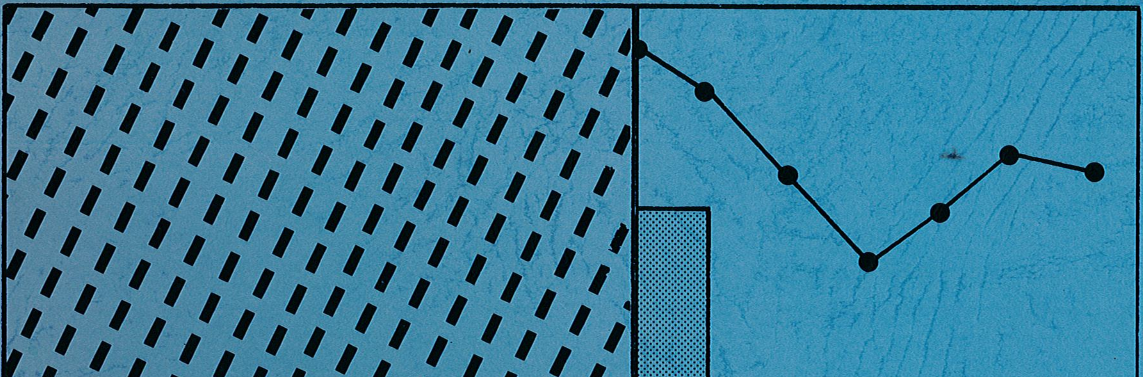
Rainfall Distribution on the Northern Swan Coastal Plain

by T.B. Butcher



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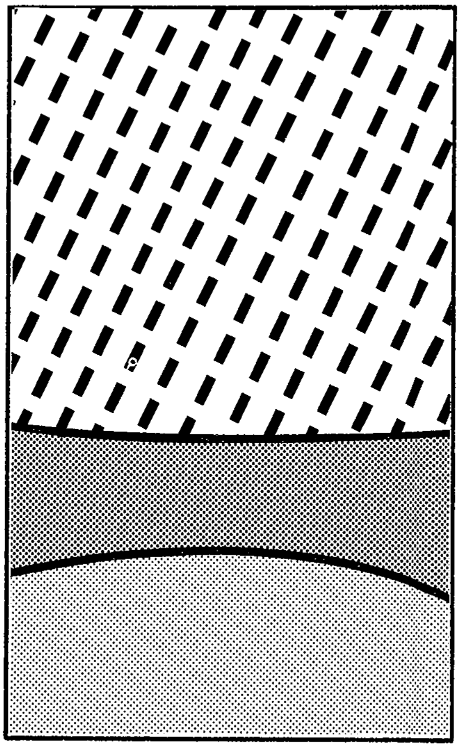

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

RAINFALL DISTRIBUTION ON THE NORTHERN SWAN COASTAL PLAIN

T.B. Butcher

ABSTRACT

Rainfall storage gauges were installed at remote sites on the Swan coastal plain, Western Australia and maintained for a 23-year period 1957-1979. Meteorological Bureau stations on the periphery of the area complement this record.

Most of the annual rainfall was received in the five winter months, May to September. There was considerable variation in the year-to-year totals but the annual pattern was similar for all stations. Rainfall decreases northwards along the coastal plain, generally increases eastward from the coast then decreases slightly towards the foothills of the Darling Range. Annual rainfall at the field sites and permanent stations were highly correlated.

Areal rainfall for the Gnangara Mound on the Swan coastal plain was calculated using the *Thiessen polygon* method. The average rainfall for the 1957-1979 period was 763 mm. As this period was the driest of the Perth station record, the study was extended to cover 1941-1979 using multiple linear regressions to predict rainfall at the field sites. This gave a better estimate of the mean. The Gnangara Mound areal mean annual rainfall for the extended 39-year period was 772 mm and the 95 per cent confidence limits of the mean were set at 726 and 818 mm.

INTRODUCTION

Information on rainfall on the Swan coastal plain, north of Perth is limited (Commonwealth Bureau of Meteorology, 1966; Commonwealth Bureau of Meteorology, 1968). Perth's climate is Mediterranean, with a mild wet winter and a hot dry summer (Commonwealth Bureau of Meteorology, 1969). Most of the rainfall is received in winter months from May to September when evapotranspiration is low.

Plantations of *Pinus pinaster* Ait have been established on the coastal plain since 1926. The area was close to the Perth market, the sandy soils were not wanted for agriculture and they were suitable for the growth of this pine species. Following investigations into establishment (Stoate, 1939), nutritional disorders (Stoate, 1950) and provenance (Perry, 1940; Hopkins, 1960), the State forest on the Swan coastal plain was seen as the most favourable pine afforestation area in Western Australia. When delineating the areas of State Forest No. 65 suitable for establishment of *P. pinaster*, Havel (1968) used native vegetation patterns to indicate the potential for pine growth because of the dearth of local climatic information.

Underlying the northern Swan coastal plain is a large underground water resource known as the Gnangara Mound. In April 1973, it was proclaimed as a water supply reserve (Western Australian Government Gazette, 1973). The Gnangara Mound covers an area of 2165 km^2, one quarter of which is covered by State Forest No. 65 (Figure 1).

Principal land use objectives for the forest area were defined by the Forests Department (1977) as water catchment protection and pine timber production.

To meet land use objectives more precise information on rainfall is required. Long-term rainfall records are available only for Perth and settlements along the periphery of the coastal plain. Shorter term records are available for forest settlements within the area, and rainfall data were collected from seven field stations scattered through the forest, during the 23-year period 1957-1979.

The purpose of this paper was to collate and analyse these data, in order to describe the distribution of rainfall and provide estimates of areal rainfall on the Gnangara Mound aquifer.

COLLECTION OF DATA

The locations of rainfall stations used in this study are shown in Figure 1 and complete station details are listed in Table 1.

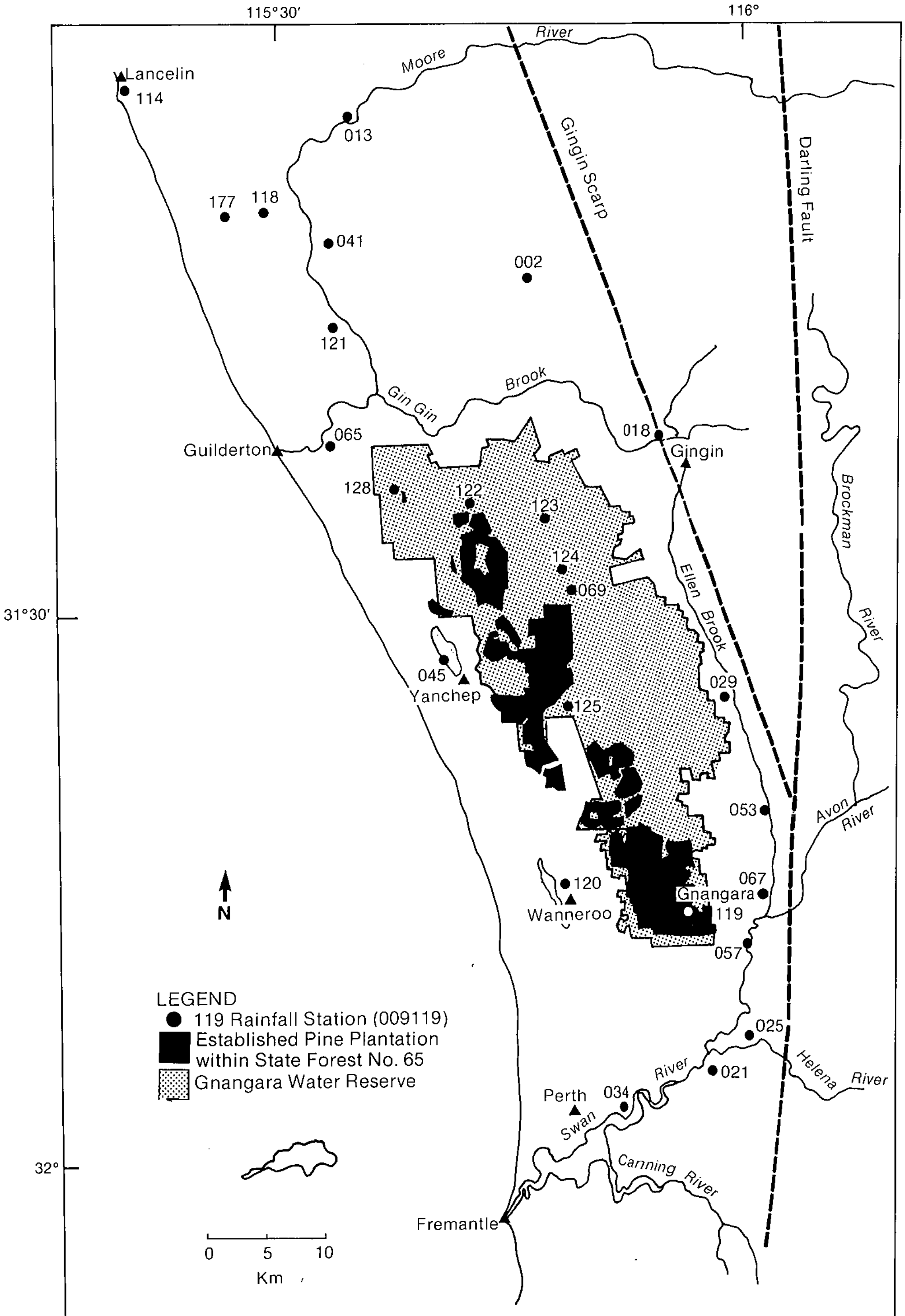


FIGURE 1: Location of rainfall stations on the Swan coastal plain.

