)

Chapter 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

On the basis of the analysis conducted, a number of retained stations were selected from the existing hydrological network of Area III by applying Fisher's and Shannon's information concepts. Table 7.1 summarizes the retained station combinations, optimum information, and marginal and relative information transmitted for all subregions in Area III. The following conclusions are drawn from this study:

1. The application of mathematically derived bivariate and multivariate gamma distribution is quite complex. Therefore, a generalized bivariate and multivariate gamma distribution is not used for this study. However, the transformation scheme from any distribution to normal distribution presented in this study seems to be a useful tool.

2. The processing of rainfall data collected in Area III shows some inconsistency and discontinuity in record length.

3. The information transmission, as derived by Fisher, is restricted to the assumption of linearity, assuming homogeneous area, and normality, mean equal to zero and variance

Table 7.1: Comparision Between Retained Stations, Optimum Information, Marginal and Relative Information Transmitted about Different Zones Using Shannon's and Fisher's Information Theories.

Zone #	Methodology	Optimum Station-No. Retained (five Station Combination)	Optimum Information	Marginal Transmitted Information %	Relative Information Transmitted %
1	Shannon	3,5,6,9,10	5.5574	6.321	79.891
	Fisher	2,7,9,9,10	8.4463	4.057	84.463
2	Shannon	2,3,4,5,7	9.9917	13.520	76.336
	Fisher	1,2,5,6,7 1,4,5,6,7 2,3,4,6,7 3,4,5,6,7	6.2351	6.167	89.073
3	Shannon	1,2,3,5,6	10.0444	13.166	77.429
	Fisher	1,2,3,4,6	6.2268	5.769	88.950
4	Shannon	1,2,3,7,9	11.9114	10.915	61.920
	Fisher	1,2,6,7,9 1,2,6,8,9	7.5930	4.450	84.367
5	Shannon	1,3,5,6,8	7.8539	10.979	69.035
	Fisher	3,4,5,6,7	6.9034	5.443	86.293
6	Shannon	1,3,4,5,6	8.4316	14.686	87.798
	Fisher	1,2,3,4,6 2,3,4,5,6	5.6184	6.812	93.640

equal to one. These assumptions may not be applicable in hydrologic network design due to non-linearity and skewness which commonly exists in time series data such as rainfall. Shannon's information criterion, however, is not restricted to the above assumptions. The suggested stations to be retained after applying Fisher's and Shannon's information concepts are shown in Figures 7.1 and 7.2 respectively.

4. In the case of hydrological network expansion of Area III, the proposed stations based on the finding presented in the last chapter are shown in Figure 7.3. The suggested locations of the stations is preliminary. The final decision on location depends on various factors such as the graphical features of the sites and its accessibility. The final retained as well as the proposed new stations in hydrological Area III are shown in Figure 7.4

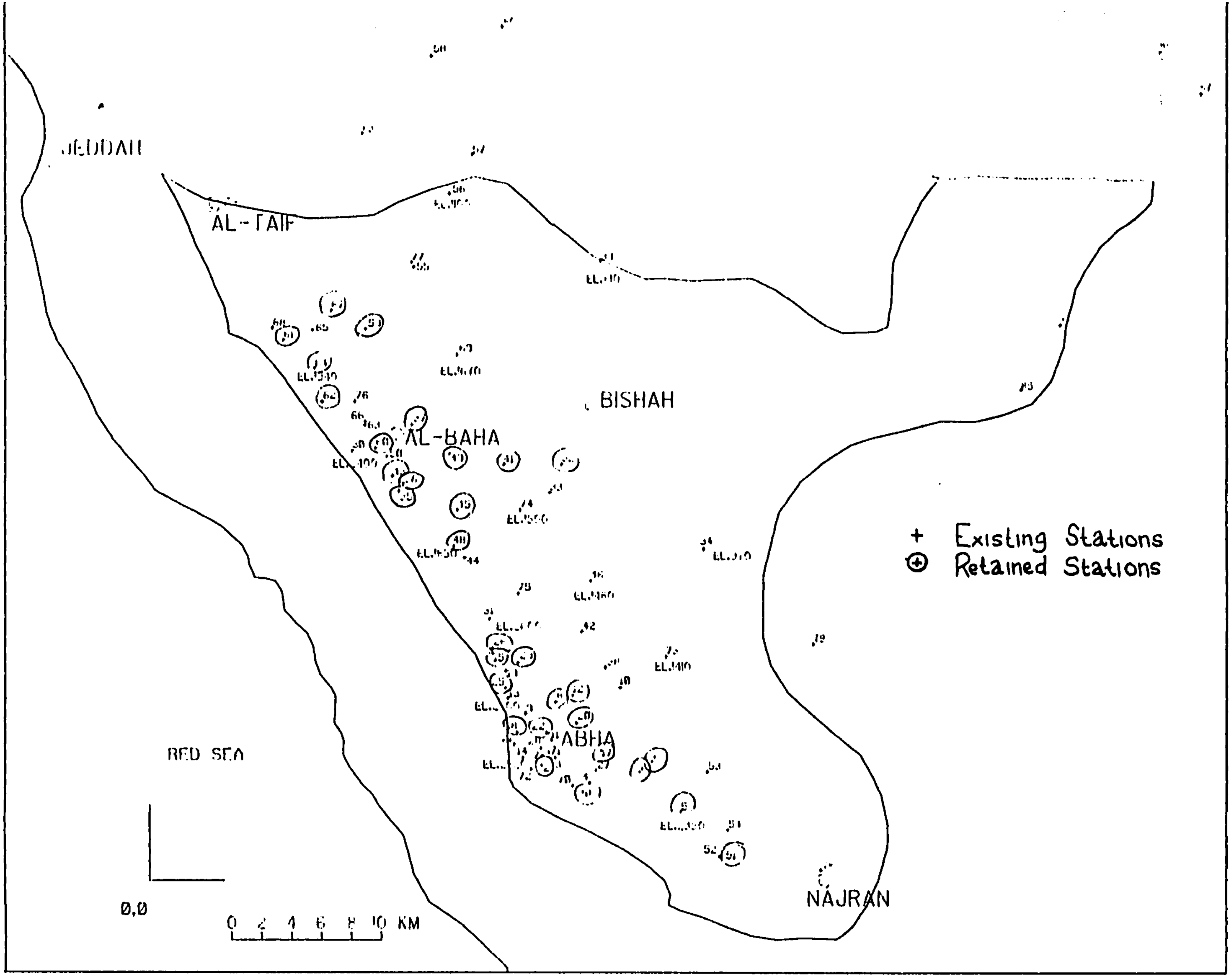


Figure 7.1: Map Showing Retained Stations Using Fisher's Information Measure.

