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HYDROMETEOROLOGICAL REPORT NO. 46

Probable Maximum Precipitation, Mekong River Basin

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.37	**Maximum precipitation**
(282.253)	**Rivers of Southeast Asia**
(282.253.11)	**Mekong**
(59)	**Southeast Asia**

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INTRODUCTION

Purpose of report

The purpose of this study is twofold; first, to determine generalized estimates of probable maximum precipitation for 5,000 to 25,000 sq. km. drainages for durations up to three days covering the Lower Mekong River Basin and second, to prepare rainfall estimates that will produce the probable maximum flood at three potential dam sites on the main stem of the Mekong River, specifically at Luang Prabang and Pakse, both in Laos and at Kratie (Sambor) in Cambodia. Figure 1-1 shows the Mekong River Basin and the three dam sites. Total drainage areas above these sites are 262,000 km^2, 539,000 km^2, and 646,000 km^2, respectively.

Authorization

The study was made as a result of a request by the Committee for Coordination of Investigations of the Lower Mekong to the U. S. Department of State, Agency for International Development. The "Mekong System Analysis" agreement between the Corps of Engineers and U. S. Agency for International Development was amended in July 1967 to include the probable maximum precipitation estimates in connection with the hydrologic characteristics and the hypothetical flood studies to be developed by the Corps of Engineers. The portion of these studies involving the probable maximum precipitation estimates was performed by the Hydrometeorological Branch, U. S. Weather Bureau, ESSA, under cooperative arrangements with the Corps of Engineers.

Authorization for this study is in a memorandum to the Weather Bureau from the Office of Chief of Engineers, Corps of Engineers, dated January 22, 1968. Additional requirements were set forth and coordination maintained with Corps of Engineers hydrologists in several conferences; particularly, those at the Hydrometeorological Branch, Weather Bureau, ESSA, Washington, D. C., February 1, 1968, and at the North Pacific Division, Corps of Engineers, Portland, Oregon, December 12-13, 1968.

The authorizing memorandum points to the need for consistent probable maximum precipitation (PMP) estimates for a number of proposed projects on tributary areas of the Mekong. Generalized PMP estimates for 5,000 to 25,000 km^2 provide the means for maintaining consistency. The memorandum further emphasizes that long-duration rains extending through the southwest monsoon season need to be considered in determining rainfall criteria that is critical for producing the probable maximum flood at the three main-stem dam sites.

Definitions

Probable maximum precipitation (PMP) is defined as the depth of rainfall that approaches the upper limit of what the atmosphere can produce. Usually, an estimate of PMP in non-mountainous regions is based largely on maximization and transposition of storms within a meteorologically homogeneous region. For mountainous areas, rains are more intimately associated with the local topography and simple storm transposition does not apply. Instead, windflow models are used that, in effect, transpose maximum rain-producing winds and take into account their reaction to the local topography. Estimates of PMP in either case have to be based on an envelopment of the transposed data. The degree of envelopment depends on how many storms are available for analysis and how extreme the record storms have been.

Probable maximum flood is defined as the flood resulting from the most severe combination of critical meteorologic and hydrologic conditions that are reasonably possible in the region. The meteorological criteria of this study that fulfill this requirement consist of rainfall frequencies over large areas for the entire southwest monsoon rainy season and portions thereof, along with rainfall from two critically-spaced typhoons.

The rainfall criteria are meant to be used for defining the probable maximum peak flood and its associated hydrograph. This is to say that critical volumes of flow for long durations are not the subject of this study.

The Lower Mekong is the portion of the Mekong River drainage in Laos, Burma, Thailand, Cambodia, and Vietnam. It excludes the portion of the drainage in China (north of about 21.5°N).

Mekong River development

A Committee for "Coordination of Investigations of the Lower Mekong," abbreviated to the "Mekong Committee," was established in 1959 under the auspices of the United Nations Economic Commission for Asia and the Far East (ECAFE). The Mekong Committee is composed of representatives of four riparian countries of the Lower Mekong; Thailand, Cambodia, Laos and Republic of Vietnam. Since establishment of the Committee, more than 25 countries have given technical and economic assistance to planning, investigating and developing the water resources of the Lower Mekong. The objectives of the Mekong Committee as quoted from its 1965 Annual Report to the United Nations Economic Commission for Asia and the Far East are:

> "The Mekong Project seeks the comprehensive development of the water resources of the Lower Mekong Basin, including mainstream and tributaries, in respect of hydro-electric power development, irrigation, flood control, drainage, navigation improvement, watershed management, water supply and related developments, for the benefits of all the people of the basin, without distinction as to nationality, religion or politics."

The great beneficial potential to the people of the region by Mekong development was summarized in an earlier report[1]:

> "The Mekong is a majestic river. Even a cursory examination of the available hydrologic and topographic data, meagre as it is, has convinced the Mission of the great potential of the Lower Mekong for service to the riparian countries in the fields of navigation, hydropower generation, irrigation and other related water uses. Since it is a snow-fed river, the Mekong has a perennial flow. The possible hydropower sites are easily accessible and are located within reasonable distance of potential load centers. The topography of the basin appears to be suitable for diversion of the river flow for irrigation of large tracts of land. The control of its floods and improvement of drainage can be accomplished with reasonable works and in most instances could be combined with its development for other purposes. Thus developed, this river could easily rank with Southeast Asia's greatest natural resources. Wise conservation and utilization of its waters will contribute more toward improving human welfare in this area than any other single undertaking."

Physical features of the basin

The Mekong River is over 4,000 kilometers long and has a total drainage area of 795,000 square kilometers.

A detailed description of the physical features of the northerly reaches of the basin is found in a United Nations publication (1-1). We quote from this publication:

> "One of the great rivers of the world, the Mekong, (which is called the Lan Tsang in China and the Mekong in Burma, Laos, Thailand, Cambodia and Viet-Nam) rises on the snow clad slopes of the Dza-Nag-Lung-Mung range in the Tibet-Sikang plateau, about latitude 33°N and longitude 94°E, at an elevation of about 5,000 metres (16,700 ft). It flows in a south-easterly direction through rugged mountain ranges for a distance of about 425 km to Chamdo town, at elevation 3,000 metres (10,000 ft). There it changes its direction to flow south and enters Yunnan province of China near Yentsing town after a distance of 300 km.

> "In Yunnan, it flows through steep gorges and mountain wastes, which are little known, for about 1,000 km. A few mountain torrents join the river from both sides. The famed Burma Road which links

[1] United Nations Technical Assistance Mission headed by Lt. Gen. Raymond A. Wheeler, "Programme of Studies and Investigations of Comprehensive Development - Lower Mekong Basin," TAA/AFE/10, January 1958.

Lashio in Burma with Kunming in China crosses the Mekong at a point approximately 23°30'N, at an elevation of about 1,450 metres (4,700 ft). From its point of exit from Chinese territory near Keng Hung where the elevation is about 300 metres (1,000 ft), it forms a common border between China and Burma for a short length of about 30 km. Its width along this stretch reaches 300 to 400 metres. Then it forms the border between Burma and Laos for approximately 200 km to near Chiang Saen town."

For the Lower Mekong, the Chaine Annamitique forms the eastern drainage divide. Elevations along the divide average approximately 600 meters from latitude 11° to 15°. Peaks rise upwards to 1500 meters in this stretch. From about 15°N to about 19°N, the ridge forms the boundary between Laos and Vietnam with elevations ranging between 600 and 900 meters. This range of mountains presents a much more formidable barrier to inflow of atmospheric moisture north of about 17-18°N than for the area south of 17-18°N.

Mountains along the western border of the basin south of 17° to 18°N are also much less formidable than the mountains farther north. These include the Cardamon Mountains near the Gulf of Siam in the southwestern portion of Cambodia. Steep mountain slopes here intercept the rain-bearing southwest winds from off the Gulf of Siam, leaving a rain shadow to the east.

In such areas of pronounced sheltering by upwind ridges, precipitation drops to a scant 50 percent or less of amounts in upwind unsheltered nonorographic areas. This is reflected in the mean precipitation map (fig. 2-8) for the southwest monsoon season. Favorable upslope areas, on the other hand, such as the slopes facing to the west or southwest in the Chaine Annamitique, have orographic rainfall increases to about 250 percent of that in low elevation regions.

Other important physical features include the Korat Plateau of Eastern Thailand which is relatively flat. However, it is surrounded by ridges with elevations mostly between 250 and 750 meters. South of about 22°N a large portion of the Mekong drainage comprises areas that are rather flat, with elevations mostly between 150 and 300 meters.