TABLE 1

DESCRIPTION OF RAINFALL STATIONS

	Rainfall Station				Record		
Code	**Name**	**Latitude**	**Longitude**	**Altitude**	**First**	**Last**	n^+
009045	Yanchep	31°32'	115°41'	25 m	1935	1979	45
009069	Yeal Swamp	31°27'	115°53'	70	1957	1979	23
009118	Bennies/Ziema Rd.	31°09'	115°29'	30	1957	1979	23
009119	Gnangara	31°47'	115°57'	50	1941	1979	39
009120	Wanneroo	31°45'	115°48'	52	1958	1979	22
009121	Melbourne/Edwards Rd.	31°14'	115°32'	40	1957	1979	23
009122	Banksia/Wapet Rd.	31°24'	115°42'	52	1957	1979	23
009123	Redwood/Casuarina Rd.	31°23'	115°47'	60	1957	1979	23
009124	Stewart/Airforce Rd.	31°27'	115°48'	63	1957	1979	23
009125	Perry/Cypress Rd.	31°35'	115°49'	70	1957	1979	23
009128	Wabling	31°24'	115°38'	25	1967	1979	13
009002	Beermullah	31°14'	115°46'	60	1917	1979	63
009013	Cowalla	31°03'	115°34'	60	1909	1969	61
009018	Gingin	31°20'	115°56'	92	1889	1979	91
009021	Guildford	31°55'	115°58'	17	1945	1979	35
009025	Midland	31°52'	116°01'	15	1915	1979	65
009029	Muchea	31°35'	115°59'	52	1912	1973	*
009034	Perth	31°57'	115°51'	19	1876	1979	104
009041	Wannerie	31°10'	115°33'	40	1914	1973	*
009053	Pearce	31°41'	116°01'	40	1938	1979	*
009057	Henly Park	31°48'	116°00'	15	1914	1979	66
009065	Caraban	31°20'	115°33'	30	1957	1973	17
009067	Upper Swan	31°46'	116°01'	15	1958	1979	22
009114	Lancelin	31°01'	115°20'	2	1966	1979	14

+ number of complete years of record
*** incomplete record**

The conventional 20 cm raingauge was the basis of measurement of rainfall in most places. In sites remote from settlements storage gauges were read at monthly intervals to provide seasonal information on rainfall patterns. Transformer oil was added to the gauges to control evaporation (Hamilton and Andrews, 1953). Recording gauges (pluviographs) were located at forest sites 009118 and 009128 in 1966, but they were inefficient and provided little information.

Sites for measurement of rainfall were spaced around the eastern boundary of the forest. Storage gauges were located on flat ground in native woodland openings. Trees and shrubs were removed from around the gauges to a distance of twice the average height of the vegetation (Horton, 1919; Pereira, 1973), and these woodland openings were maintained for the duration of the study. Storage gauges were installed vertically in a pit, with the orifice at a height of 30 cm above ground level (Ward, 1975) (Fig. 2).

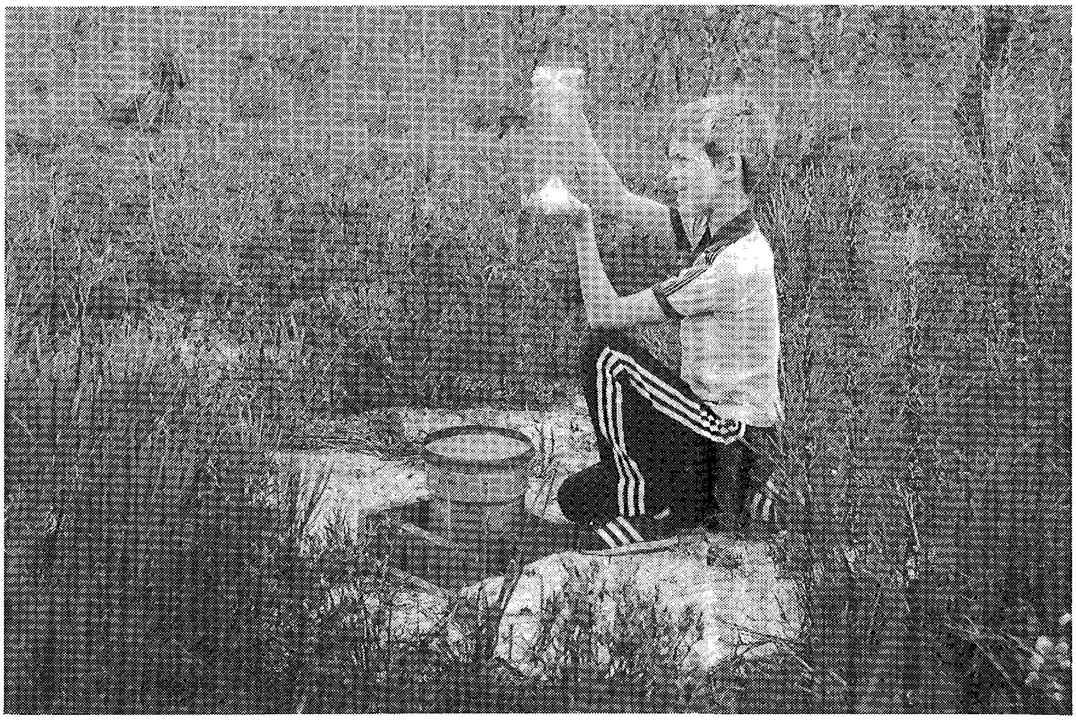


FIGURE 2: Storage raingauge at forest site 009125.

Forest sites 009069, 009118, 009121, 009122, 009123, 009124 and 009125 were installed in 1956 and 009128 in 1966. Rainfall data were collected at irregular time intervals until 1966 and were used only for annual analysis. From March 1966, rainfall was recorded on the first day of the month. After the reading, the gauges were cleaned with kerosene and a 3 mm layer of SAE30 grade oil was added to prevent evaporation of the next month's rainfall.

Forests Department settlement and Commonwealth Bureau of Meteorology raingauges were read daily, at 0900 hours.

ANALYSIS OF DATA

The mean is the best known and most commonly used rainfall statistic. Together with the standard deviation, which measures the dispersion, it is possible to calculate the probability of the occurrence of values within a certain range. The reliability of the estimate of the mean is calculated as the standard error.

If the distribution is normal then the mean has the same value as the median, which represents the central tendency of the distribution. Most annual rainfall totals on the coastal plain have a distribution approaching normality but monthly totals show a marked departure from the normal curve. For this reason the arithmetic mean was regarded as a poor indicator of monthly rainfall occurrence and the median was used.

The frequency distribution of annual rainfall was used by Gibbs and Maher (1967) to report and forecast occurrences of rainfall. Their terminology of "much below average" for the lowest 20 per cent of values etc. is used in this paper.

The analysis of rainfall data is complicated by its variation in time and space, requiring a diversity of techniques for its presentation and interpretation (Bruce and Clark, 1966). The common method to show time changes in rainfall is the bar-graph (Figs. 4 to 8). Major trends in rainfall occurrence can be shown by cumulative-departure mean curves or by progressive-average curves. Both were applied to the data but the long-term trends were better illustrated using the progressive-average curve. These were drawn for periods of five years, with each plotted point being the mean that would have been computed had the record been initiated five years earlier (Figs. 4 to 8).

Comparisons between stations should always be based on a common period of records, particularly when short-term periods are used. In this study, three time periods are used for comparison, viz:

Monthly rainfall analysis, n = 14, period 1966-1979.
Annual rainfall analysis, n = 23, period 1957-1979.
Annual rainfall analysis, n = 39, period 1941-1979.

The particular time period used can be related to the long-term average by progressive-average curves and by assessing how representative the current period average is to the long-term mean.

The variation of rainfall in space is usually illustrated by isohyetal maps, lines joining points of equal rainfall. Linear relationships between stations need to be computed to allow extrapolation to draw the isohyets. It is also necessary to check the consistency of station records when forming these relationships. This is done by double-mass curve analysis, a method first proposed by Merriam (1937). Data for each station in turn is accumulated and graphed against the cumulative data of five or more standard record stations. This will be a straight line so long as the relationship is a fixed ratio. Any break in the line is due to a change in the ratio and reflects a change in the physical environment e.g. gauge position alteration, growth of vegetation, method of recording.

The amount of rain collected by a single raingauge must be regarded as representing only the particular spot occupied by the gauge. How representative this site is needs to be ascertained to determine the sampling network of the catchment. This was studied in detail at forest site 009118.

An estimate of the average annual rainfall over the Gnangara Mound area is required for hydrologic modelling. Hall (1972) reviewed 15 methods for estimating areal rainfall including the commonly used *arithmetic mean, Thiessen polygon,* and *isohyetal* methods (Pierrehumbert, 1976). The simplest to use is the *arithmetic mean,* but Thiessen (1911) pointed out errors due to unequal weighting of stations. He suggested the *polygon* method to calculate the corresponding area of each station and used this as a weighting factor for station rainfall. The method is dependent on a linear variation of rainfall; it overcomes any irregularites in the spacing of raingauge stations, is expedient to use and is repeatable by different analysts. The *isohyetal* method is theoretically the most accurate (Holtan *et al.*, 1962) but is also the most laborious to use and its accuracy depends on the skill of the analyst. If linear interpolation is used, the result will essentially be the same as the *Thiessen polygon* method (Linsley *et al.*, 1958).

SEASONAL VARIABILITY OF RAINFALL

The climate of south-western Australia is governed by the movement of the travelling anticyclone belt which lies off the south coast in summer and moves northward across the State in winter (Gentilli, 1971). There is a marked variation in average monthly rainfall during the year, most of the rain being recorded in the middle of the year with little in the summer months. Complete climatic records are available for Perth, located on the southern boundary of the coastal plain study area. Data from the Bureau of Meteorology is summarized in Table 2.

TABLE 2

CLIMATIC DATA FOR PERTH STATION

						MONTH								YEAR
	n^+	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	MEAN
Rainfall (mm)	103	8	12	20	46	124	183	174	137	80	56	21	14	875
Evaporation* (mm)	15	267	229	198	120	90	63	68	81	111	161	198	251	1837
Max. Temp. (°C)	69	30	31	29	24	21	19	18	18	20	22	25	28	24
Min. Temp. (°C)	68	19	19	17	14	12	11	9	9	10	12	14	17	14

[+] number of complete years of record

[*] evaporation measured using a Class A pan with bird guard.

Rainfall at the forest field sites was measured on the first day of each month for the period 1966-1979. This period was used to analyse the monthly variation of rainfall for all stations on the coastal plain. Medians of monthly and annual rainfall are shown in Table 3. Medians based on the 39-year record of key stations are also included for comparison with the short-term record.

Figure 3 shows histograms of Perth, Gnangara, Yanchep and Gingin median monthly rainfall expressed as percentages of the annual rainfall for the 39-year study. Nearly 80 per cent of the annual rainfall is received in the five-month period, May to September. This fact is important hydrologically. Evaporation is low in the winter months (Table 2) and most of the rainfall is potentially available for infiltration and recharge of the aquifers. There is very little rainfall through the summer season when potential evaporation is high.