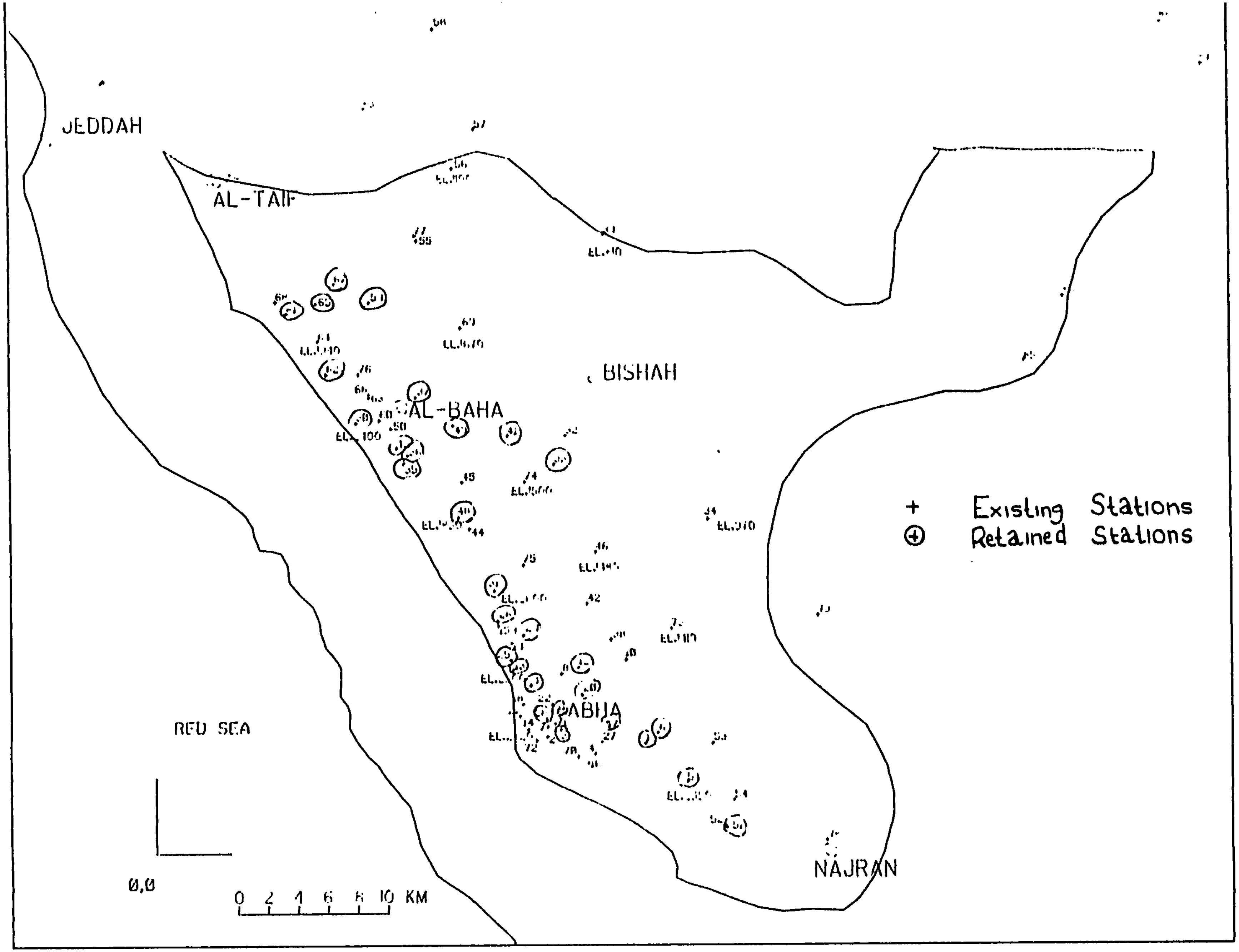


Figure 7.2: Map Showing Retained Stations Using Shannon's Information Measure.