Rainfall data sources

The riparian countries afford many valuable sources of rainfall data. References (1-2) through (1-37) summarize these and other sources. References (1-34) and (1-36) were two valuable sources of Chinese data.

The U. S. Corps of Engineers (1-37) also provided tabulations of daily rainfall amounts for some 200 stations in the Lower Mekong drainage.

One shortcoming of these data is that they are not concurrent. This can be seen in figure 1-2 where the number of reporting stations in each country are plotted for each year from 1911 to 1965.

In addition to the daily-rainfall records summarized in table 1-1, monthly, seasonal and hourly data were also available in the Corps of Engineers tabulations. The hourly data are limited to stations in Cambodia and Thailand.

All available sources of rainfall data were searched for mean rainfall values to construct mean monthly (August and September) and mean May through September precipitation charts (chapter II). These data are summarized in table 1-2 by countries. The primary sources of data and periods of record are shown. Numbers assigned to the stations are also shown for information. Where spellings of station names varied in the differing sources, the spellings on a National Geographic Society Map (1-38) were adopted, wherever possible.

Table 1-1

SUMMATION OF DAILY RAINFALL RECORDS (1906-1965) PROVIDED BY THE CORPS OF ENGINEERS

Country	No. of Stations	Years of Record
Vietnam	2	20 or more
	6	15 to 19
	10	10 to 14
Cambodia	13	20 or more
	8	15 to 19
	19	10 to 14
	40	less than 10
Laos	8	20 or more
	4	15 to 19
	16	10 to 14
	18	less than 10
Thailand	1	20 or more
	11	15 to 19
	35	10 to 14
	7	less than 10
Totals	24	20 or more
	29	15 to 19
	80	10 to 14
	65	less than 10

Table 1-2

RAINFALL STATIONS

Cambodia

Station	Latitude	Longitude	Years of Record	Source*	Station No.	Primary Period of Record
Angtassom	11°00'	104°41'	15	C	139	1932-1944
Bacprea	13°08'	103°24'	8	E	73	1933-1940
Barai (Baray) (K-Thom area)	12°23'	105°04'	29	C	91	1917-1963B
Barai (D'Angkor)	13°25'	103°51'	10	C	62	1935-1944
Batheay	11°59'	104°57'	7	C	98	1952-1960B
Bamnak	12°18'	104°10'	11	C	83	1934-1944
Bat Rokar	11°09'	104°53'	8	E	134	1939-1942 1961-1964
Battambang	13°06'	103°02'	42	E	75	1920-1964B
Benghi	10°57'	105°04'	5	E	143	1939-1942
Bokor	10°36'	104°02'	22	C		1922-1943
Boribe	12°27'	104°22'	4	E	170	1961-1964
Chalang	11°52'	106°15'	28	C	128	1932-1960B
Chambak	11°14'	104°48'	4	E	133	1939-1942
Chamkar Andong	12°20'	105°11'	25	C	92	1930-1960B
Chamkar Leu	12°18'	105°20'	20	C	93	1931-1944B
Chantrey	11°17'	105°43'	8	C		1917-1926B
Cheom Ksan	14°14'	104°55'	22	C		1917-1940B
Chhlong	12°16'	105°58'	24	C	70	1931-1960B
Chhuk	11°07'	104°37'	14	C		1932-1944
Chup	11°56'	105°35'	32	C	104	1928-1960B
Dap Bat	12°30'	103°50'	14	E	81	1952-1965
Gatille	12°13'	106°50'	11	F		1934-1944

*The following designators are used throughout the table:

"AF" - U. S. Air Force (1-16)
"B" - breaks in record
"C" - Cambodia (1-4, 1-6, 1-8, 1-10, 1-14, 1-27, 1-37)
"E" - U. S. Corps of Engineers (1-37)
"F" - French Indo China (1-7)
"N" - U. S. Navy (1-19)
"T" - Thailand (1-2, 1-3, 1-5, 1-10, 1-12, 1-18 thru 1-23, 1-37)
"U" - unknown
"Y" - China (1-34) and "Atlas" (1-36)

The references listed are either the principal sources of data or typical references in cases where the exact name of the publications changed through the years. In some instances, the references noted served as supporting information.

Table 1-2

RAINFALL STATIONS

(Cambodia Cont'd.)

Station	Latitude	Longitude	Years of Record	Source*	Station No.	Primary Period of Record
Kampot	10°37'	104°13'	44	Misc	238	U
Kantroy	11°49'	106°18'	28	C	131	1932-1960B
Kasko	10°52'	105°19'	12	E	144	1920-1928
Kas Kong	11°06'	103°10'	9	C		1917-1926B
Kas Moul	11°26'	103°01'	15	C		1928-1943B
Kas Thom (Koh Thom)	11°10'	105°04'	12	C	172	1912-1929
Kep (Poivre area)	10°29'	104°18'	20	C		1930-1960B
Kirivong	10°41'	104°53'	29	C		1918-1944
Kompong Cham	12°00'	105°27'	37	E	102	1920-1965B
Kompong Chhnang	12°15'	104°39'	24	C	85	1913-1944B
Kompong Kleang	13°06'	104°07'	28	C	64	1917-1944
Kompong Rau	10°55'	105°50'	6	C		1939-1944
Kompong Sne	13°06'	102°37'	3	E	111	1940-1942
Kompong Speu	11°26'	104°32'	32	C	132	1917-1944
Kompong Thom	12°42'	104°52'	35	C	66	1913-1944
Kompong Trabek	11°08'	105°28'	6	E	113	1939-1942
Kompong Trach (Kampot area)	10°33'	104°28'	30	C		1917-1944
Kompong Trach (Svay-Rieng area)	11°28'	105°45'	12	C		1926-1937
Kompong Tralach	11°55'	104°45'	26	C	88	1917-1944B
Krakor	12°32'	104°12'	19	E	80	1939-1953B
Kratie	12°29'	106°01'	22	E	69	1920-1943B
Kralanh	13°33'	103°33'	19	C	61	1921-1940
Krek	11°46'	105°56'	11	C		1928-1944B
Leach	12°21'	103°41'	6	C	82	1941-1944B
Loeuk Dek	11°08'	105°07'	4	E	136	1939-1942
Lomphat (Lom Sak)	13°30'	106°59'	5	Misc	241	U
Mimot	11°49'	106°11'	20	C	130	1930-1960
Maung Russei (Muong Russey)	12°47'	103°25'	13	E	78	1935-1953B 1961-1964
O-Raing (O-Rang)	12°22'	107°19'	8	E	171	1958-1965
Pailin	12°49'	102°37'	23	C	243	1917-1940B
Peam Prous	12°19'	103°07'	3	C		1942-1944
Peam Cheang (Chikang)	11°52'	105°32'	3	C		1961-1963
Petit Takeo	11°33'	104°20'	9	C		1952-1960
Pha Ao	12°02'	104°57'	12	E	96	1952-1964B

Table 1-2

RAINFALL STATIONS

(Cambodia Cont'd.)

Station	Latitude	Longitude	Years of Record	Source*	Station No.	Primary Period of Record
Phnom Penh	11°33'	104°51'	23	C	90	1907-1929
Phnom Srok	13°45'	103°18'	7	E	60	1961-1969
Pochentong	11°34'	104°51'	48	E	168	1911-1964B
Prek Chhlong	11°52'	106°15'	28	C	129	1932-1960B
Prek Kak	12°15'	105°38'	30	C	94	1927-1960B
Prek Leap	11°39'	104°52'	14	E	95	1950-1964B
Prey Totung	11°24'	104°47'	11	E	101	1952-1964B
Prey Veng	11°29'	105°29'	11	E	110	1920-1928B
Pursat	12°33'	103°50'	35	E	79	1912-1964B
Reang Kesey	12°58'	103°14'	7	E	77	1960-1964
Sambor	12°46'	105°58'	25	C	68	1919-1944
Samrong	14°13'	103°33'	15	C	58	1923-1940B
Sdoch Ach Romeas	12°04'	104°32'	10	C	86	1934-1944
Siem Pang	14°00'	106°20'	13	C	54	1929-1941
Siem Reap	13°22'	103°51'	21	E	63	1920-1964B
Sisophon	13°35'	103°02'	13	C	237	1917-1929
Skoun	12°04'	105°04'	6	E	97	1925-1930B
Slakou	11°05'	104°34'	8	E	138	1962-1965
Snaipol	11°41'	105°13'	5	E	108	1939-1942
Snam Crabeu	11°34'	102°57'	9	C		1921-1929
Snoc Trou	12°29'	104°26'	13	C		1917-1929
Snuol	12°07'	106°27'	21	C	127	1930-1944B
Soc Noc	10°59'	106°08'	20	C		1917-1939B
Staung	12°57'	104°33'	26	C	65	1918-1944B
Stung Trang	12°15'	105°31'	21	C		1917-1937
Stung Treng	13°31'	105°58'	41	F	67	1912-1965B
Sre Umbell (Umbell)	11°09'	103°43'	14	C		1929-1944B
Suong	11°54'	105°38'	28	C	105	1917-1944
Svay Chek	13°51'	102°56'	10	C		1930-1939
Svay Rieng (Soai-Riong)	11°05'	105°48'	13	C	239	1917-1929
Takeo	11°00'	104°47'	40	C	140	1913-1960B
Tani	10°47'	104°39'	15	C	142	1931-1942
Thmarpitt	12°01'	105°35'	9	C		1921-1929
Toul Samrong	13°23'	103°03'	6	E	72	1934-1940B
Tuk Khleang	11°30'	105°08'	9	E	109	1920-1928B
Val d'Emeraude	10°38'	104°05'	8	F		U
Veal Trea	13°08'	103°10'	14	E	76	1950-1964B
Veunesai (Virachei)	14°00'	106°45'	26	C	56	1917-1942