Annual rainfall diminishes by 100 mm between the southern and northern boundaries of the study area (Table 3) but there was little variation in the distribution of monthly totals (Figure 3) as a percentage of annual rainfall, throughout the area.

TABLE 3

ANALYSIS OF MEDIAN MONTHLY AND ANNUAL RAINFALL FOR THE 14-YEAR PERIOD, 1966-1979

	MEDIAN RAINFALL (mm)												
STATION	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**	**ANNUAL**
009125	6	11	10	57	92	172	169	96	84	42	18	8	777
009069	7	13	9	56	83	186	144	98	69	40	17	3	755
009124	2	13	11	55	80	158	149	96	64	42	18	4	696
009123	5	16	6	50	90	150	164	92	65	44	17	4	700
009122	4	15	9	60	85	156	161	93	69	41	14	2	704
009128	1	14	10	52	90	140	135	93	70	49	15	3	667
009121	2	15	14	52	87	161	129	83	82	38	11	4	708
009118	3	9	6	46	95	159	113	81	62	39	14	4	671
009119	5	7	8	43	103	169	150	104	55	42	14	4	795
009119*	3	4	8	39	106	175	152	107	58	45	18	7	795
009120	4	8	7	53	105	184	134	103	74	41	14	5	739
009045	4	10	6	52	94	168	155	104	81	49	11	3	730
009045*	3	4	8	39	100	173	152	115	70	42	18	6	771
009034	3	9	11	53	87	186	172	111	61	53	16	4	800
009034*	4	6	10	49	115	190	168	117	65	53	17	10	869
009018	6	18	9	43	82	145	144	92	67	51	13	5	700
009018*	3	3	10	40	94	145	141	100	58	46	14	5	694

* 39 year record, 1941-1979

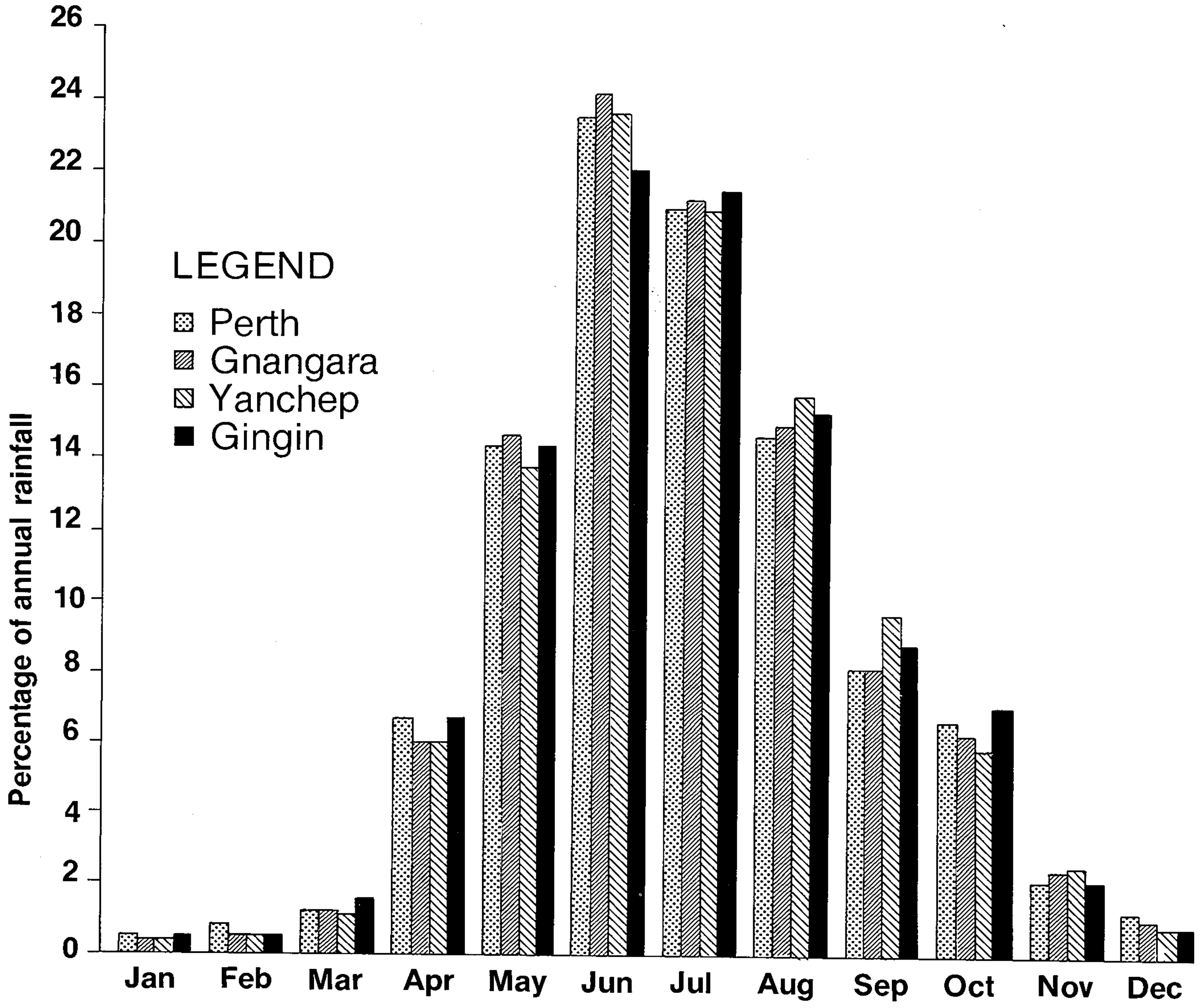
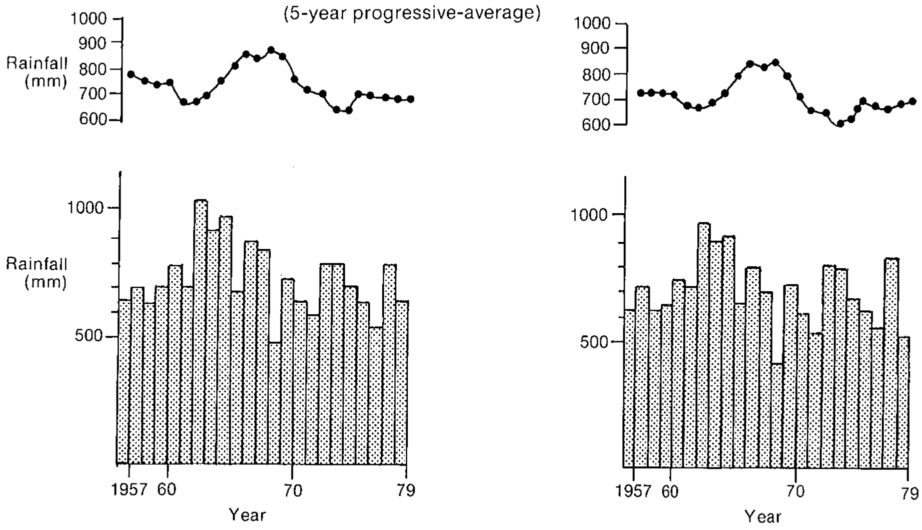


FIGURE 3: Distribution of monthly rainfall as a percentage of annual rainfall at Perth, Gnangara, Yanchep and Gingin stations. All data are based on median values in the 39-year (1941-1979) study period.

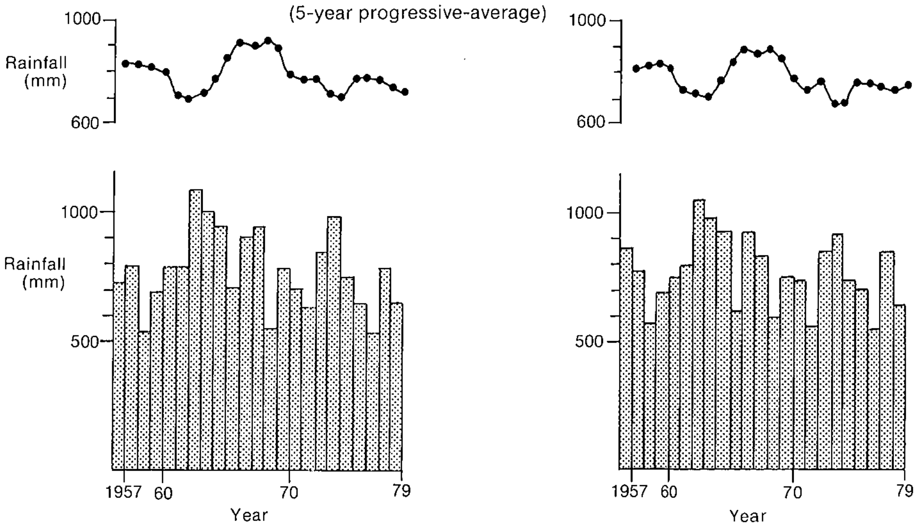
TEMPORAL VARIABILITY OF RAINFALL

Annual rainfall at the forest sites, over the 23-year period 1957-1979 is illustrated as bar-graphs in Figures 4 and 5. A longer period, 1941-1979 is used in Figure 6 for Yanchep and Gnangara forest stations. The total record is depicted in Figure 7 for Perth (1876-1979) and in Figure 8 for Gingin (1889-1979). Progressive five-year average rainfall curves are shown on each figure and 23-year progressive-average curves are shown on Figures 7 and 8.