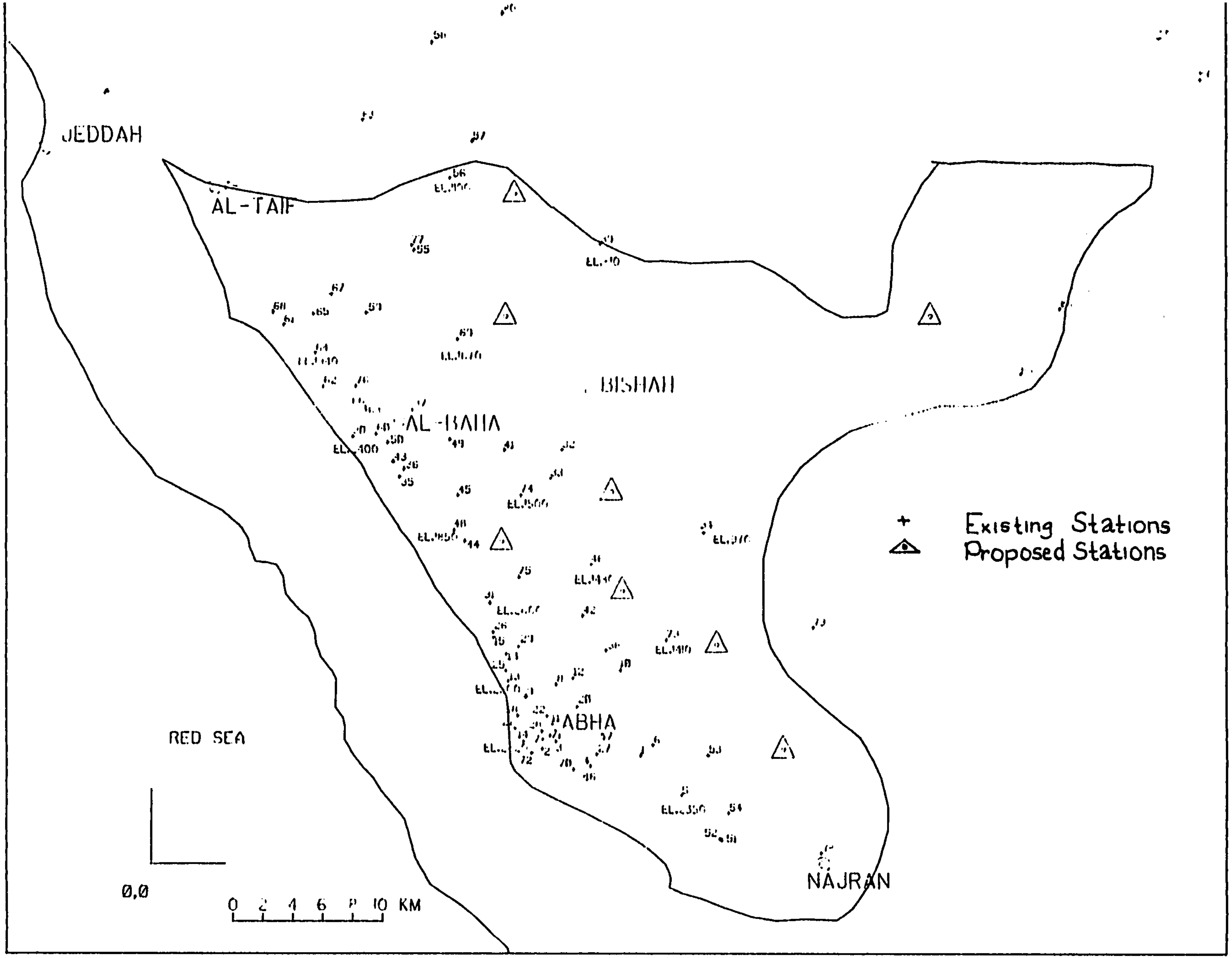


Figure 7.3: Map Showing Proposed Station Locations in Hydrological Area III.

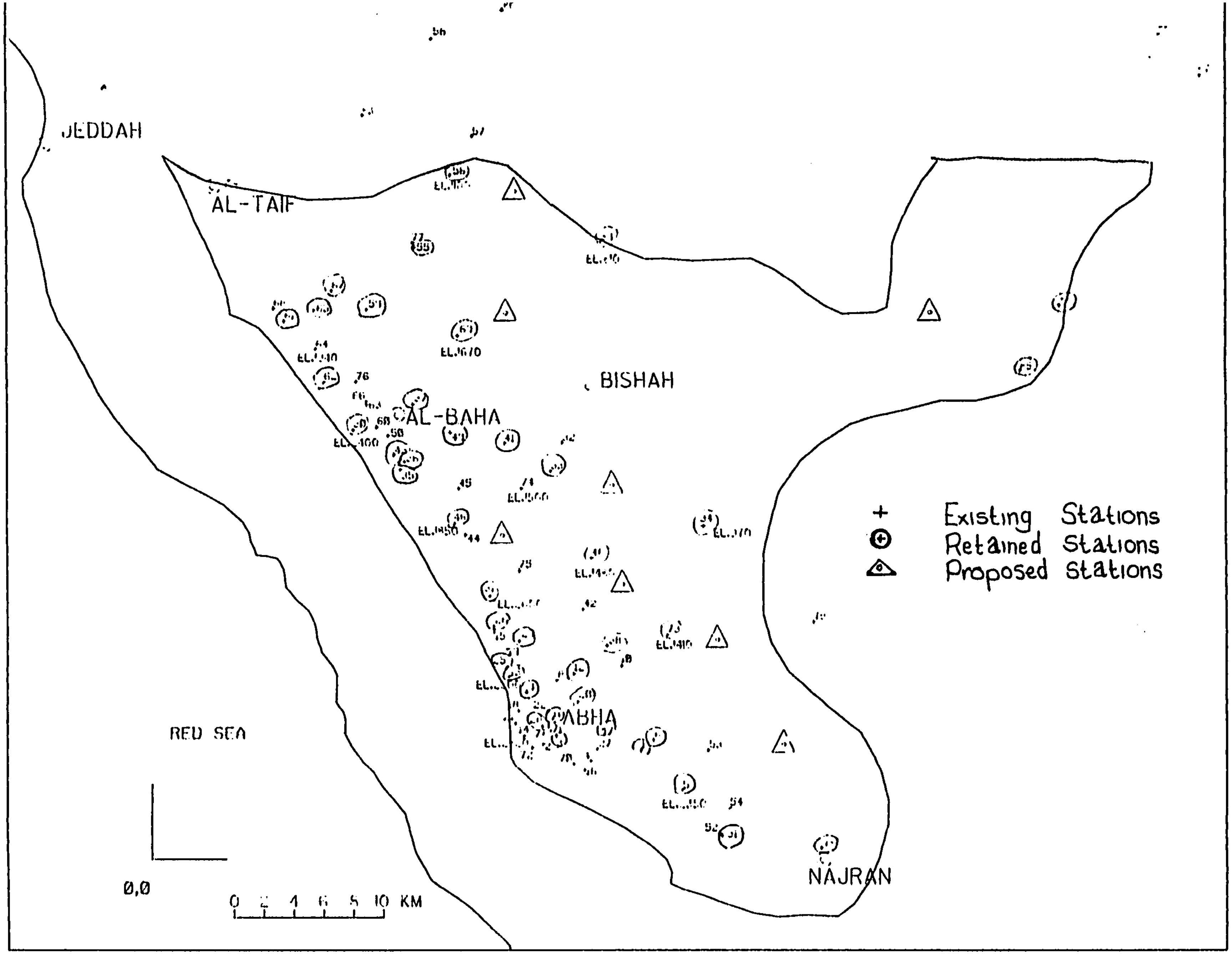


Figure 7.4: Map Showing Locations of Retained and Proposed Stations in Hydrological Area III of Saudi Arabia.