Table 1-2

RAINFALL STATIONS

China

Station	Latitude	Longitude	Years of Record	Source*	Primary Period of Record
Chang-tu	31°09'	97°10'	4	Y	1952-1955
En-shih	30°16'	100°22'	4	Atlas	1933-1938B
Ho-chin	26°25'	100°10'	9	Y	1938-1948B
Hsin-ping	24°05'	101°59'	7	Y	1938-1944
Kan-tzu	31°38'	99°59'	5	Atlas	1951-1955
Li-kiang (Li-chiang)	26°53'	100°10'	7	Y	1943-1949
Meng-ting (Keng-ma)	23°33'	99°07'	3	Y	1936-1938
Pao-shan	25°10'	99°10'	10	Y	1938-1949B
Pa-tang (Ba-tang)	30°01'	98°56'	8	Y	1924-1942B
Ssu-mao	22°33'	101°02'	3	Atlas	1924-1926
Ta-li	25°43'	100°11'	11	Y	1940-1950
Tao-fu	30°59'	100°08'	2	Y	1941-1942
Ta-yun	28°30'	98°45'	3	Y	1940-1942
Teng-chung	25°00'	98°41'	24	Y	U
Yuan-chiang	23°39'	102°00'	13	Y	1936-1948
Yu-shu	32°52'	96°40'	3	Atlas	1953-1955

Table 1-2

RAINFALL STATIONS

Laos

Station	Latitude	Longitude	Years of Record	Source*	Station No.	Primary Period of Record
Attopeu	14°54'	106°52'	22	Misc	46	U
Ban Houei Sai	20°15'	100°25'	32	E	12	1912-1945B
Bassac	14°30'	106°00'	3	E	44	1935-1938B
Boneng	17°57'	104°34'	13	Misc	25	U
Borikhane	18°33'	103°43'	12	E	18	1929-1943B
Boun Neua	21°37'	101°54'	14	E	4	1930-1943
Boun Tai	21°43'	101°59'	11	E	5	1930-1943B
Hua Muong	20°09'	103°41'	10	Misc		U
Keng Kok	16°27'	105°11'	6	E	34	1935-1939
Kham Keut	18°15'	104°43'	13	E	22	1929-1943B
Kham Thong Niai	15°32'	105°46'	8	E	38	1930-1938B
Khong	14°07'	105°51'	14	Misc	55	U
Lao Ngam	15°33'	106°15'	8	E	37	1930-1939B
Luang Prabang	19°53'	102°08'	44	E	13	1920-1964B
Mahaxay	17°24'	105°11'	10	E	27	1929-1938B
Muong Khoua	21°05'	102°30'	6	F		U
Muong Luong Namtha	21°02'	101°25'	12	E	8	1929-1943B
Muong Ngoi	20°42'	102°42'	7	E	11	1930-1938B
Muong Nham	18°55'	103°44'	10	E	16	1930-1943B
Muong Ou Neua	22°18'	101°53'	21	E	1	1924-1944
Muong Phine	16°32'	106°01'	11	E	33	1929-1939
Muong Sai	20°11'	104°53'	9	E	10	1927-1938B
Muong Sing	21°06'	101°09'	16	E	7	1924-1944B
Muong Soi	20°18'	104°33'	11	Misc		U
Muong Son	20°27'	103°19'	12	F		U
Nape	18°18'	105°05'	21	E	21	1922-1945B
Nong Met	15°17'	106°33'	5	E	41	1929-1938B
Paklay	18°12'	101°24'	12	E	23	1929-1940
Paksane	18°25'	103°38'	16	E	20	1924-1943B
Pakse	15°07'	105°47'	23	E	43	1929-1964B
Pak Song	15°11'	106°12'	8	E	42	1929-1943B
Phiafay	14°47'	105°55'	5	E	45	1930-1939B
Phong Saly	21°42'	102°05'	19	E	3	1922-1944B
Samneua	20°25'	104°04'	15	E	236	1930-1944
Sam Teu	19°59'	104°47'	10	Misc		U
Saravane	15°43'	106°25'	11	E	36	1929-1942B
Seno	16°40'	105°00'	16	E	30	1949-1964
Souvanna Khili	15°25'	105°48'	8	E	40	1930-1939B
Tchepone	16°41'	106°14'	12	E	29	1923-1938B
Thakhek	17°24'	104°48'	15	E	28	1929-1942B

Table 1-2

RAINFALL STATIONS

Laos (Cont'd.)

Station	Latitude	Longitude	Years of Record	Source*	Station No.	Primary Period of Record
Thateng	15°31'	106°22'	7	E	39	1929-1938B
Tha Thom	18°59'	103°35'	5	E	15	1930-1937B
Tourakhom	18°27'	102°30'	10	E	19	1930-1943B
Vang Vieng	18°56'	102°27'	11	E	17	1929-1943B
Vieng Pou Kha	20°45'	100°58'	9	E	9	1929-1939B
Vientiane	17°57'	102°34'	42	E	24	1920-1965B
Xieng Kho	20°49'	104°08'	10	Misc		U
Xiangkhoang	19°28'	103°08'	26	E	14	1929-1959B

Table 1-2

RAINFALL STATIONS

North Vietnam

Station	Latitude	Longitude	Years of Record	Source*	Primary Period of Record
Chue Le	18°13'	105°40'	8	Misc	U
Cua Rao	19°17'	104°25'	12	AF	U
Dien Bien Phu	21°19'	103°01'	18	F	U
Ha Tinh	18°21'	105°54'	12	AF	U
Ky Anh	18°05'	106°18'	13	Misc	U
Lai Chau	22°04'	103°09'	14	AF	U
La Trong	17°53'	105°48'	10	Misc	U
Muong Sen	19°24'	104°08'	9	Misc	U
Pho Chau	18°30'	105°25'	9	Misc	U
Son La	21°20'	103°54'	16	AF	U
Tien Tri	18°16'	106°07'	12	AF	U
Vinh	18°40'	105°39'	34	AF	U