Melbourne/Edwards Rd (009121)

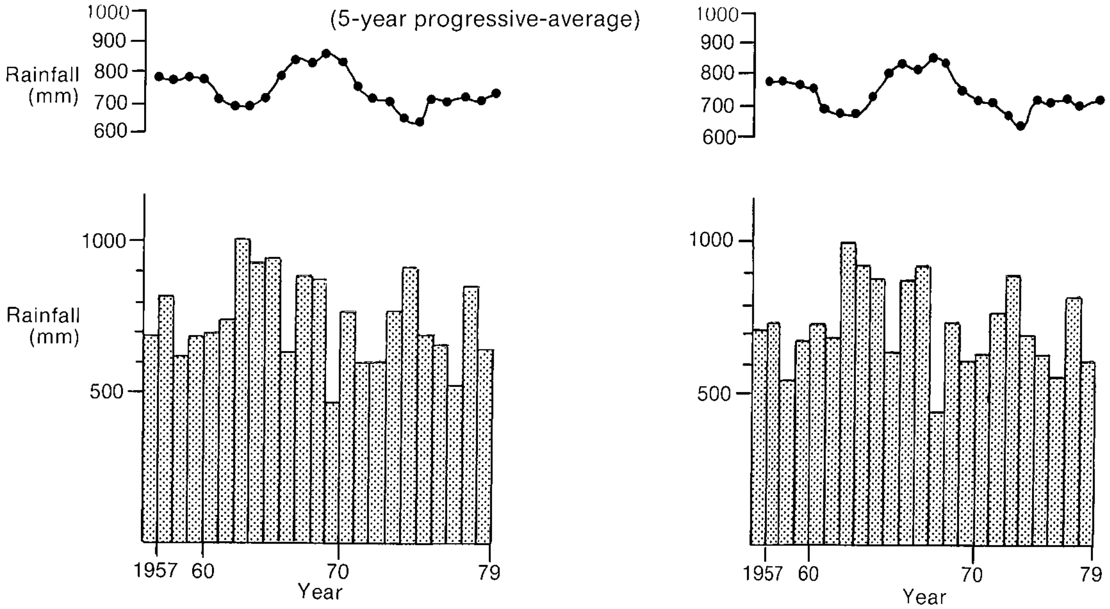
Bennies/Ziema Rd (009118)



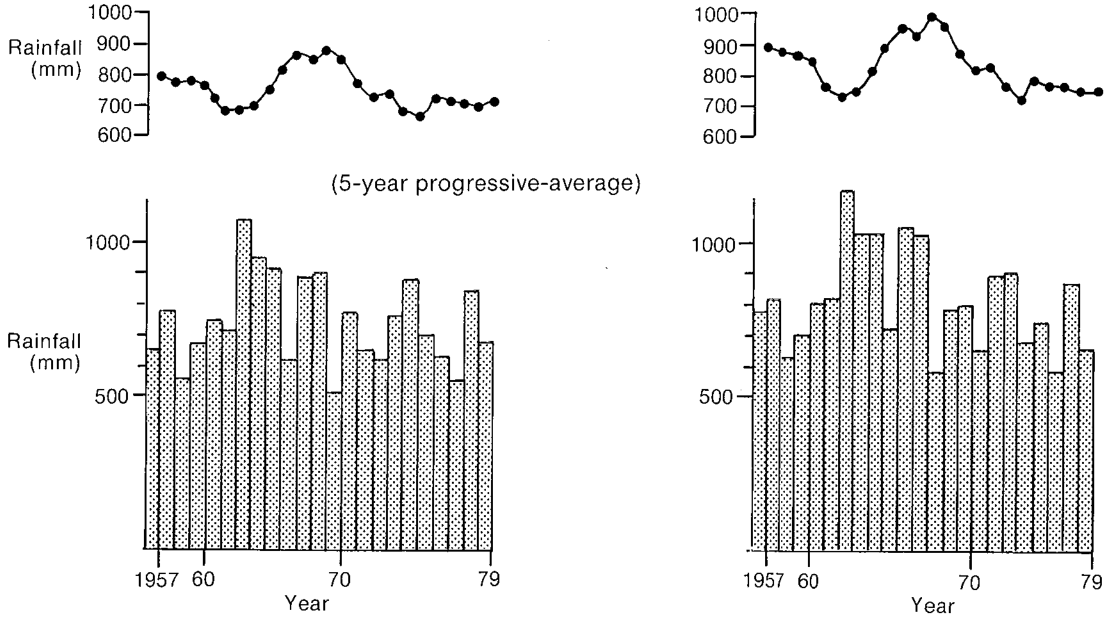
Yeal Swamp (009069)

Wanneroo (009120)

FIGURE 4:
Bar-graphs and five-year progressive-average curves of annual rainfall for the period 1957-1979 at forest sites, 009121, 009118, 009069 and 009120.

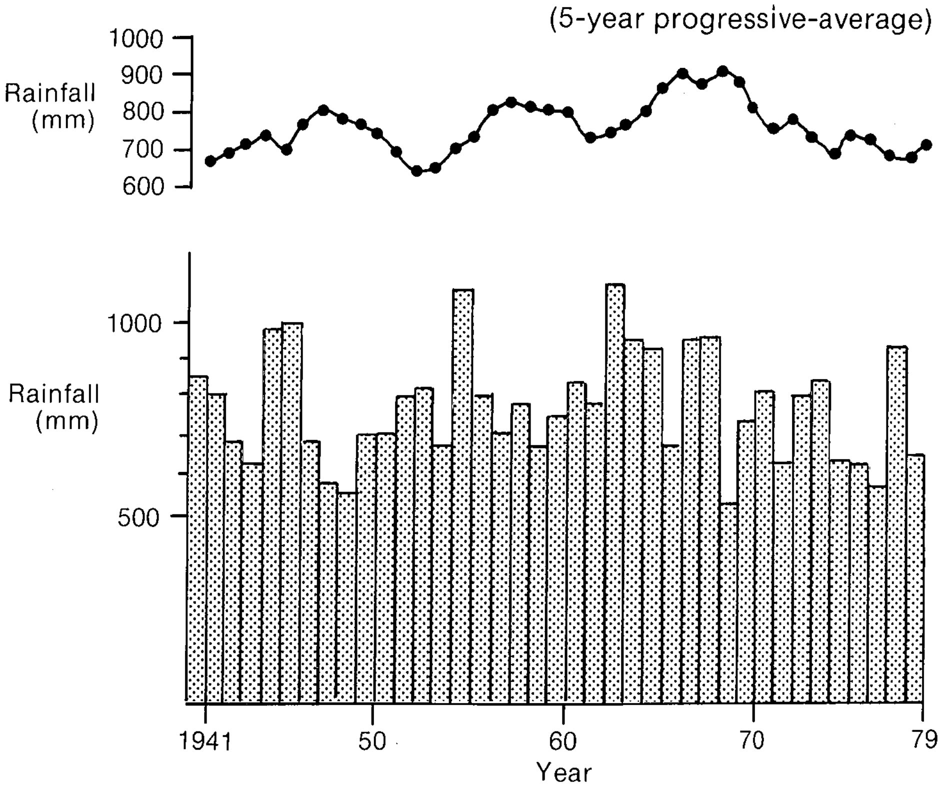


Banksia/Wapet Rd (009122) **Redwood/Casuarina Rd (009123)**

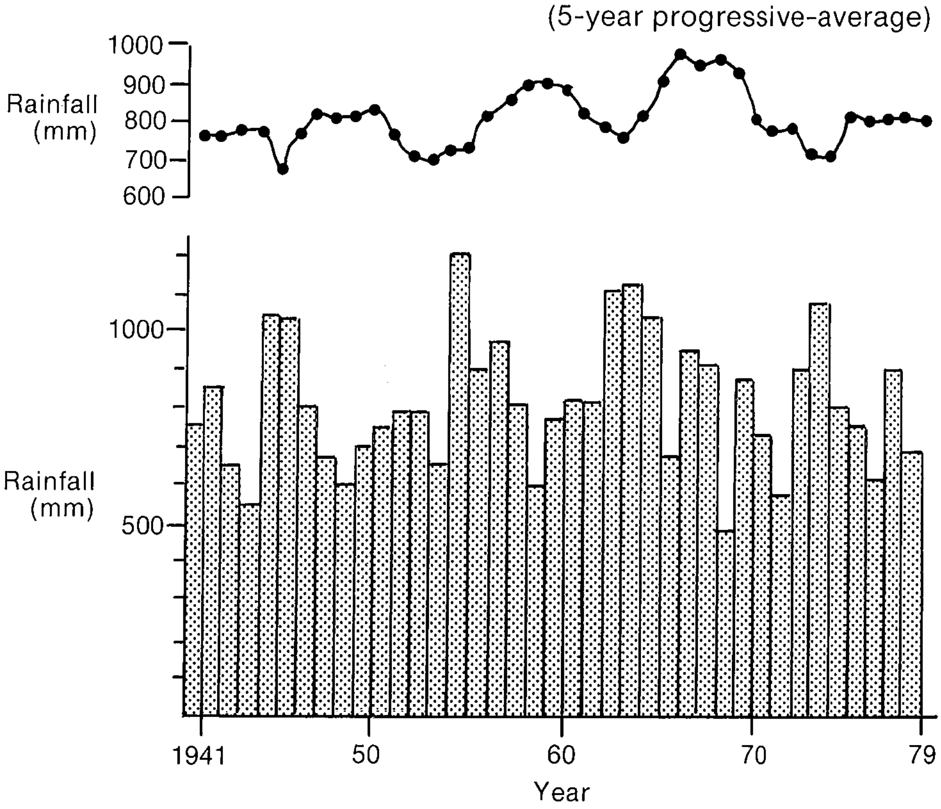


Stewart/Airforce Rd (009124) **Perry/Cypress Rd (009125)**

FIGURE 5:
Bar-graphs and five-year progressive-average curves of annual rainfall for the period 1957-1979 at forest sites 009122, 009123, 009124 and 009125.



Yanchep (009045)



Gnangara (009119)

FIGURE 6: Bar-graphs and five-year progressive-average curves of annual rainfall for the period 1941-1979 at Yanchep (009045) and Gnangara (009119) forest stations.