7.2 Recommendations

Based on the analysis presented in this study the following recommendations are made:

1. Scientific methods should be applied when designing hydrological networks in order to give a correct picture of a real representation of a variable such as precipitation.

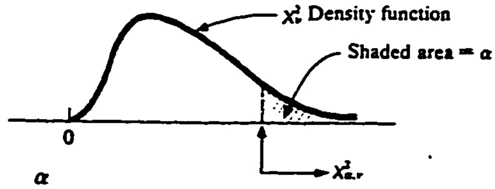
2. Hydrological network reduction or expansion should be performed regularly to check the integrity of the existing network.

3. Unlike Fisher's information theory, Shannon's information theory does not depend on normality or on linearity in its derivation. Shannon's information theory should be applied to check the status of the existing hydrological networks for other hydrological areas of the Kingdom of Saudi Arabia.

4. For other types of networks such as air-monitoring, run-off gages, etc., Shannon's information method is suggested for network design. This is due to its advantages over the other types of network design methods, especially for large areas where heterogeneity is expected.

APPENDIX - A

Table A Critical Values $\chi^2_{\alpha,\nu}$ for the Chi-Squared Distribution (Devore, 1982).



ν \ α	.995	.99	.975	.95	.90	.10	.05	.025	.01	.005
1	0.000	0.000	0.001	0.004	0.016	2.706	3.843	5.025	6.637	7.882
2	0.010	0.020	0.051	0.103	0.211	4.605	5.992	7.378	9.210	10.597
3	0.072	0.115	0.216	0.352	0.584	6.251	7.815	9.348	11.344	12.837
4	0.207	0.297	0.484	0.711	1.064	7.779	9.488	11.143	13.277	14.860
5	0.412	0.554	0.831	1.145	1.610	9.236	11.070	12.832	15.085	16.748
6	0.676	0.872	1.237	1.635	2.204	10.645	12.592	14.440	16.812	18.548
7	0.989	1.239	1.690	2.167	2.833	12.017	14.067	16.012	18.474	20.276
8	1.344	1.646	2.180	2.733	3.490	13.362	15.507	17.534	20.090	21.954
9	1.735	2.088	2.700	3.325	4.168	14.684	16.919	19.022	21.665	23.587
10	2.156	2.558	3.247	3.940	4.865	15.987	18.307	20.483	23.209	25.188
11	2.603	3.053	3.816	4.575	5.578	17.275	19.675	21.920	24.724	26.755
12	3.074	3.571	4.404	5.226	6.304	18.549	21.026	23.337	26.217	28.300
13	3.565	4.107	5.009	5.892	7.041	19.812	22.362	24.735	27.687	29.817
14	4.075	4.660	5.629	6.571	7.790	21.064	23.685	26.119	29.141	31.319
15	4.600	5.229	6.262	7.261	8.547	22.307	24.996	27.488	30.577	32.799
16	5.142	5.812	6.908	7.962	9.312	23.542	26.296	28.845	32.000	34.267
17	5.697	6.407	7.564	8.682	10.085	24.769	27.587	30.190	33.408	35.716
18	6.265	7.015	8.231	9.390	10.865	25.989	28.869	31.526	34.805	37.156
19	6.843	7.632	8.906	10.117	11.651	27.203	30.143	32.852	36.190	38.580
20	7.434	8.260	9.591	10.851	12.443	28.412	31.410	34.170	37.566	39.997
21	8.033	8.897	10.283	11.591	13.240	29.615	32.670	35.478	38.930	41.399
22	8.643	9.542	10.982	12.338	14.042	30.813	33.924	36.781	40.289	42.796
23	9.260	10.195	11.688	13.090	14.848	32.007	35.172	38.075	41.637	44.179
24	9.886	10.856	12.401	13.848	15.659	33.196	36.415	39.364	42.980	45.558
25	10.519	11.523	13.120	14.611	16.473	34.381	37.652	40.646	44.313	46.925
26	11.160	12.198	13.844	15.379	17.292	35.563	38.885	41.923	45.642	48.290
27	11.807	12.878	14.573	16.151	18.114	36.741	40.113	43.194	46.962	49.642
28	12.461	13.565	15.308	16.928	18.939	37.916	41.337	44.461	48.278	50.993
29	13.120	14.256	16.147	17.708	19.768	39.087	42.557	45.772	49.586	52.333
30	13.787	14.954	16.791	18.493	20.599	40.256	43.773	46.979	50.892	53.672
31	14.457	15.655	17.538	19.280	21.433	41.422	44.985	48.231	52.190	55.000
32	15.134	16.362	18.291	20.072	22.271	42.585	46.194	49.480	53.486	56.328
33	15.814	17.073	19.046	20.866	23.110	43.745	47.400	50.724	54.774	57.646
34	16.501	17.789	19.806	21.664	23.952	44.903	48.602	51.966	56.061	58.964
35	17.191	18.508	20.569	22.465	24.796	46.059	49.802	53.203	57.340	60.272
36	17.887	19.233	21.336	23.269	25.643	47.212	50.998	54.437	58.619	61.581
37	18.584	19.960	22.105	24.075	26.492	48.363	52.192	55.667	59.891	62.880
38	19.289	20.691	22.878	24.884	27.343	49.513	53.384	56.896	61.162	64.181
39	19.994	21.425	23.654	25.695	28.196	50.660	54.572	58.119	62.426	65.473
40	20.706	22.164	24.433	26.509	29.050	51.805	55.758	59.342	63.691	66.766