Burma

Keng Tung	21°18'	99°37'	9	(1-39)	1951-1960

Table 1-2

RAINFALL STATIONS

South Vietnam

Station	Latitude	Longitude	Years of Record	Source*	Station No.	Primary Period of Record
Ban Me Thuot	12°41'	108°05'	25	Misc	117	U
Bao Loc	11°27'	107°47'	25	Misc		U
Ben Cat	11°12'	106°37'	22	AF		U
Ben Cui	11°19'	106°18'	30	F		U
Bentre	10°14'	106°22'	10	E	158	1920-1929B
Bien Hoa	10°58'	106°48'	41	Misc		U
Bon Jeng Drom	12°38'	107°34'	7	Misc		U
Budop	11°39'	106°59'	8	F		U
Bu Nard	11°38'	107°14'	5	F		U
Can Tho	10°02'	105°47'	19	E	163	1920-1956B
Chaudoc	10°42'	105°07'	15	E	146	1920-1930B 1960-1964
Cheo Reo	13°25'	108°26'	10	Misc		U
Dai Ngai	9°45'	106°04'	10	F	165	U
Dak Jappau	13°57'	108°38'	13	Misc		U
Dakmil	12°26'	107°39'	13	E	119	1952-1964
Da Lat	11°57'	108°26'	36	Misc		U
Da Lat/Lien Khang	11°45'	108°23'	8	Misc		U
Diom	11°49'	108°34'	10	Misc		U
Djiring	11°34'	108°04'	30	AF		U
Yang	12°42'	108°16'	4	E	115	1928-30
Go Cong	10°22'	106°40'	38	Misc	157	1908-1944B
Hue	16°24'	107°41'	31	Misc		U
Huong Hoa	16°37'	106°37'	11	F		U
Khanh Duong	12°42'	108°47'	13	F		U
Khe Sanh	16°38'	106°50'	14	F		U
Kon Plong	14°38'	108°23'	8	Misc		U
Kontum	14°30'	108°01'	24	E	47	1917-1940
Lac Thien	12°24'	108°08'	8	F		U
Lang Hanh	11°38'	108°16'	28	Misc		U
Long Dinh	10°21'	106°18'	10	F		U
Long Xuyen	10°24'	105°24'	32	Misc		U
My Tho	10°21'	106°22'	10	F		U
Phung Hiep	9°39'	105°49'	10	F		U
Phuoc Long	11°49'	106°57'	13	F		U
Quang Tri	16°44'	107°11'	34	AF		U
Quan Loi	11°37'	106°38'	28	Misc		U
Rach Gia	10°00'	105°05'	9	E	164	1920-1930B
Sa Dec	10°18'	105°45'	11	E	153	1920-1930B
Saigon	10°49'	106°40'	48	Misc		U

Table 1-2

RAINFALL STATIONS

South Vietnam (Cont'd.)

Station	Latitude	Longitude	Years of Record	Source*	Station No.	Primary Period of Record
Soctrang	9°30'	106°00'	30	AF	166	U
Tan An	10°32'	106°25'	46	Misc		U
Tan Chau	10°48'	105°14'	26	AF	145	U
Travinh	9°56'	106°20'	11	E	161	1920-1930B

Table 1-2

RAINFALL STATIONS

Thailand

Station	Latitude	Longitude	Years of Record	Source*	Station No.	Primary Period of Record
Aranyaprathet	13°42'	102°31'	30	AF	231	U
Buriram	15°00'	103°07'	13	E	199	1952-1964
Bua Yai	15°35'	102°25'	9	E	207	1953-1963B
Chaturat	15°34'	101°51'	9	E	205	1954-1963B
Chaiyaphum	15°45'	102°02'	47	T	206	1911-1960
Chakkarat	15°00'	102°16'	10	E	197	1953-1963
Chanthaburi	12°37'	102°07'	50	T	190	1911-1960
Chiang Khan	17°52'	101°36'	6	Misc		U
Chiang Mai	18°47'	98°59'	48	T		1911-1960
Chiang Rai	19°55'	99°50'	50	T	174	1911-1960
Chok Chai	14°44'	102°10'	11	E	194	1953-1963
Chum Phae	16°32'	102°06'	14	E	232	1952-1965B
Kabin Buri	14°10'	101°01'	13	E	189	1952-1964
Kalasin	16°26'	103°30'	14	E	214	1951-1964
Khon Kaen	16°22'	102°51'	49	T	213	1911-1960
Klong Yai	11°47'	102°53'	30	AF	192	U
Khok Krathiam	14°52'	100°39'	8	N		U
Nakhon Ratchasima (Khorat)	14°58'	102°07'	50	T	196	1911-1960
Kuchinarai	16°32'	104°04'	14	E	215	1952-1965
Lampang	18°15'	99°30'	50	T		1911-1960
Lamphun	18°35'	99°01'	20	Misc		U
Lamplaimat (Lam Plai Mat)	15°01'	102°50'	7	E	198	1954-1963B
Loei	17°30'	101°30	49	T	222	1911-1960
Loeng Nak Tha	16°09'	104°36'	8	N		U
Lop Buri	14°48'	100°37'	50	T		1911-1960
Maha Sarakham	16°11'	103°18'	20	Misc	212	U
Mukdahan	16°33'	104°44'	30	AF	225	U
Nakhon Phanom	17°30'	104°20'	46	T		1911-1960
Nan	18°47'	100°47'	48	T	175	1911-1960
Nang Rong	14°38'	102°48'	11	E	193	1953-1965B
Nong Khai	17°51'	102°44'	13	E	220	1952-1965B
Non Thai	15°12'	102°19'	9	E	233	1953-1963B
Pak Thong Chai	14°43'	102°01'	11	E	195	1953-1963
Phayakkhaphum Phisai	15°31'	103°21'	13	E	226	1953-1965
Phetchabun	16°25'	101°28'	50	T	221	1911-1960
Phrae	18°10'	100°08'	46	T	176	1911-1960

Table 1-2

RAINFALL STATIONS

Thailand (Cont'd.)

Station	Latitude	Longitude	Years of Record	Source*	Station No.	Primary Period of Record
Phutthaisong	15°32'	103°01'	12	E	208	1953-1964
Prachin Buri	14°10'	101°10'	50	T	188	1911-1960
Prakhon Chai	14°37'	103°05'	10	E	234	1953-1963B
Roi Et	16°03'	103°41'	50	T	210	1911-1960
Sakon Nakhon	17°10'	104°09'	46	T	216	1911-1960
Satuk	15°18'	103°08'	9	E	204	1953-1963B
Sara Buri	14°30'	100°55'	20	Misc		U
Sawang Daen Din	17°28'	103°28'	14	E	218	1952-1965
Sisaket	15°07'	104°20'	14	E	201	1952-1965
Surin	14°53'	103°29'	50	T	200	1911-1960
That Phanom	16°57'	104°44'	12	E	230	1952-1963
Tha Uthen	17°34'	104°36'	11	E	235	1953-1963
Trat	12°14'	102°30'	20	Misc	191	U
Ubon Ratchathani	15°15'	104°53'	50	T	202	1911-1960
Udon Thani	17°26'	102°46'	50	T		1911-1960
Wanon Niwat	17°38'	103°46'	10	E	219	1952-1965B