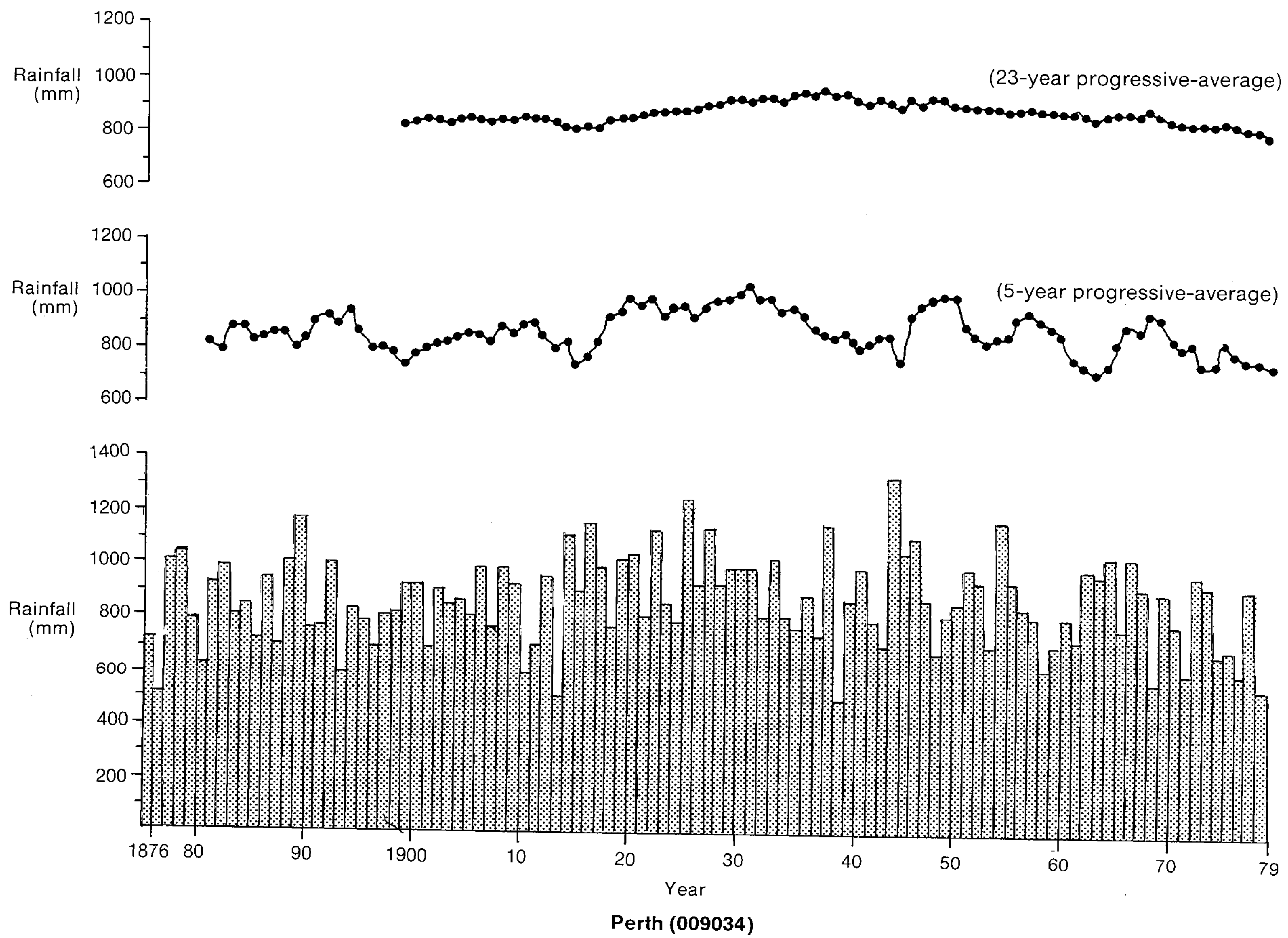


FIGURE 7: Bar-graph, five-year and 23-year progressive-average curves of annual rainfall for the period 1876-1979 at Perth (009034) station.

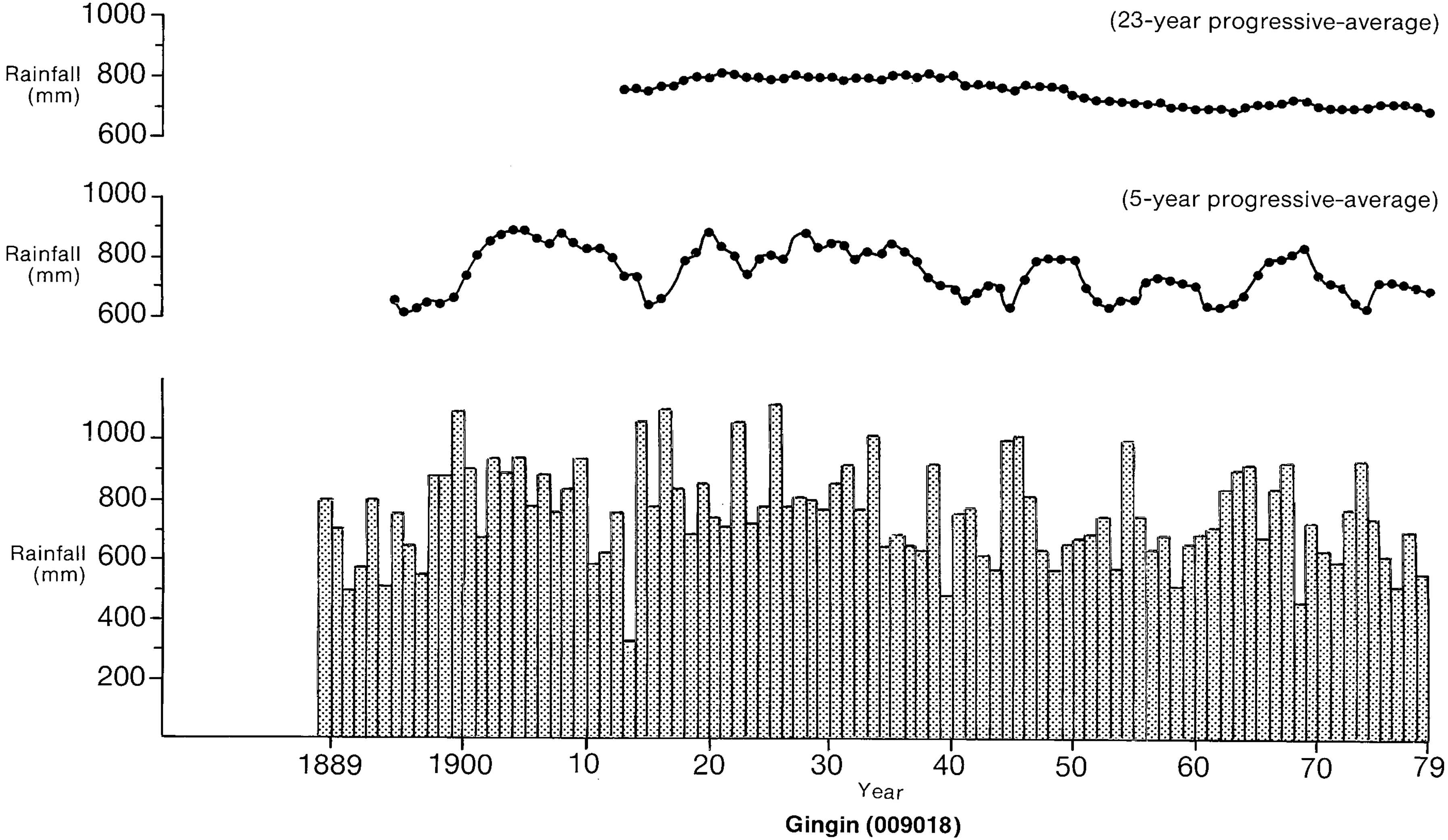


FIGURE 8: Bar-graph, five-year and 23-year progressive-average curves of annual rainfall for the period 1889-1979 at Gingin (009018).

The year-to-year variation in annual rainfall is fairly uniform over the coastal plain. Peaks and troughs all correspond in these figures. Referencing the years 1963 and 1969, annual rainfall was in the lowest and highest decile groupings respectively for all stations.

Median, mean and standard deviation of annual rainfall for each of the study periods is given for the stations in Table 4. Where there were missing data, values were calculated by multiple regression and used to compute the mean. Information from the forest sites was extended to a period of 39 years by this method.

TABLE 4

ANALYSIS OF ANNUAL RAINFALL FOR THE THREE STUDY PERIODS

	1966-1979 n = 14 years			1957-1979 n = 23 years				1941-1979 n = 39 years		
STATION	Median	Mean	S.D.+	Median	Mean	S.D.	S.E.*	Median	Mean	S.D.
009045	730	732	147	771	770	145	62	771	770	145
009069	755	740	138	778	769	151	65	*#781*	*785*	*154*
009118	671	669	115	708	703	127	55	*683*	*707*	*122*
009119	795	771	163	822	819	175	76	795	810	173
009120	739	731	130	747	767	144	62	*753*	*766*	*141*
009121	708	701	114	707	734	131	57	*708*	*739*	*131*
009122	704	705	139	704	735	140	60	*711*	*736*	*136*
009123	700	708	140	716	731	140	60	*727*	*736*	*142*
009124	696	710	127	718	738	143	62	*733*	*745*	*145*
009125	777	777	149	797	810	159	69	*797*	*823*	*157*
009128	667	702	140	*733*	*735*	*136*	*59*	*710*	*720*	*136*
009002	668	656	142	661	678	141	61	661	688	133
009013	*660*	*647*	*131*	*660*	*673*	*140*	*60*	*660*	*679*	*139*
009018	700	697	140	685	709	134	58	694	722	140
009021	776	749	144	819	787	149	64	821	821	153
009025	726	708	148	757	755	158	68	804	809	167
009029	*642*	*676*	*143*	*772*	*748*	*167*	72	*771*	*754*	*159*
009034	800	789	165	816	809	155	67	869	860	174
009041	*703*	*696*	*130*	*736*	*716*	*116*	*50*	*743*	*748*	*125*
009053	645	658	149	*646*	*682*	*171*	*74*	*648*	*693*	*159*
009057	709	720	161	770	779	185	*80*	795	814	184
009065	*689*	*688*	*120*	*698*	*718*	*130*	*56*	*721*	*748*	*132*
009067	686	710	145	713	734	168	72	*689*	*726*	*162*
009114	647	623	88	*635*	*639*	*83*	*36*	*634*	*642*	*80*
Gn. Mound	714	729	135	768	763	143	62	*773*	*772*	*143*

+	standard deviation
*	standard error, 95% probability level
# *(italic)*	incomplete record, multiple regression to calculate missing values

The main study has a 23-year record, 1957-1979. The length of the record necessary for a stable mean is related to the variability of the rainfall, but 30 years is usually regarded as a reasonable period. Our raingauge-run ceased after only 23 years because analysis had shown that the estimation of the average rainfall was not being greatly improved through continued sampling.

Similar coefficients of variation (the standard deviation divided by the mean) were calculated for the 14-, 23- and 39-year study periods (Table 4). Perth station had a coefficient of variation of around 20 per cent for record lengths of 14 years through to 104 years. Similar coefficients were calculated for all stations on the coastal plain. Standard errors of the 23-year means were calculated; the 95 per cent probability range of each station mean is shown in Table 4.

The mean annual rainfall is dependent on the particular time period chosen as well as the length of the record. Perth and Gingin station records were used to determine how representative the 1957-1979 raingauge study period was. At Perth the 1957-1979 period mean of 809 mm was the lowest 23-year average on record. Similarly at Gingin (Fig. 8) the mean of 709 mm was equivalent to the lowest 23-year average on record. The highest 23-year average rainfall values for Perth (967 mm) and Gingin (832 mm) were both recorded in the period 1915-1937.