For $\nu > 40$, $\chi^2_{\alpha,\nu} \doteq \nu\left(1 - \frac{2}{9\nu} + z_\alpha\sqrt{\frac{2}{9\nu}}\right)^3$

CHI-SQUARE TEST FOR
STATION "A105"

RAINFALL	OBSERVED FREQUNCY (O)	ALPHA	BETA	COMMULATIVE FREQUNCY	EXPECTED FREQUNCY (E)	(E-O)**2 / E
1	2	1.674	8.909	1.5206	4.5284	0.478
2	4	1.674	8.909	4.5284		
3	6	1.674	8.909	8.3384	3.8100	1.260
4	3	1.674	8.909	12.6171	8.8121	0.540
5	8	1.674	8.909	17.1505		
6	4	1.674	8.909	21.7913	8.6436	0.048
7	4	1.674	8.909	26.4349		
8	4	1.674	8.909	31.0066	9.0183	1.010
9	2	1.674	8.909	35.4532		
10	6	1.674	8.909	39.7375	4.2843	0.687
11	6	1.674	8.909	43.8345	4.9070	0.884
12	4	1.674	8.909	47.7283		
13	1	1.674	8.909	51.4101	11.0418	2.300
14	1	1.674	8.909	54.8763		
15	3	1.674	8.909	58.1275		
16	2	1.674	8.909	61.1672	9.1249	1.070
17	1	1.674	8.909	64.0012		
18	6	1.674	8.909	66.6368	2.6356	4.290
19	1	1.674	8.909	69.0825		
20	1	1.674	8.909	71.3476	6.8048	0.006
21	5	1.674	8.909	73.4416		
22	1	1.674	8.909	75.3744		
23	1	1.674	8.909	77.1557		
24	1	1.674	8.909	78.7953		
25	1	1.674	8.909	80.3026		
26	2	1.674	8.909	81.6867		
27	1	1.674	8.909	82.9563		
28	1	1.674	8.909	84.1198	22.5584	0.014
29	2	1.674	8.909	85.1851		
31	2	1.674	8.909	87.0507		
33	1	1.674	8.909	88.6075		
35	1	1.674	8.909	89.9031		
36	2	1.674	8.909	90.4662		
38	1	1.674	8.909	91.4458		
40	1	1.674	8.909	92.2567		
45	3	1.674	8.909	93.7183		
50	1	1.674	8.909	94.6175		

$\chi^2_{calculated} = 12.587$

DF = 12 - 2 = 10

$\chi^2_{table} = \chi^2_{0.05,\ 10} = 18.307$

$\because\ \chi^2_{table} > \chi^2_{calculated}$

$\therefore$ Accept the assumed distribution

CHI-SQUARE TEST FOR STATION "A108"

RAINFALL	OBSERVED FREQUNCY (O)	ALPHA	BETA	COMMULATIVE FREQUNCY	EXPECTED FREQUNCY (E)	(E-O)**2 / E
1	89	0.601	12.55	95.956	96	0.51
2	37	0.601	12.55	141.375	45	1.42
3	39	0.601	12.55	175.317	34	0.73
4	37	0.601	12.55	202.663	27	3.70
5	24	0.601	12.55	225.483	23	0.04
6	28	0.601	12.55	244.925	20	3.20
7	14	0.601	12.55	261.716	17	0.53
8	12	0.601	12.55	276.357	15	0.60
9	14	0.601	12.55	289.216	13	0.08
10	8	0.601	12.55	300.574	11	0.82
11	11	0.601	12.55	310.651	10	0.10
12	8	0.601	12.55	319.624	9	0.11
13	9	0.601	12.55	327.638	8	0.13
14	7	0.601	12.55	334.814	7	0.00
15	6	0.601	12.55	341.254	7	0.14
16	4	0.601	12.55	347.045	6	0.70
17	6	0.601	12.55	352.260	5	0.20
18	6	0.601	12.55	356.964	5	0.20
19	6	0.601	12.55	361.213	5	0.20
20	3	0.601	12.55	365.054		
21	4	0.601	12.55	368.531	7	3.57
22	5	0.601	12.55	371.681		
23	4	0.601	12.55	374.538		
24	1	0.601	12.55	377.131		
25	1	0.601	12.55	379.485		
26	4	0.601	12.55	381.625		
27	2	0.601	12.55	383.570		
28	2	0.601	12.55	385.341		
29	1	0.601	12.55	386.952		
30	2	0.601	12.55	388.420		
31	1	0.601	12.55	389.758		
32	1	0.601	12.55	390.977	30	0.30
35	1	0.601	12.55	394.029		
36	1	0.601	12.55	394.874		
37	1	0.601	12.55	395.646		
38	1	0.601	12.55	396.351		
40	1	0.601	12.55	397.584		
45	1	0.601	12.55	399.854		
85	1	0.601	12.55	403.862		
100	1	0.601	12.55	404.000		

$X^2_{calculated} = 17.278$

DF = 21 - 2 = 19

$X^2_{0.05,\ 19\ (table)} = 30.143 > X^2_{calculated}$

∴ Accept the hypothesis.