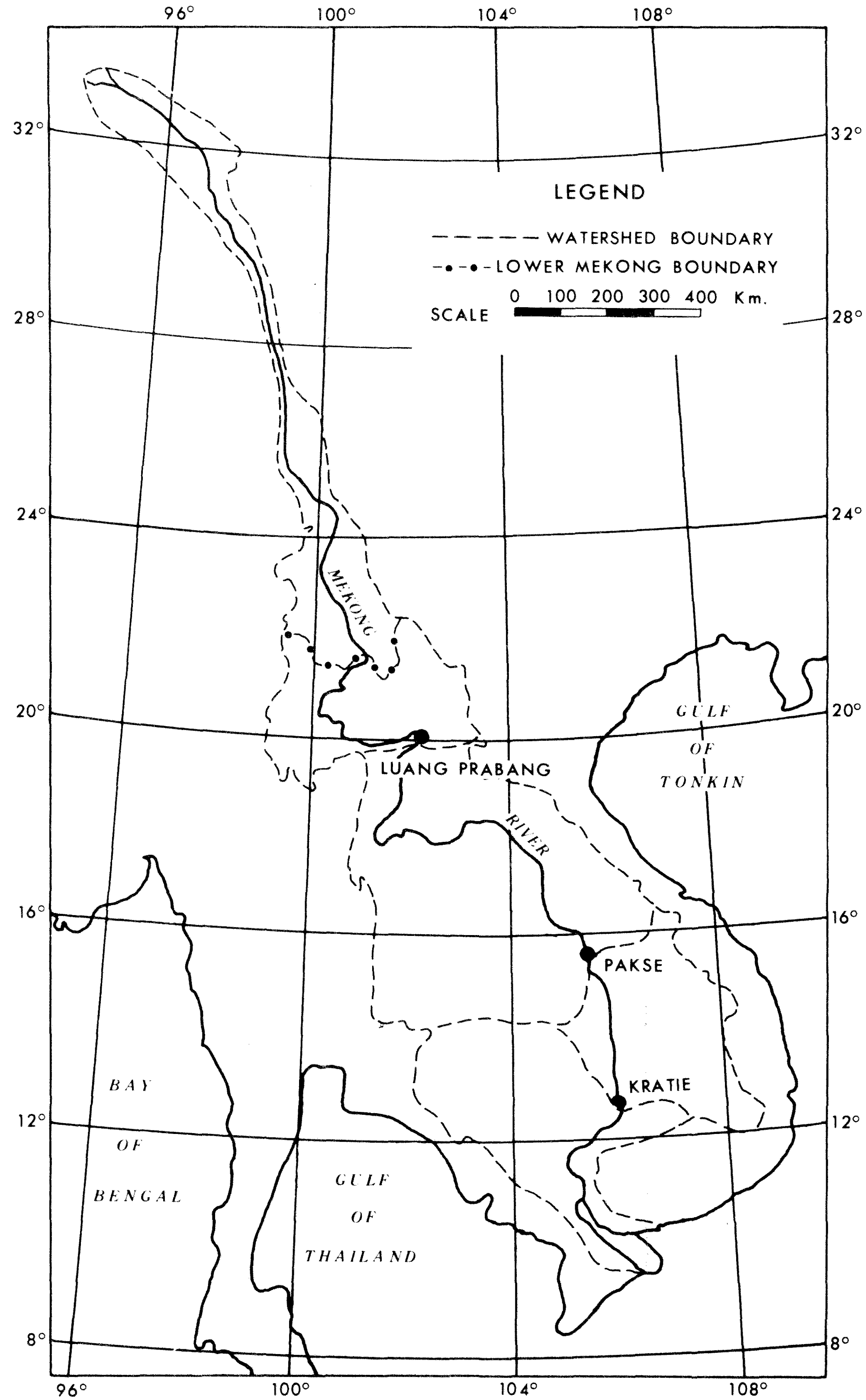

Figure 1-1. Drainage basin locations

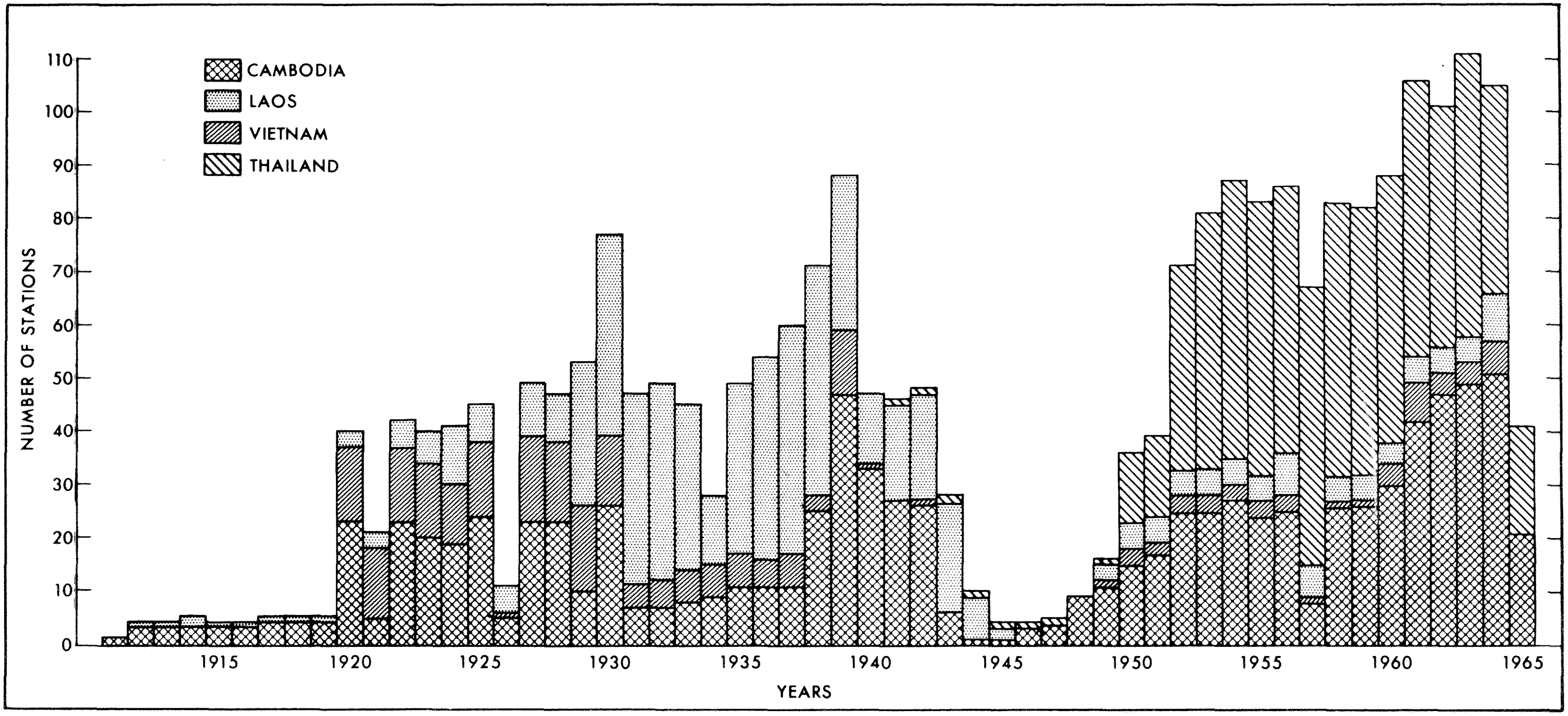

Figure 1-2. Summary of available daily rainfall data by country

Chapter II

RAINFALL CLIMATOLOGY OF THE MEKONG BASIN

Introduction

The southwest and northeast monsoons exert a dominant influence on the rainfall climate of the Mekong drainage, resulting in marked wet and dry seasons. The southwest monsoon is the heavy-rain season, lasting from May through September in the southern reaches of the basin, but decreasing markedly in length in the most northerly portion of the basin in mainland China.

During the height of the southwest monsoon season, rather high moisture is present in the air throughout the Mekong drainage area. Thus, mechanisms for releasing the ever-present moisture become important in determining rainfall magnitude. These mechanisms may vary from small-area showers or thundershowers set off by the sun's heating of the earth to typhoons which may produce prodigious rain amounts over areas as large as 200,000 square kilometers.

In this chapter, discussions of general features of weather types and daily rainfall characteristics are followed by development of mean monthly and seasonal rainfall charts. These mean charts are part of the information used in the derivation of extreme rainfall criteria.

Weather types

Broad-scale disturbances. A variety of disturbances of the atmospheric wind flow appears to take part in enhancing the production of rainfall in the Mekong Basin during the southwest monsoon season. Rainbird (2-1) has recently summarized the types of disturbances involved in rainfall in the Mekong. He found that both low-level and medium-level disturbances were conducive to high streamflows on selected basins in the Mekong drainage. Riehl (2-2) had previously identified three main types of large-scale disturbances that provide the heavier rain episodes in the southwest monsoon season. These are:

1. Low-pressure disturbances in the lower levels of the atmosphere with well-developed circulations to elevations of about 3 kilometers.

2. Middle-layer low-pressure disturbances with the most pronounced circulations between 3 and 6 kilometers.

3. Shear lines without definite low-pressure centers. Again these are most pronounced at 3-6 kilometers.

Such low-pressure disturbances in the broad-scale weather patterns serve to organize the rainfall and increase the general raininess. On many days, when such identifiable broad-scale features are lacking the rains may be more scattered coming in the form of showers and scattered thunderstorms.

Chin (2-3) has summarized tracks of tropical cyclones for the period 1885-1953. All the tracks which appeared to possibly affect the rainfall in the Mekong were noted. The number of such disturbances for September and for the May through September season were then related to areal rainfall over Eastern Thailand, it being the portion of the Mekong drainage with the longest continuous period of rain records. No significant relationship of total monthly or seasonal rainfall to the number of such disturbances was obvious. This suggests that the lesser disturbances play an important role in the monthly rain production in the Mekong.

Smaller scale disturbances. On occasion, and perhaps rather frequently, there may be some organization and intensification of the rain by virtue of disturbances or local wind circulation features of an order of magnitude less than the larger scale synoptic disturbances discussed above. Such disturbances are called "mesoscale" and they are of a type that is not ordinarily clearly detected by the normal spacing of weather observations.

Special techniques are required to detect such disturbances. For a discussion of this scale of weather disturbances, see Fujita (2-4). Various techniques have been used to detect such disturbances in spite of the ordinary large spacing between weather stations. Rainbird adopted a technique previously used in tropical Central America by Griffiths and Henry (2-5) in which a "contingency index" is used to determine rain relationships over varying distances. This technique applied to rainfall in the Mekong Basin showed that mesoscale processes were quite active within the broader scale synoptic controls (2-1).

Henry (2-6) has also done some preliminary work with the detection of mesoscale disturbances in Cambodia. Working with hourly rainfall data, he finds that "mesoscale systems are active at all seasons of the year and at all times of the day."