Perth's long-term average (104 years) is 875 mm, which is 66 mm or 8 per cent higher than the mean of the current 1957-79 period. Similarly, the long-term average for Gingin (91 years), 757 mm, is 48 mm or 7 per cent higher than the current period.

The rainfall study was thus conducted during the driest period on record. Indications are that averages for the 1957-1979 period may need to be increased by as much as 7 per cent to give a more reliable estimate of the long-term mean annual rainfall.

SPATIAL VARIABILITY OF RAINFALL

Variation in space was examined at two levels. Firstly, within a raingauge station to determine how representative the point measurement of rainfall was and secondly, between stations to determine the range of rainfall over the coastal plain.

Three gauges were established on forest site 009118. These were a pluviograph and a storage gauge, separated from the station storage gauge at a distance of 2 m and 130 m respectively. Rainfall was recorded monthly and the gauges were maintained over a 75-month period. Data were analysed on a monthly and annual basis. Near unity coefficients of correlation were calculated between each of the gauges. The annual rainfall collected in each gauge is shown in Table 5. The coefficient of variation for each year's estimate was less than 5 per cent and generally around 2 per cent of the average. Neighbouring gauges differed by 1 per cent in the estimate of the mean annual rainfall. This increased to 4 per cent at a distance of 130 m from the station gauge.

TABLE 5

VARIABILITY OF POINT MEASUREMENTS OF RAINFALL

Year	Station	009118 site 2m	 130m	Mean	C.V.+	Network* Mean	 C.V.
1967	807mm	809	800	805	0.5%	801	11
1968	756	731	708	732	2.7	764	9
1969	475	479	429	461	4.9	460	7
1970	743	712	719	725	1.8	726	5
1971	679	688	628	665	4.0	642	5
1972	557	561	539	552	2.0	588	7
1973	781	771	801	784	1.6	768	4
Mean	685	679	661	675		678	

* Network of 11 raingauges surrounding the 009118 site, sampling an area of 3850 km^2.

\+ Coefficient of variation.

The concentration of gauges at forest site 009118 was extended to include the 11 raingauges within a 35 km radius. While individual year and the mean annual rainfall estimates were similar for the 0.05 km^2 concentrated network and the 3850 km^2 extended network, the variation coefficients doubled (Table 5).

Variability is also a function of the size of the area, as the difference in rainfall amounts recorded within an area increases as the area increases. For large areas the range of rainfall may increase only slightly as the area increases, justifying the use of a smaller number of gauges (Horton, 1923). Corbett (1965) suggested a sparse network of gauges where the storm type was cyclonic and the terrain was relatively flat.

The World Meteorological Organization (1965) guideline for the minimum density of gauges in flat, Mediterranean regions is one gauge per 600-900 km^2.

Figure 9 illustrates the topography of the coastal plain and plateau hinterland, and its effect on annual rainfall, computed as the mean of the 1957-1979 period. The five cross sections cover the latitudinal range of the study area and each section is about 100 km wide. The land surface of the plain is flat and there is no topographic influence on rainfall. Rainfall increases slightly with increasing distance from the coast and decreases near the base of the Western Australian plateau. There is an abrupt increase in rainfall at the edge of the plateau where it rises some 250 m above the plain. Rainfall gradually diminishes with increasing distance inland. This rainfall pattern is similar for all cross sections.

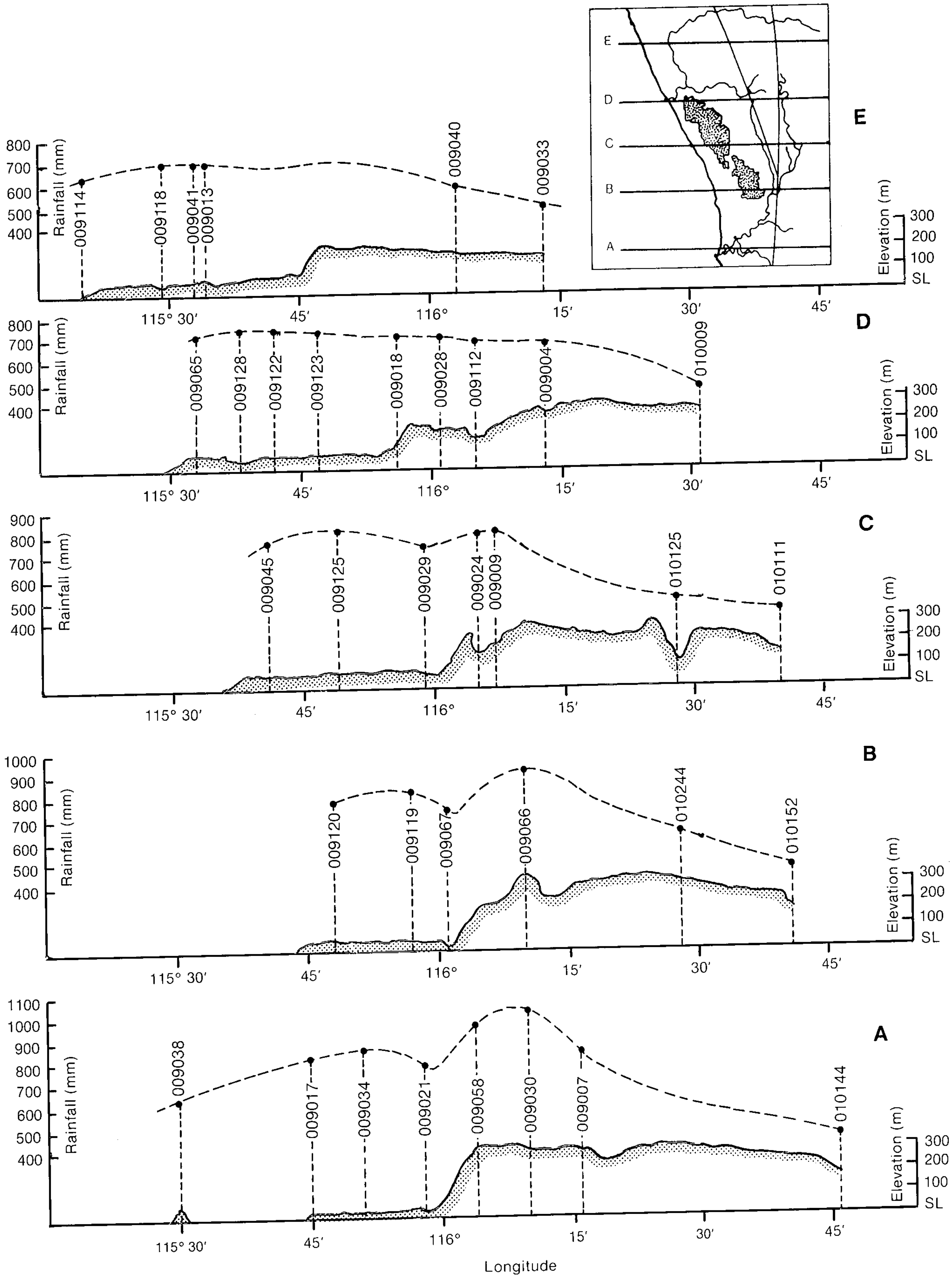


FIGURE 9: Distribution of annual rainfall (mean for 1957-1979) over the coastal plain and Western Australian plateau hinterland. Sections are taken at approximate latitudes of A 32°; B 31°45'; C 31°35'; D 31°20'; and E 31°.

Rainfall information is only required on a monthly or annual basis, so with the general uniformity of the rainfall distribution a sparse network of gauges on the coastal plain can provide the necessary information on rainfall variability. Our network appears to have been adequate for this purpose.

Before examining the relationship between stations in the network, it was first necessary to check the consistency of the rainfall record at each station. This was done for the period 1957-1979 using double-mass curves (Searcy and Hardison, 1960). Eleven stations were used to form the background pattern for checking individual stations. These were 009002, 009018, 009034, 009045, 009069, 009119, 009120, 009122, 009123, 009124 and 009125. The individual station being checked was deleted from the background pattern before analysis.

All field sites had a straight line relationship indicating a consistent rainfall record. There were breaks in the double-mass curves for the Gnangara record (1972) and Gingin record (1965) but they were only minor and no adjustment was required. However, there was a major break in the Henly Park (009057) record in 1974 after the gauge was moved from an open field to a more sheltered position. The slope of the double-mass curve was 1.07 for the period 1957-1974 and 0.89 for 1974-1979. This latter period record was adjusted to the uniform set of conditions to give a consistent rainfall record over the 23-year period. This was required for computation of the multiple linear regression models for use in calculations of areal rainfall. Double-mass curve examples are illustrated in Figure 10 for stations 009125, 009119, 009069, 009057 and 009018.