APPENDIX - B

1	2	3	4	5	6	7	8
1.3851	0.0673	0.1388	0.1067	0.0030	0.0634	0.0757	0.1002
0.0673	1.4050	0.1554	0.0722	0.0042	0.0180	0.0332	0.1088
0.1388	0.1554	1.5378	0.0922	0.0364	0.0529	0.0954	0.1681
0.1067	0.0722	0.0922	1.1433	0.0741	0.0973	0.0723	0.0501
0.0030	0.0042	0.0364	0.0741	1.4783	0.1273	0.1773	0.0942
0.0634	0.0180	0.0529	0.0973	0.1273	1.5326	0.0970	0.1418
0.0757	0.0332	0.0954	0.0723	0.1773	0.0970	1.4327	0.2738
0.1002	0.1088	0.1681	0.0501	0.0942	0.1418	0.2738	1.5227

GLE STATION CASE
****

PT. INF. TRANS.	STATION RETAINED
1.9403	1
1.8641	2
2.2771	3
1.7081	4
1.9948	5
2.1303	6
2.2576	7
2.4597-------------------	8

STATION CASE
****

PT. INF. TRANS.	BEST INF. TRANSFER	STATION COMBINATION	
3.3043	42	1	2
3.5484	44	1	3
3.0867	45	1	4
3.5810	7	1	5
3.5966	8	1	6
3.6789	8	1	7
3.8013	56	1	8
3.5268	64	2	3
3.1628	47	2	4
3.5934	15	2	5
3.6237	16	2	6
3.6893	48	2	7
3.7780	56	2	8
3.4103	13	3	4
3.8752	7	3	5
3.8543	15	3	6
3.9051	8	3	7
3.9568-------------------	8--------------	3----	8
3.2914	8	4	5

3.3131	8	4	6
3.3988	14	4	7
3.5595	32	4	8
3.5615	62	5	6
3.5906	58	5	7
3.8678	60	5	8
3.7181	60	6	7
3.9308	58	6	8
3.7240	58	7	8

REE STATION CASE
****

OPT. INF. TRANS.	BEST GRID COMB.	STATION COMBINATION		
4.7981	63	1	2	3
4.4447	155	1	2	4
4.9438	107	1	2	5
4.9509	108	1	2	6
5.0331	108	1	2	7
5.0975	189	1	2	8
4.6566	158	1	3	4
5.1360	107	1	3	5
5.1100	107	1	3	6
5.1659	108	1	3	7
5.2175	108	1	3	8
4.6224	106	1	4	5
4.6381	108	1	4	6
4.7206	105	1	4	7
4.8379	243	1	4	8
5.0279	6	1	5	6
5.0101	6	1	5	7
5.1854	225	1	5	8
5.1144	9	1	6	7
5.2251	222	1	6	8
5.0433	222	1	7	8
4.6600	158	2	3	4
5.1249	134	2	3	5
5.1040	161	2	3	6
5.1548	135	2	3	7
5.2064	135	2	3	8
4.7020	106	2	4	5
4.7091	108	2	4	6
4.7915	105	2	4	7
4.8557	162	2	4	8
5.0549	24	2	5	6
5.0223	177	2	5	7
5.1640	234	2	5	8
5.1498	180	2	6	7
5.2270	231	2	6	8
5.0202	231	2	7	8
4.9263	25	3	4	5
4.9004	25	3	4	6

4.9565	24	3	4	7
5.0079	27	3	4	8
5.2856	22	3	5	6
5.2364	6	3	5	7
5.3408	9	3	5	8
5.3458	18	3	6	7
5.3857	15	3	6	8
5.1988	6	3	7	8
4.7443	6	4	5	6
4.7297	24	4	5	7
4.9436	81	4	5	8
4.8341	27	4	6	7
4.9834	78	4	6	8
4.8015	78	4	7	8
5.0191	240	5	6	7
5.2818	240	5	6	8
5.0267	237	5	7	8
5.1397	236	6	7	8

UR STATION CASE
****

OPT. INF. TRANS.	BEST GRID COMB.	STATION COMBINATION			
5.8347	208	1	2	3	4
6.2399	16	1	2	3	5
6.2672	64	1	2	3	6
6.1354	52	1	2	3	7
6.1526	52	1	2	3	8
5.8488	114	1	2	4	5
5.8800	114	1	2	4	6
5.8017	126	1	2	4	7
5.8586	125	1	2	4	8
6.3491	78	1	2	5	6
6.1993	78	1	2	5	7
6.3578	80	1	2	5	8
6.2866	80	1	2	6	7
6.3318	80	1	2	6	8
6.2820	80	1	2	7	8
6.0607	118	1	3	4	5
6.0919	118	1	3	4	6
5.9939	126	1	3	4	7
6.0111	126	1	3	4	8
6.5413	78	1	3	5	6
6.3914	78	1	3	5	7
6.4906	80	1	3	5	8
6.4457	78	1	3	6	7
6.4646	80	1	3	6	8
6.4148	80	1	3	7	8
6.0277	77	1	4	5	6
5.8779	77	1	4	5	7
6.0450	80	1	4	5	8
5.9738	80	1	4	6	7

6.0190	80	1	4	6	8
5.9695	78	1	4	7	8
6.2833	4	1	5	6	7
6.4088	2	1	5	6	8
6.2590	2	1	5	7	8
6.3633	4	1	6	7	8
6.0641	118	2	3	4	5
6.0952	118	2	3	4	6
5.9973	126	2	3	4	7
6.0145	126	2	3	4	8
6.5302	94	2	3	5	6
6.3803	94	2	3	5	7
6.4794	96	2	3	5	8
6.4397	126	2	3	6	7
6.4586	128	2	3	6	8
6.4037	96	2	3	7	8
6.1073	77	2	4	5	6
5.9575	77	2	4	5	7
6.1160	80	2	4	5	8
6.0448	80	2	4	6	7
6.0900	80	2	4	6	8
6.0404	78	2	4	7	8
6.3103	16	2	5	6	7
6.4358	14	2	5	6	8
6.2712	198	2	5	7	8
6.3987	200	2	6	7	8
6.3316	13	3	4	5	6
6.1818	13	3	4	5	7
6.2809	16	3	4	5	8
6.2361	13	3	4	6	7
6.2550	16	3	4	6	8
6.2054	14	3	4	7	8
6.5410	13	3	5	6	7
6.6402	14	3	5	6	8
6.4852	2	3	5	7	8
6.5946	8	3	6	7	8
5.9998	4	4	5	6	7
6.1252	2	4	5	6	8
5.9786	14	4	5	7	8
6.0830	16	4	6	7	8
6.2680	254	5	6	7	8