Conclusions. The above discussion supports the viewpoint that the long-period buildup in rainfall depths during the southwest monsoon season in the Mekong likely comes primarily from a succession of disturbed conditions. Some unknown portions possibly may be due to more or less "random" shower or thundershower activity in relatively homogeneous tropical air masses. But the important point for this study is that this type of random activity alone will not produce floods.

In this report, one of the most pronounced types of disturbances in the atmosphere - the typhoon - plays an important role in estimating maximum rainfall for a few days duration. This type of disturbance needs to be dealt with specifically, therefore, in maximizing rainfall for three days. The duration extends to six days when two typhoons are used in rapid succession (see chapter IV). For maximization of longer duration rainfall over large areas (chapter V), the specific identification of the type of disturbance is not an integral part of the adopted procedure. The rainfall, rather than a series of specific disturbances, is maximized.

The typhoon

The most important weather event for heavy rain for several days in the Mekong Basin is the typhoon. Maximum rains for durations of a day or two over areas of up to at least 100,000 square kilometers come from such storms.

A statistical analysis was made of tropical cyclonic storms approaching Southeast Asia from the east. Between 1884 and 1967 (2-3) (2-7), approximately 500 disturbances of this type affected the area. Figure 2-1 shows the resulting seasonal distribution of the tropical storms with maximum activity in September but with October as a close second. All of these had distinct cyclonic wind circulations at sea; most were fully developed typhoons (winds over 65 knots). In some the cyclonic wind circulation could still be identified overland. In others this feature was lost, but the disturbed conditions producing rain remained.

The geographical distribution of tropical disturbances was summarized in terms of the number passing through 2-1/2 degree latitude-longitude squares. If a storm passed through two squares, it was counted twice. Figure 2-2 shows the results. The large decrease in number of storms passing inland should be noted. Also to be noted is the sharp decrease in storms both to the north and south of the mean point of ingress. The mean track for September, the month of maximum typhoons, is also shown.

These are some of the broad-scale general features of typhoons in Southeast Asia. Chapter III makes comparisons of typhoons in this region and other parts of the world.

Characteristics of daily rainfall

Maximum daily rainfall. Maximum daily rainfall at most stations in the Mekong drainage has ranged between 125 and 250 mm, although a few locations have experienced more than 500 mm in a day. This contrasts with Vietnam coastal stations to the east of the basin where amounts over 400 mm in a day are more common. Figure 2-3 shows maximum 1-day rains, with years of record, at Lower Mekong stations. The Corps of Engineers data (1-37) are used in this analysis.

Rain days. The number of days with rain varies with location. In the rainier months, at the most favorable upslope stations, it rains almost every day. In the more sheltered regions, during the less rainy months of the southwest monsoon season, ten or fewer rain days a month is not uncommon.

Daily distribution of rainfall in months of heavy rain. A study was made of the daily distribution of rains in months of large rainfall amounts. Cumulative rainfall curves (mass curves) are shown for four cases in figures 2-4 through 2-7. A 12-station average rainfall was used in southern Laos (figs. 2-4 and 2-5), 11-station average in northern Laos (fig. 2-6) and a 9-station average in northeastern Thailand (fig. 2-7).

Three of these months (figs. 2-4, 2-5, and 2-7) illustrate a strong tendency for the rain to concentrate in spells of up to 5 days duration, although rain occurred at one or more stations in a given region each day. The northern Laos case of August 1938 (fig. 2-6) is an example of more uniform distribution of rain during the month.

We conclude that, although spells of rainfall are somewhat characteristic, a more uniform distribution of daily rainfalls over large areas is also acceptable.

Mean monthly and seasonal rainfall

May through September, the southwest monsoon season, is the period that produces most of the annual rainfall over the Mekong. August or September is the month of largest rainfall for most stations. Figure 2-8 shows May through September mean rainfall. Generalized topography of the Mekong Basin is shown on figure 2-9. Mean August and September rainfalls are given in figures 2-10 and 2-11. The discussion that follows deals first with the Lower Mekong.

Mean rainfall maps, Lower Mekong. Reliable rainfall observations naturally are the primary and indisputable foundation in any mean rainfall map. All available values of mean precipitation for stations (table 1-2) in and close to the Mekong Basin for May-September, August, and September were plotted on maps. Locations of the data points are shown on figure 2-9. It can be seen that there are but few observations in the mountainous areas. It is therefore necessary to incorporate orographic effects into the analyses by indirect means. Experimentation with various pairs of orographic and nonorographic rainfall stations, considering degree of sheltering by mountains, distance from the coast, etc., resulted in the concepts that follow. The mean isohyets for the Lower Mekong (figs. 2-8, 2-10, 2-11) were constructed by drawing to the data points and considering these effects.

Unsheltered interior upslope areas, were defined as mountain slopes facing west through south with no intervening close-by mountains to exert a strong sheltering effect. For such areas the precipitation approximately doubles in the first 1000 meters rise in elevation. A comparison of the station pair, Pakse and Pak Song, Laos indicated such a relationship. Little, if any, additional increase is suggested above the 1000 meter level, unless especially steep slopes continue to higher elevations.

Upslopes near the coast, depicted by a location such as Val D'Emeraude, Cambodia show more marked rainfall increases than within the bounds of the

Mekong drainage itself. However, in drawing the isohyets, spillover of rainfall into the basin from such upslopes near the coast was considered.

Sheltered areas, characterized by being immediately to the lee of substantial barriers are robbed of rainfall that they might otherwise experience. In the Mekong Basin such regions are rather sizeable, for example, a good portion of the Korat Plateau in northeast Thailand. Precipitation in the sheltered portions of these areas is only about one-half of the upwind nonorographic values.

Mean rainfall maps, Upper Mekong. Development of mean rainfall maps for the Mekong drainage in China was a special problem. In or very near the drainage above the stream gage at Chiang Saen there were eight available stations with mean monthly rainfalls based on from 3 to 11 years of data. The average length of record is 6 years. An additional eight stations with means for an average of 9 years up to 150 km outside the drainage were also available. All stations are in valleys surrounded by much higher terrain where long-period rainfall is assumed to be greater.

Comparisons between rainfall and stream runoff give some indication of the inadequacy of the rainfall data in the Upper Mekong. The mean May-September rainfall for the drainage above Chiang Saen (fig. 5-7) based on the average of station data is 620 mm while the mean runoff for 6 years of record at Chiang Saen is 308 mm. The ratio of runoff to rainfall is 0.50. For the drainage between Chiang Saen and Luang Prabang the mean station rainfall is 1250 mm and the mean runoff is 257 mm, giving a ratio of runoff to rainfall of 0.21. There is no reason to expect this large a difference in ratio of runoff to rain in the two areas; it appears that the few stations in the drainage north of Chiang Saen greatly underestimate the basin mean rainfall.

An atlas of Chinese climatology (1-36) shows maps of mean monthly rainfall. The Upper Mekong is near the edge of the maps and analyses do not extend over the Mekong drainage south of 24° latitude. Nonetheless these analyses gave some indication of gross rainfall patterns and were used for guidance.

Mean monthly precipitation maps were drawn for the Upper Mekong by joint consideration of the runoff to rainfall ratios previously discussed, the Chinese Atlas maps, and mean monthly rainfall data. The comparisons of runoff to rainfall above and below Chiang Saen led to drawing smooth isohyets that considerably enveloped the few rainfall values in river valleys. The isohyets followed the broad-scale pattern over China (1-36) without introducing details due to terrain considerations. Details of the terrain were not known and available rainfall-elevation relations, developed for the Lower Mekong, were not considered appropriate for the Upper Mekong. Average basin rain depths for the individual monthly maps May through September were added to obtain the seasonal total. A May through September station-rainfall map was plotted and analyzed to reproduce this May-September total.

Seasonal variation

The seasonal trend in rainfall during the southwest monsoon season in the Lower Mekong shows a gradual increase in monthly values beginning in May, reaching a peak in August at some locations and in September at others. In August and September the most favorable upslope regions receive more than 800 mm of rainfall. At the more sheltered interior locations, mean monthly precipitation of less than 200 mm is experienced in the rainier months. Early in the monsoon season, in May, the monthly precipitation varies generally from less than 200 mm to somewhat more than 500 mm.

Seasonal variation of rainfall for several selected stations is shown by the histograms in figure 2-12. The progression of the southwest and northeast monsoons during the year is also shown. The positions of the monsoons are intended to represent average dates when the seasonal shift in winds takes place.