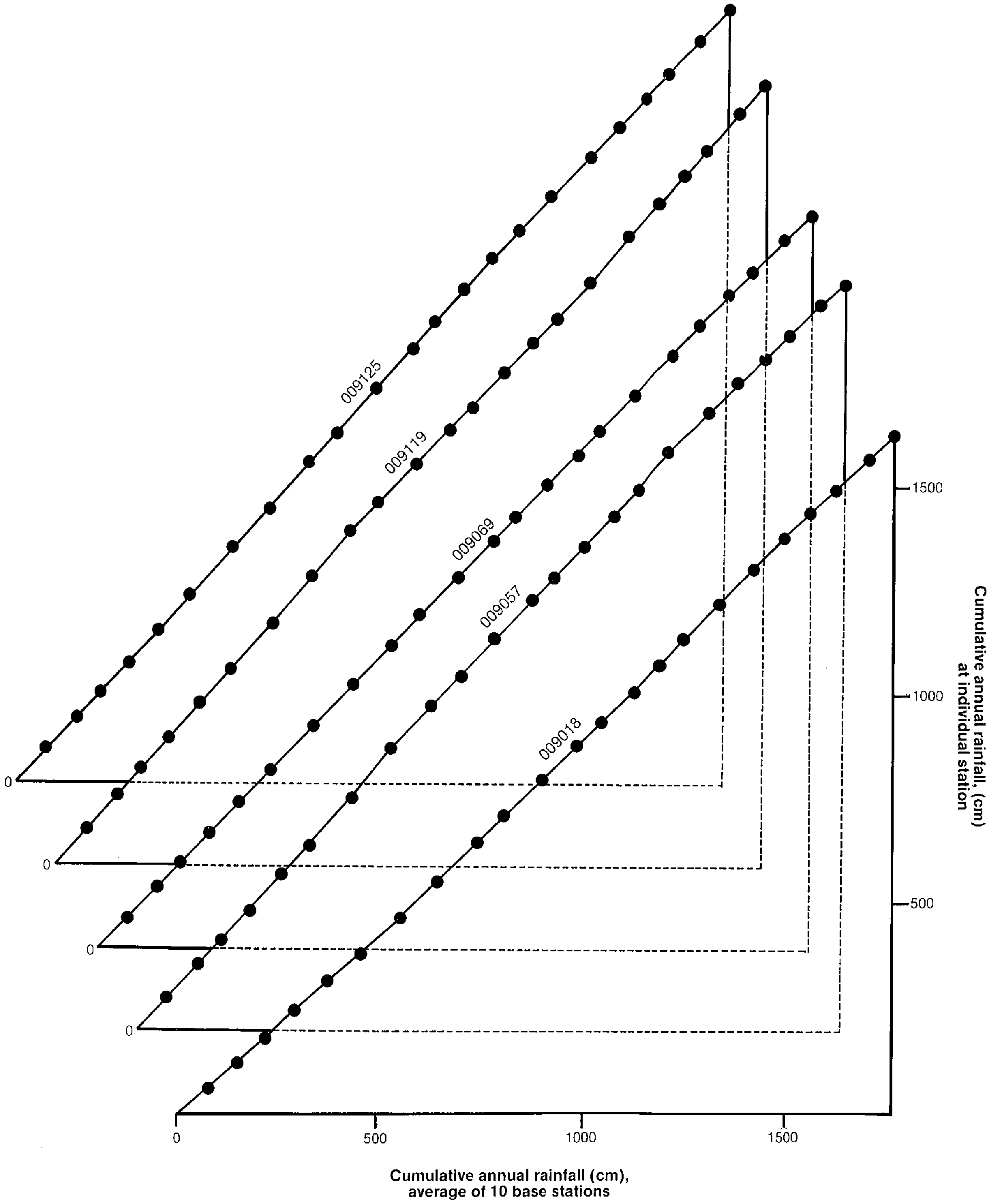


FIGURE 10: Double-mass curves of annual rainfall for individual stations 009125, 009119, 009069, 009057 and 009018.

The rainfall pattern of an area is commonly shown as an isohyetal map. Because stations are not uniformly distributed, a certain amount of interpolation is necessary to form these lines; this assumes a linear relationship between adjacent stations. Coefficients of correlation (R) were calculated for every station combination in the study. The correlation between adjacent stations was always high ($R>0.9$), and similarly for distant stations e.g. $R = 0.87$ for Perth and Gingin annual rainfall. The smallest correlation coefficient calculated was $R = 0.74$, for the Yanchep and Beermullah annual rainfall.

The isohyetal map for the 23-year study period is shown as Figure 11. It should be remembered that this probably represents the driest period of the 100-year record and that isohyets could be adjusted by approximately 7 per cent to give a better estimate of the long-term mean annual rainfall.

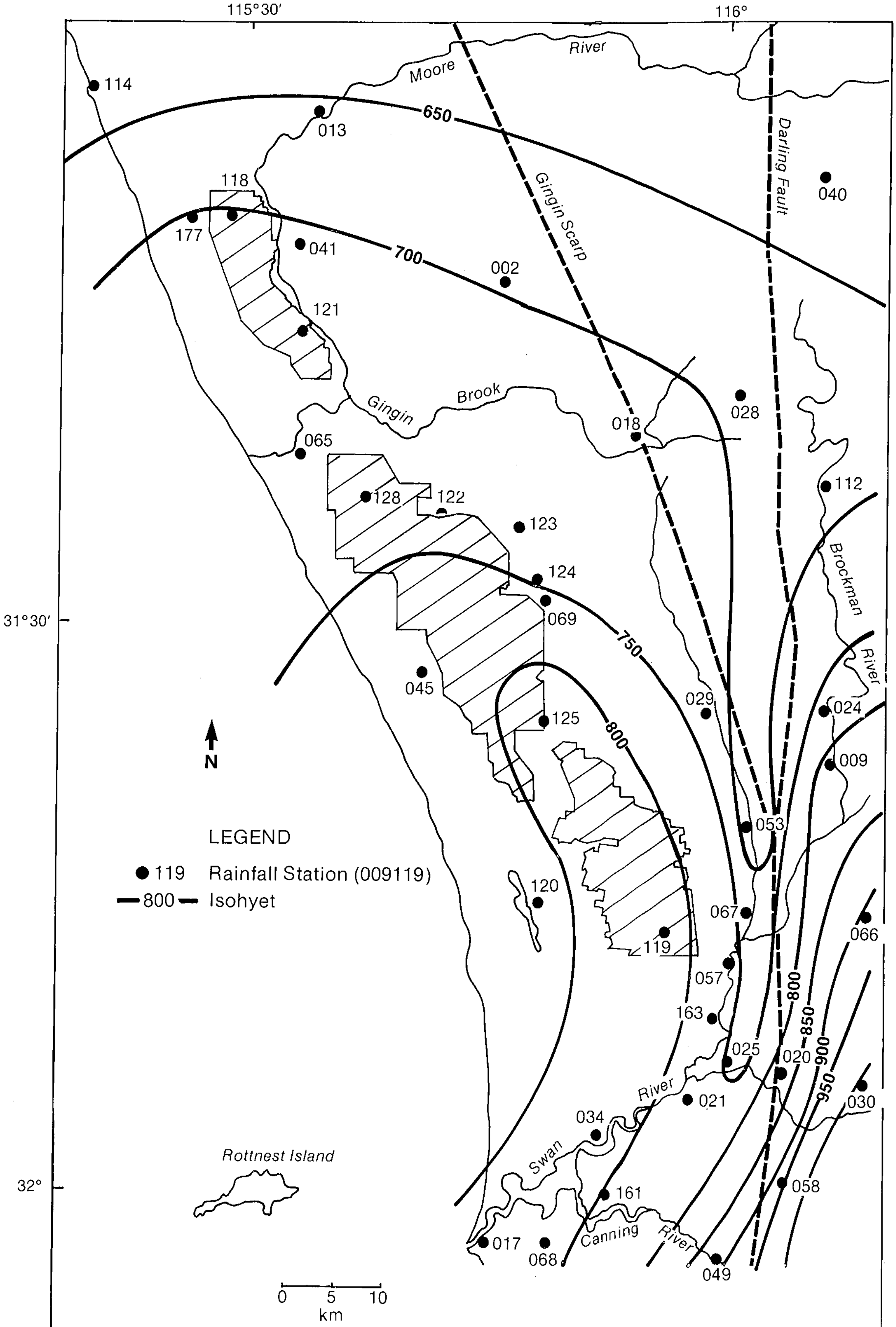


FIGURE 11: Isohyetal map of annual rainfall on the Swan coastal plain (mean for 1957-1979 period).

AREAL RAINFALL ON THE GNANGARA MOUND

The *polygon* method proposed by Thiessen (1911) was used to calculate the areal rainfall on the Gnangara Mound. Polygons were constructed on each of the rainfall stations as illustrated in Figure 12. Areas were planimetered from polygons drawn on 1:100 000 scale maps and accumulated for each station to form the 2165 km^2 area of the Gnangara Mound (Table 6). The areal annual rainfall was then computed for the years 1957 to 1979. The average for this period was 763 mm, and the median 768 mm.

TABLE 6

AREAL MEAN ANNUAL RAINFALL ON THE GNANGARA MOUND FOR THE 1957-1979 PERIOD, BASED ON THE THIESSEN POLYGON METHOD

Station Code	Station Area km^2	Annual Rainfall 1957-1979 Mean mm	Mound $10^6 m^3$	Areal* %
009002	7	678	5	0.3
009018	78	709	55	3.3
009021	60	787	47	2.9
009025	30	755	23	1.4
009029	139	748	104	6.3
009034	148	809	120	7.3
009045	192	770	148	9.0
009053	83	682	57	3.4
009057	35	779	27	1.6
009065	69	718	49	3.0
009067	29	734	22	1.3
009069	139	769	107	6.5
009119	153	819	125	7.6
009120	300	767	230	13.9
009122	127	735	93	5.7
009123	118	731	86	5.2
009124	66	738	48	2.9
009125	231	810	187	11.3
009128	161	735	118	7.1
Gn. Mound	2165	763	1652	100.0

* Contribution of station to the areal total rainfall.