E STATION CASE
****

OPT. INF. TRANS.	BEST GRID COMB.	STATION COMBINATION				
7.3104	100	1	2	3	4	5
7.3415	100	1	2	3	4	6
7.2435	95	1	2	3	4	7
7.2608	95	1	2	3	4	8
7.7909	20	1	2	3	5	6
7.6411	20	1	2	3	5	7

.7402	19	1	2	3	5	8
.6954	20	1	2	3	6	7
.7142	19	1	2	3	6	8
.6644	19	1	2	3	7	8
.3857	42	1	2	4	5	6
.2359	42	1	2	4	5	7
.3944	44	1	2	4	5	8
.3232	44	1	2	4	6	7
.3684	44	1	2	4	6	8
.3188	45	1	2	4	7	8
.6376	29	1	2	5	6	7
.7630	30	1	2	5	6	8
.6132	30	1	2	5	7	8
.7175	29	1	2	6	7	8
.5779	42	1	3	4	5	6
.4280	42	1	3	4	5	7
.5272	44	1	3	4	5	8
.4823	42	1	3	4	6	7
.5012	44	1	3	4	6	8
.4516	45	1	3	4	7	8
.7967	27	1	3	5	6	7
.8959	30	1	3	5	6	8
.7460	30	1	3	5	7	8
.8503	29	1	3	6	7	8
.3248	29	1	4	5	6	7
.4503	30	1	4	5	6	8
.3004	30	1	4	5	7	8
.4047	29	1	4	6	7	8
.6642	1	1	5	6	7	8
.5813	42	2	3	4	5	6
.4314	42	2	3	4	5	7
.5306	44	2	3	4	5	8
.4857	42	2	3	4	6	7
.5046	44	2	3	4	6	8
.4550	45	2	3	4	7	8
.7907	42	2	3	5	6	7
.8898	45	2	3	5	6	8
.7349	35	2	3	5	7	8
.8443	49	2	3	6	7	8
.3958	29	2	4	5	6	7
.5213	30	2	4	5	6	8
.3714	30	2	4	5	7	8
.4757	29	2	4	6	7	8
.6997	80	2	5	6	7	8
.5871	1	3	4	5	6	7
.6862	5	3	4	5	6	8
.5364	5	3	4	5	7	8
.6407	4	3	4	6	7	8
.8956	5	3	5	6	7	8
.3839	4	4	5	6	7	8

APPENDIX - C

1	2	3	4	5	6	7	8
.0000	0.5848	0.6261	0.6153	0.5215	0.5439	0.5237	0.5875
.5848	1.0000	0.6372	0.5300	0.5238	0.5395	0.5231	0.5740
.6261	0.6372	1.0000	0.5555	0.5621	0.5646	0.5453	0.6402
.6153	0.5300	0.5555	1.0000	0.5394	0.5231	0.5166	0.5593
.5215	0.5238	0.5621	0.5394	1.0000	0.5542	0.5523	0.5927
.5439	0.5395	0.5646	0.5231	0.5542	1.0000	0.5329	0.6317
.5237	0.5231	0.5453	0.5166	0.5523	0.5329	1.0000	0.5731
.5875	0.5740	0.6402	0.5593	0.5927	0.6317	0.5731	1.0000

.E STATION CASE
****

. INF. TRANS.	STATION RETAINED
.0027	1
.9123	2
.1310	3
.8394	4
.8459	5
.8900	6
.7669	7
.1585	8

TATION CASE
****

. INF. TRANS.	BEST INF. TRANSFER	STATION COMBINATION	
.4314	41	1	2
.5647	48	1	3
.4054	9	1	4
.5253	8	1	5
.5449	8	1	6
.5099	5	1	7
.6377	24	1	8
.4938	64	2	3
.4285	41	2	4
.4605	16	2	5
.4707	8	2	6
.4178	5	2	7
.5845	64	2	8
.5754	1	3	4
.5759	3	3	5
.5664	1	3	6
.5857	1	3	7
.6200	16	3	8
.4066	16	4	5

5.4382	32	4	6
5.3591	8	4	7
5.6270	32	4	8
5.3715	58	5	6
5.2958	33	5	7
5.5658	64	5	8
5.3571	1	6	7
5.5268	64	6	8
5.5854	64	7	8

EE STATION CASE
****

OPT. INF. TRANS.	BEST GRID COMB.	STATION COMBINATION		
5.9275	81	1	2	3
5.8317	136	1	2	4
5.9517	108	1	2	5
5.9713	108	1	2	6
5.9362	100	1	2	7
6.0530	189	1	2	8
5.9494	122	1	3	4
6.0096	98	1	3	5
6.0000	95	1	3	6
6.0194	95	1	3	7
6.0499	108	1	3	8
5.9100	27	1	4	5
5.9296	27	1	4	6
5.8946	19	1	4	7
6.0224	81	1	4	8
6.0101	6	1	5	6
5.9730	5	1	5	7
6.0450	63	1	5	8
6.0120	5	1	6	7
6.0060	63	1	6	8
6.0647	63	1	7	8
5.9383	122	2	3	4
5.9387	125	2	3	5
5.9292	122	2	3	6
5.9485	122	2	3	7
5.9828	162	2	3	8
5.9517	108	2	4	5
5.9713	108	2	4	6
5.9183	100	2	4	7
6.0530	162	2	4	8
5.9453	15	2	5	6
5.9082	14	2	5	7
5.9918	243	2	5	8
5.9378	5	2	6	7
5.9528	243	2	6	8
6.0114	243	2	7	8
6.0203	7	3	4	5
6.0108	1	3	4	6