Rainfall at Luang Prabang (fig. 2-12) typifies the southwest monsoon regime while Val D'Emeraude shows orographic accentuation of the southwest monsoon. In contrast, Da Nang's seasonal trend in monthly rainfall typifies a station exposed to the northeast monsoon.

Contribution of snowmelt to runoff

The reliance on runoff as an indicator of precipitation (chapter V) led us to make an investigation of the availability of snow in the Upper Mekong as a source of runoff.

Snow depths were available for 11 stations in China for five to ten years of record. The station elevations ranged from 500 meters to 2400 meters, with a mean near 1800 meters. The maximum snow depth reported was 5 cm at Chao-t'ung with elevation of 1930 meters and located at 27°20'N, 103°45'E. There were no stations as far north as 28°. None of the available stations are very representative of the northern Mekong Basin with its higher latitude and elevation.

Photographs taken from satellites of the region were checked for indications of snow cover. From a manned space flight photograph in March 1969 of the eastern extension of the Himalayas and part of the Upper Mekong Basin virtually no snow was detectable in the basin. Photographs from other unmanned space flights in 1967 and 1968 seem to confirm little if any snow after March, although these photographs are not as clear and are harder to interpret.

We conclude that the marked rise in runoff at Chiang Saen from May to August is due to rain with any contribution from snowmelt rather insignificant.

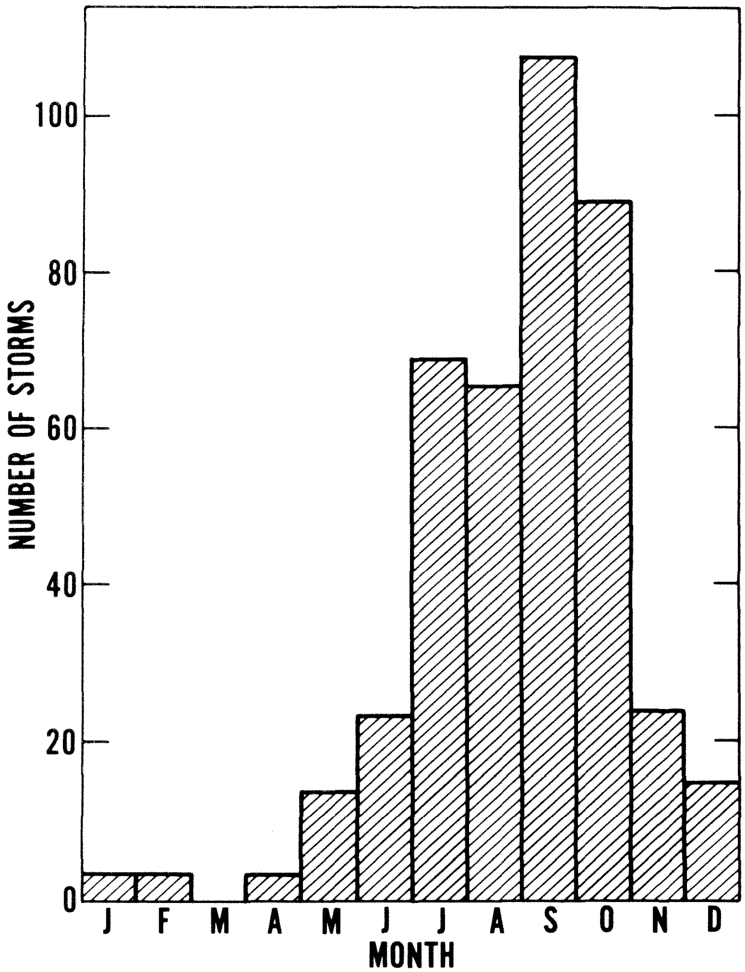

Figure 2-1. Seasonal distribution of tropical storms (1884-1967)

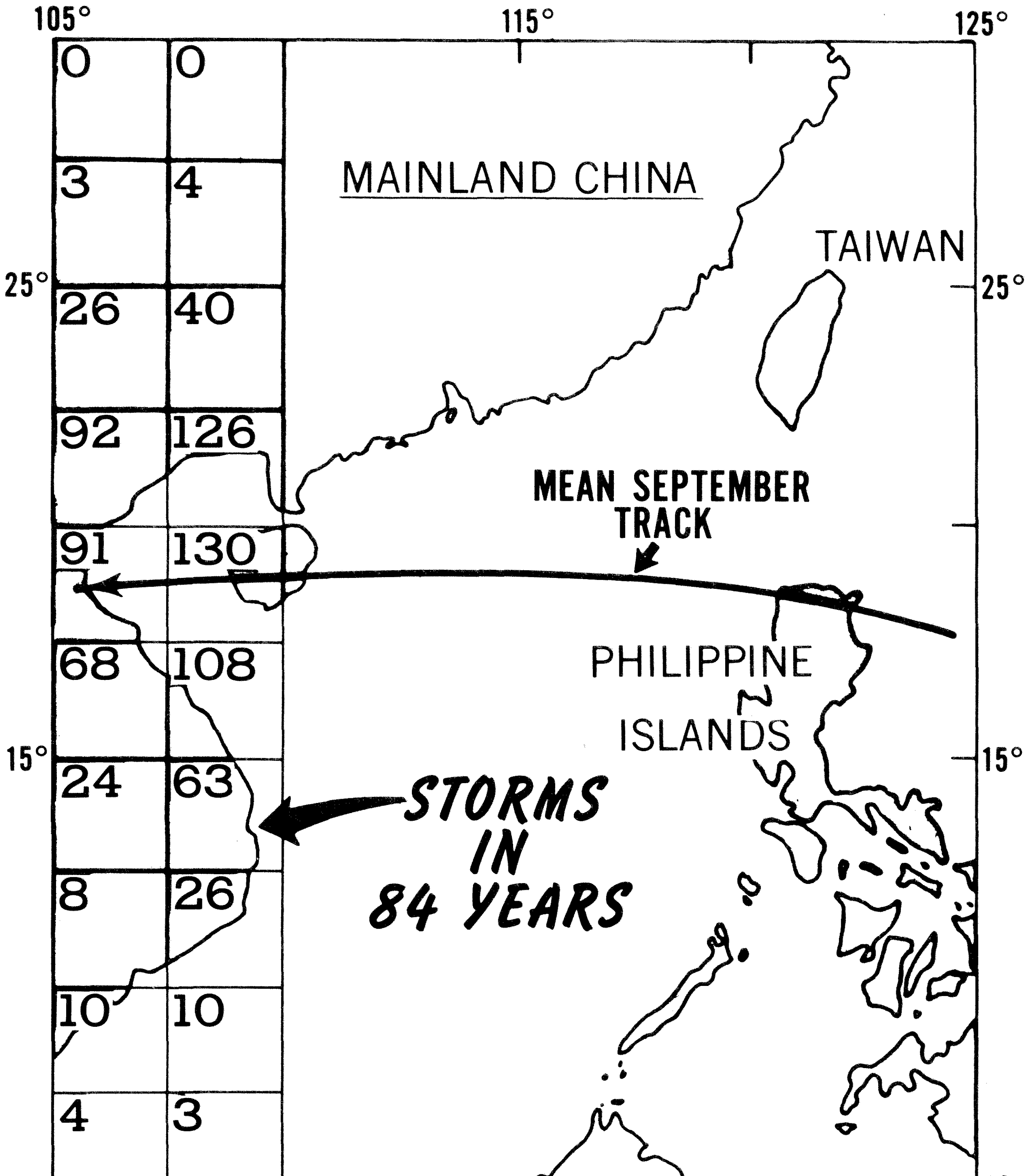

Figure 2-2. Geographical distribution of tropical storms (1884-1967)