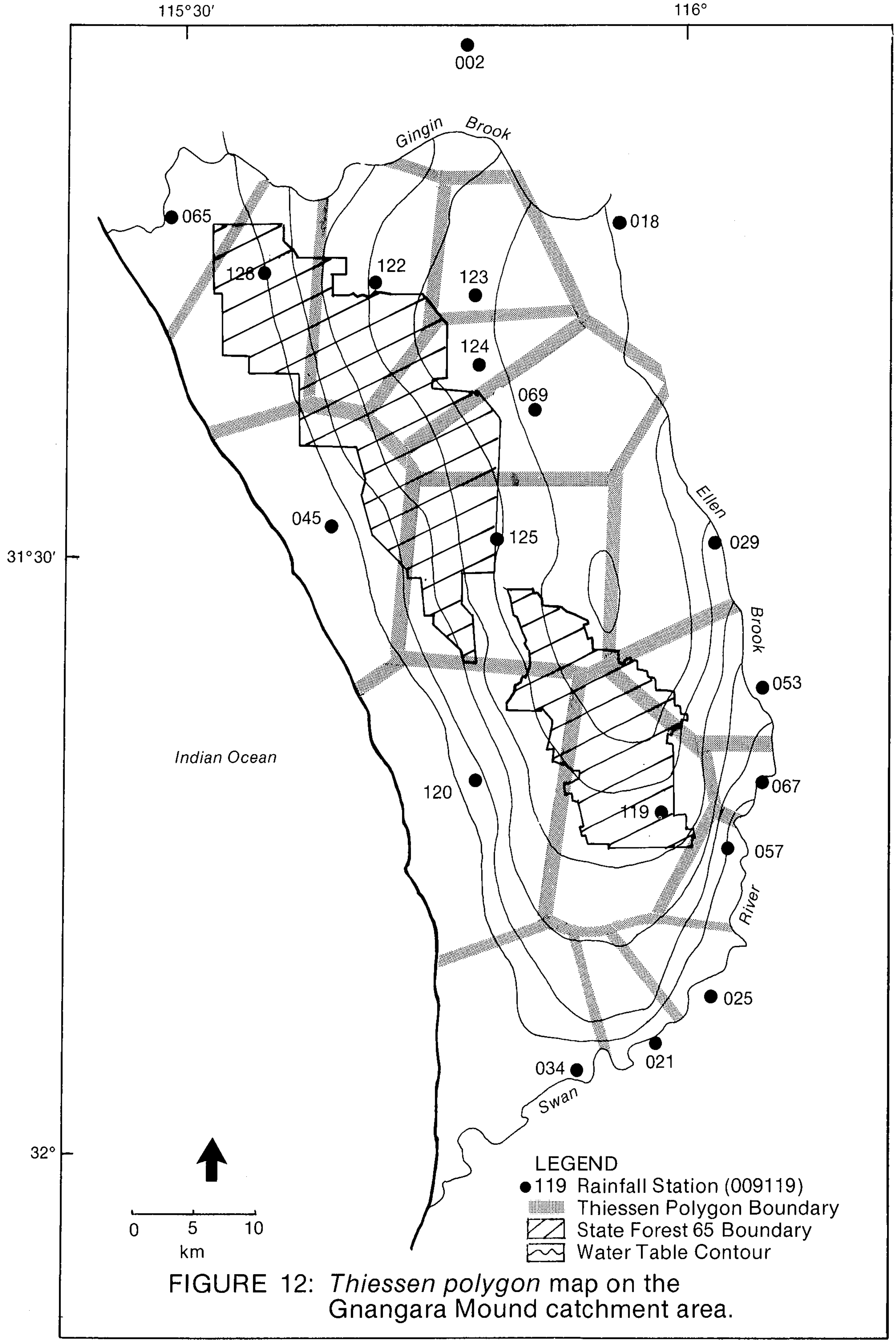


FIGURE 12: *Thiessen polygon* map on the Gnangara Mound catchment area.

The 1957-1979, 23-year record was extended to 1941-1979 using the multiple regression models listed in Table 7 to calculate the missing station values. Equations were constructed from data of the 1957-1979 period using sub sets of permanent station annual rainfall that gave the best predictions of annual rainfall for the short-term field stations. These equations were then used to generate data for the field stations over the period 1941-1957. These generated data and observed data at the reference stations were used to calculate rainfall for the Gnangara Mound for the period 1941-1979. The calculated annual values and actual values are shown in Figure 13. The very close agreement can be seen in this figure; the largest difference was 3 per cent. The calculated and the actual mean annual rainfall of the Gnangara Mound for the 1957-1979 period was the same value, 763 mm; standard deviations were both 143 mm.

Gnangara Mound annual rainfall over the extended 1941-1979 period averaged 772 mm, and the median was 773 mm. The 95 per cent probability range of the mean was calculated as 726-818 mm. The "much above average" rainfall level was found to be 915 mm i.e. two years in ten can be expected to receive equal or greater rainfall. Similarly the "much below average" rainfall level was found to be 650 mm.

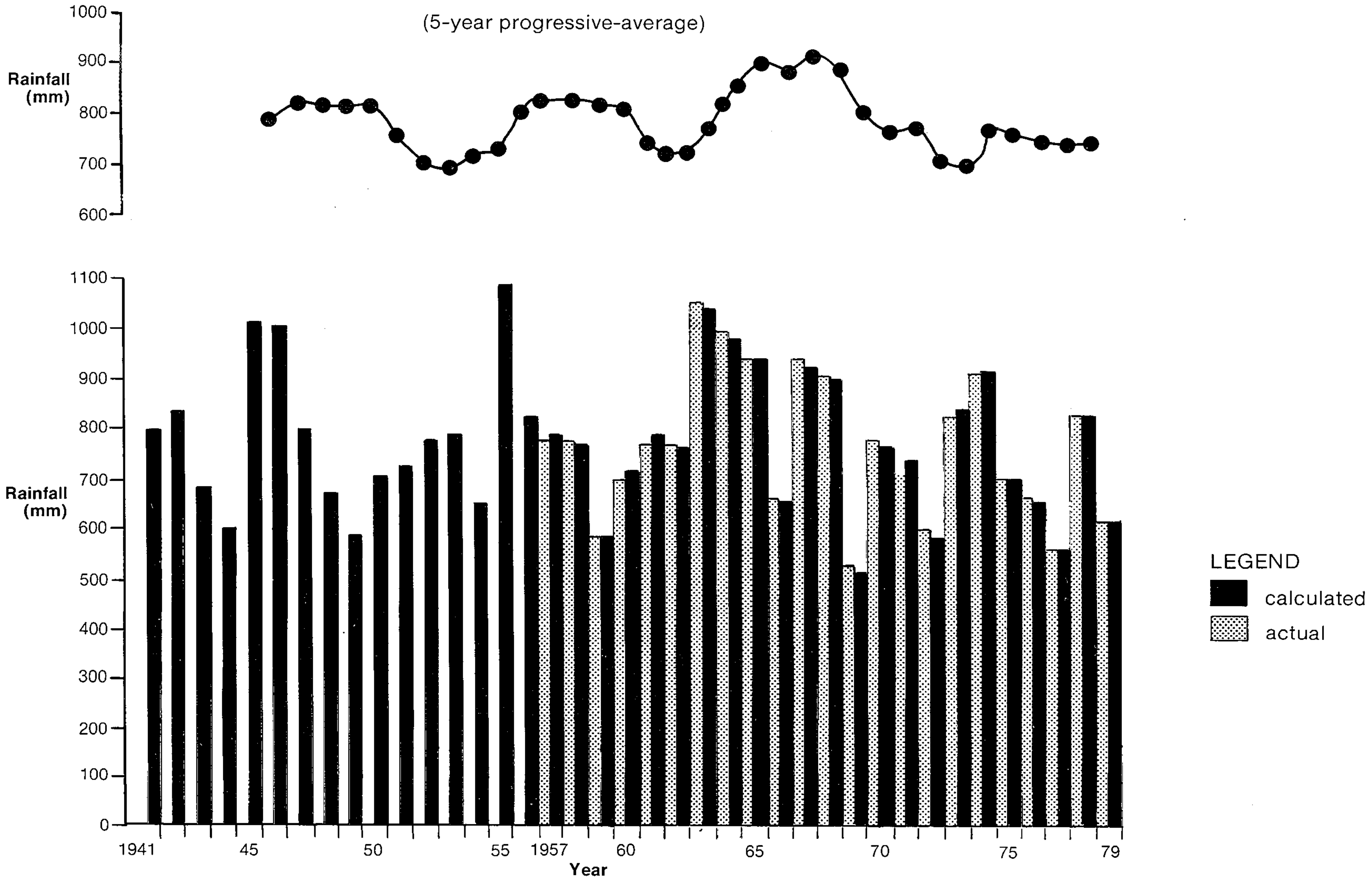


FIGURE 13: Bar-graphs of actual and calculated annual rainfall, five-year progressive-average curve of areal rainfall on the Gnangara Mound 1941-1979.

TABLE 7

MULTIPLE LINEAR REGRESSION MODELS USED FOR THE CALCULATION OF MISSING STATIONS IN THE GNANGARA MOUND AREAL RAINFALL DETERMINATION. VARIABLES ARE STATION ANNUAL RAINFALL IN mm.

Dependent Variable	Independent Variable	Multiple R
009029	0.881 (009119) + 0.504 (009045) - 0.539 (009034) + 112.2	0.97
009053	0.921 (009018) + 8.0	0.86
009065	0.476 (009025) + 0.462 (009002) + 46.2	0.90
009067	0.910 (009119) - 11.4	0.90
009069	0.571 (009120) + 0.546 (009018) - 55.7	0.97
009122	0.250 (009119) + 0.363 (009045) + 0.329 (009002) + 27.3	0.92
009123	0.459 (009018) + 0.314 (009045) + 0.210 (009119) - 8.3	0.95
009124	0.434 (009045) + 0.329 (009018) + 0.276 (009120) - 40.2	0.93
009125	0.603 (009045) + 0.418 (009057) + 7.7	0.96
009128	0.684 (009045) + 0.972 (009119) - 0.803 (009057) + 67.8	0.96

CONCLUSION

The distribution of rainfall on the coastal plain was found to be remarkably uniform. There was an identical frequency pattern of monthly rainfall for all stations, though the actual amounts varied between stations. Rainfall gradually decreases northwards along the coastal plain, the average falling by about 100 mm through one degree of latitude. Generally it increases eastward with distance from the coast, then decreases slightly towards the foot of the Darling Range. Annual rainfall events were found to be highly correlated between all stations.

Average annual rainfall was calculated for all stations for the 1957-1979, 23-year study period. Coefficients of variation were all about 20 per cent, and the 95 per cent probability range for the means were calculated to be 70 mm or less. This study period was shown to be the driest of the 104-year record for the Perth station. Indications are that all station means should be adjusted upwards by about 7 per cent to give a more realistic approximation of the long-term mean. Rainfall averages for the extended 39-year period 1941-1979 gave a better estimate of the mean.

The station network was adequate to measure the variation in space of the annual rainfall. This was integrated by the *Thiessen polygon* method to assess the average rainfall over the Gnangara Mound. The mean areal rainfall for the 1957-1979 period was calculated as 763 mm and the same value was computed using the Gnangara Mound regression models. This has enabled extrapolation to compute an areal mean for the 39-year period, 1941-1979. The mean was 772 mm and the 95 per cent confidence limits were set at 726 and 818 mm.

There was very close approximation of the actual and calculated annual rainfall events for the Gnangara Mound. Future areal rainfall, based on permanent stations, can be calculated with confidence using this model. It will be necessary to maintain a check on the consistency of the records of stations used in the model.

The primary land use objectives on the coastal plain are timber and water production. Rainfall does not impose any restrictions on the establishment of pine plantations in this region. However, it will be necessary to adjust management practices in the northern areas because of the decreased rainfall (Butcher, 1979).

Water production from the Gnangara Mound is dependent on the incident rainfall for infiltration and accretion to the groundwater body. The extreme rainfall events have the greatest impact on the level of the unconfined aquifer (Butcher, in preparation). A simple model could be developed within the *polygon* framework using variables such as winter rainfall, average depth to water-table, vegetation type and density, and land use to estimate the amount of rainfall recharging the aquifer.

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