6.0302	1	3	4	7	
6.0607	27	3	4	8	
6.0112	4	3	5	6	
6.0236	1	3	5	7	
6.0273	27	3	5	8	
6.0211	1	3	6	7	
5.9883	27	3	6	8	
6.0470	27	3	7	8	
5.9034	78	4	5	6	
5.8543	14	4	5	7	
6.0342	81	4	5	8	
5.9053	41	4	6	7	
5.9953	81	4	6	8	
6.0539	81	4	7	8	
5.8192	119	5	6	7	
5.9341	243	5	6	8	
5.9927	243	5	7	8	
5.9537	243	6	7	8	

R STATION CASE
****

OPT. INF. TRANS.	BEST GRID COMB.	STATION COMBINATION			
6.3122	256	1	2	3	4
6.3654	64	1	2	3	5
6.3629	64	1	2	3	6
6.3822	64	1	2	3	7
6.2873	64	1	2	3	8
6.2923	65	1	2	4	5
6.2878	113	1	2	4	6
6.3080	113	1	2	4	7
6.2442	113	1	2	4	8
6.3975	80	1	2	5	6
6.3994	80	1	2	5	7
6.3589	80	1	2	5	8
6.4384	80	1	2	6	7
6.3396	80	1	2	6	8
6.3487	77	1	2	7	8
6.3873	86	1	3	4	5
6.3847	86	1	3	4	6
6.4041	86	1	3	4	7
6.3092	86	1	3	4	8
6.4449	78	1	3	5	6
6.4573	70	1	3	5	7
6.3694	72	1	3	5	8
6.4548	70	1	3	6	7
6.3599	70	1	3	6	8
6.3792	70	1	3	7	8
6.3558	16	1	4	5	6
6.3577	16	1	4	5	7
6.3173	16	1	4	5	8
6.3967	16	1	4	6	7

6.2979	16	1	4	6	8
6.3071	13	1	4	7	8
6.4578	4	1	5	6	7
6.3784	2	1	5	6	8
6.3803	2	1	5	7	8
6.3803	2	1	6	7	8
6.3762	86	2	3	4	5
6.3736	86	2	3	4	6
6.3930	86	2	3	4	7
6.2981	86	2	3	4	8
6.3741	94	2	3	5	6
6.3864	86	2	3	5	7
6.2985	88	2	3	5	8
6.3839	86	2	3	6	7
6.2890	86	2	3	6	8
6.3083	86	2	3	7	8
6.3975	80	2	4	5	6
6.3994	80	2	4	5	7
6.3589	80	2	4	5	8
6.4384	80	2	4	6	7
6.3396	80	2	4	6	8
6.3443	77	2	4	7	8
6.3930	8	2	5	6	7
6.3136	6	2	5	6	8
6.3155	6	2	5	7	8
6.3062	2	2	6	7	8
6.4557	13	3	4	5	6
6.4680	1	3	4	5	7
6.3801	4	3	4	5	8
6.4655	1	3	4	6	7
6.3706	1	3	4	6	8
6.3900	1	3	4	7	8
6.4590	1	3	5	6	7
6.3711	2	3	5	6	8
6.3834	1	3	5	7	8
6.3809	1	3	6	7	8
6.3511	64	4	5	6	7
6.2717	62	4	5	6	8
6.2616	6	4	5	7	8
6.2736	22	4	6	7	8
6.1875	85	5	6	7	8

/E STATION CASE
****

OPT. INF. TRANS.	BEST GRID COMB.	STATION COMBINATION				
6.7501	125	1	2	3	4	5
6.7476	125	1	2	3	4	6
6.7669	125	1	2	3	4	7
6.6720	125	1	2	3	4	8
6.8078	20	1	2	3	5	6
6.8201	25	1	2	3	5	7

6.7322	24	1	2	3	5	8
6.8176	25	1	2	3	6	7
6.7227	25	1	2	3	6	8
6.7420	25	1	2	3	7	8
6.7822	44	1	2	4	5	6
6.7841	44	1	2	4	5	7
6.7436	44	1	2	4	5	8
6.8231	44	1	2	4	6	7
6.7243	44	1	2	4	6	8
6.7334	41	1	2	4	7	8
6.8842	29	1	2	5	6	7
6.8048	30	1	2	5	6	8
6.8067	30	1	2	5	7	8
6.8067	30	1	2	6	7	8
6.8296	42	1	3	4	5	6
6.8420	32	1	3	4	5	7
6.7541	34	1	3	4	5	8
6.8395	32	1	3	4	6	7
6.7446	32	1	3	4	6	8
6.7639	32	1	3	4	7	8
6.8927	27	1	3	5	6	7
6.8048	30	1	3	5	6	8
6.8171	27	1	3	5	7	8
6.8146	27	1	3	6	7	8
6.8425	4	1	4	5	6	7
6.7631	5	1	4	5	6	8
6.7650	5	1	4	5	7	8
6.7650	5	1	4	6	7	8
6.8261	1	1	5	6	7	8
6.8185	42	2	3	4	5	6
6.8309	32	2	3	4	5	7
6.7430	34	2	3	4	5	8
6.8284	32	2	3	4	6	7
6.7335	32	2	3	4	6	8
6.7528	32	2	3	4	7	8
6.8218	32	2	3	5	6	7
6.7339	35	2	3	5	6	8
6.7462	32	2	3	5	7	8
6.7437	32	2	3	6	7	8
6.8842	29	2	4	5	6	7
6.8048	30	2	4	5	6	8
6.8067	30	2	4	5	7	8
6.8067	30	2	4	6	7	8
6.7613	2	2	5	6	7	8
6.9034	1	3	4	5	6	7
6.8155	5	3	4	5	6	8
6.8279	1	3	4	5	7	8
6.8254	1	3	4	6	7	8
6.8188	1	3	5	6	7	8
6.7194	25	4	5	6	7	8

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