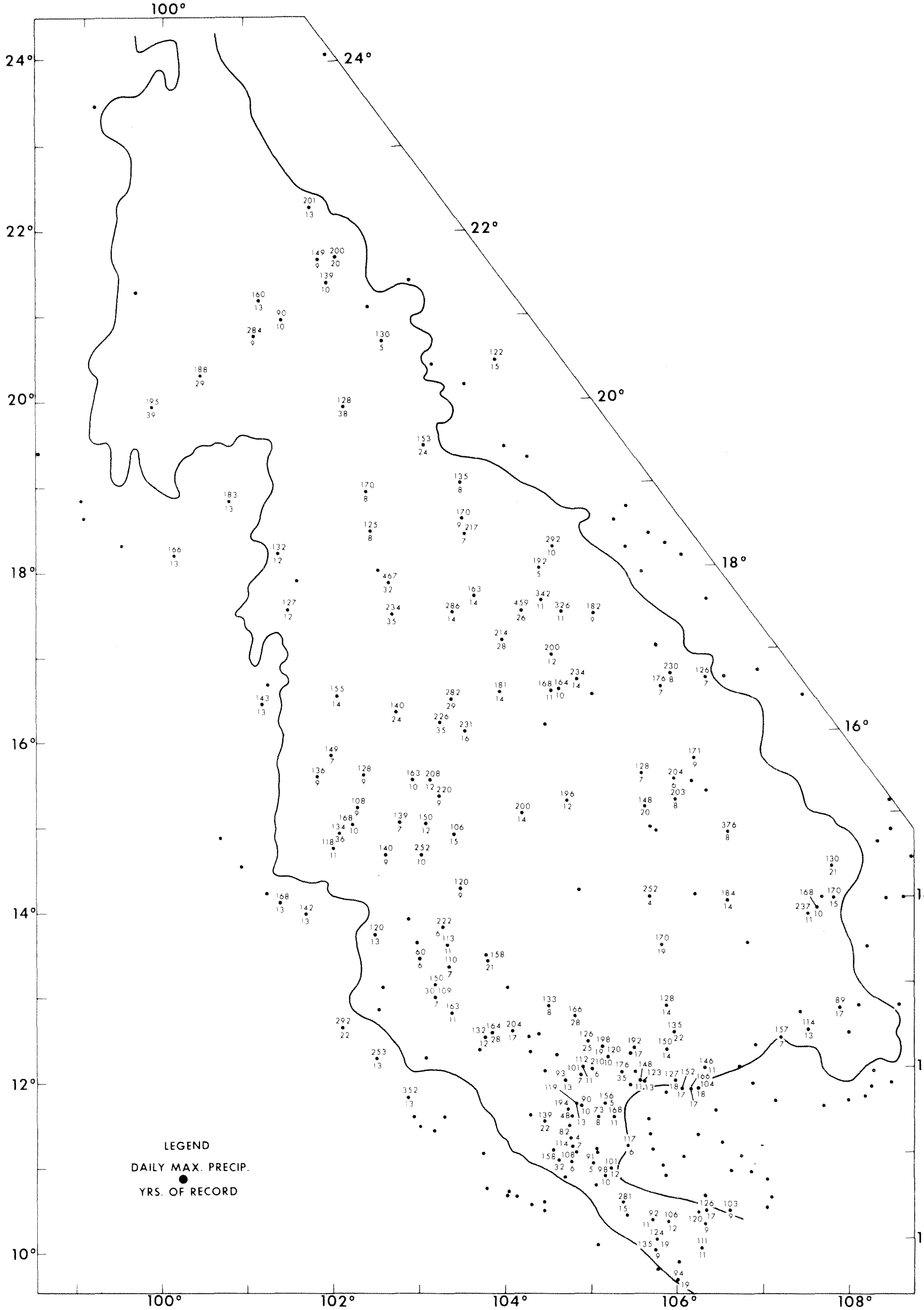

Figure 2-3. Maximum observed 1-day rains (mm)

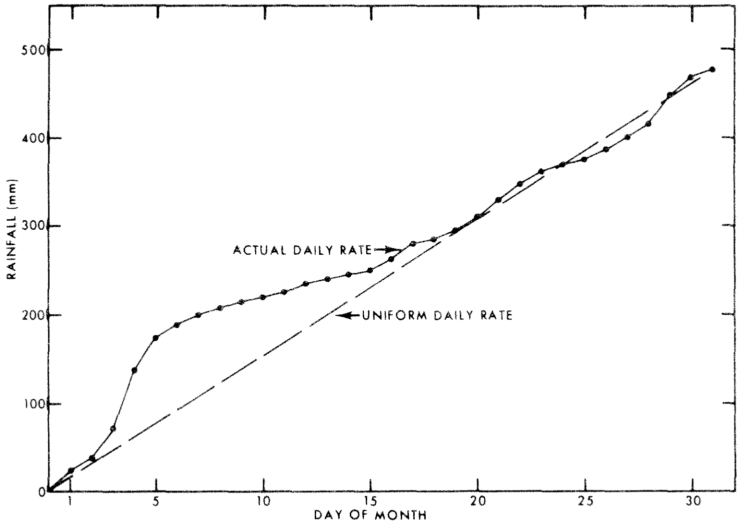

Figure 2-4. Cumulative daily rainfall (mm) over southern Laos in August 1937

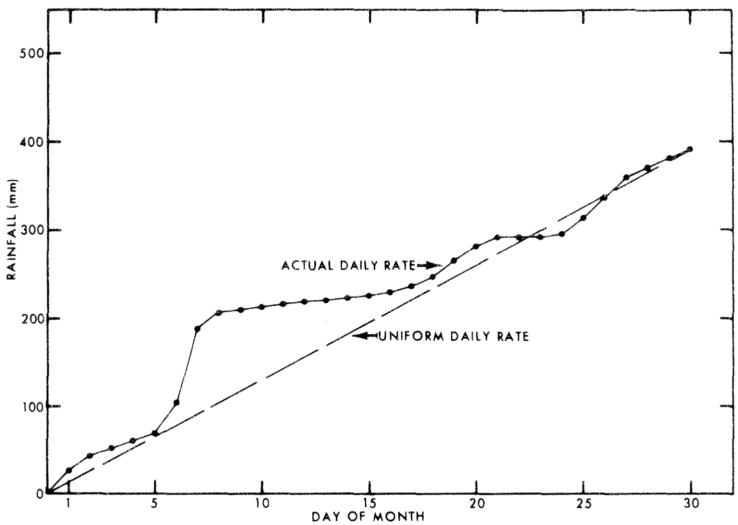

Figure 2-5. Cumulative daily rainfall (mm) over southern Laos in June 1938

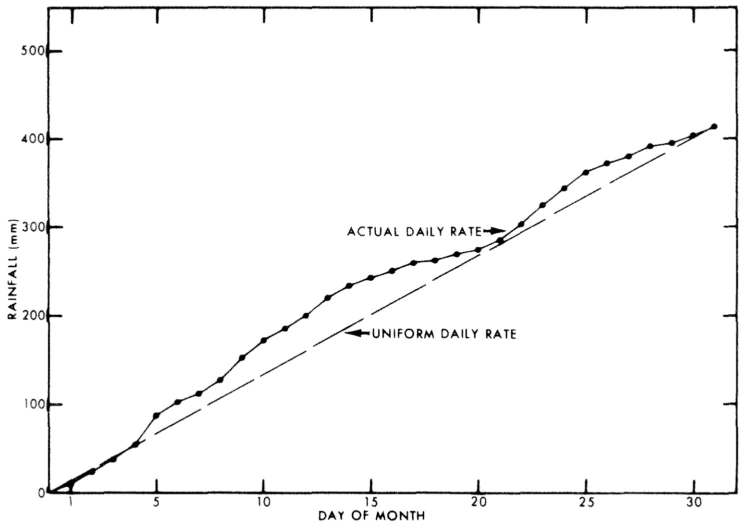

Figure 2-6. Cumulative daily rainfall (mm) over northern Laos in August 1938

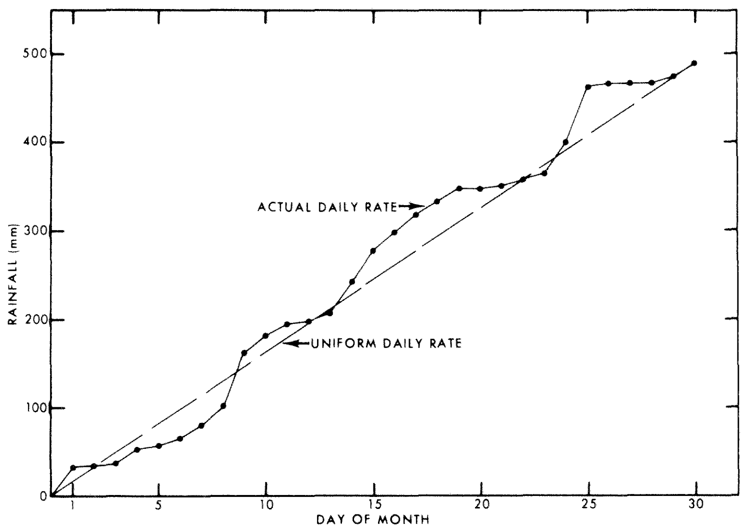

Figure 2-7. Cumulative daily rainfall (mm) over northeastern Thailand in Sept 1961

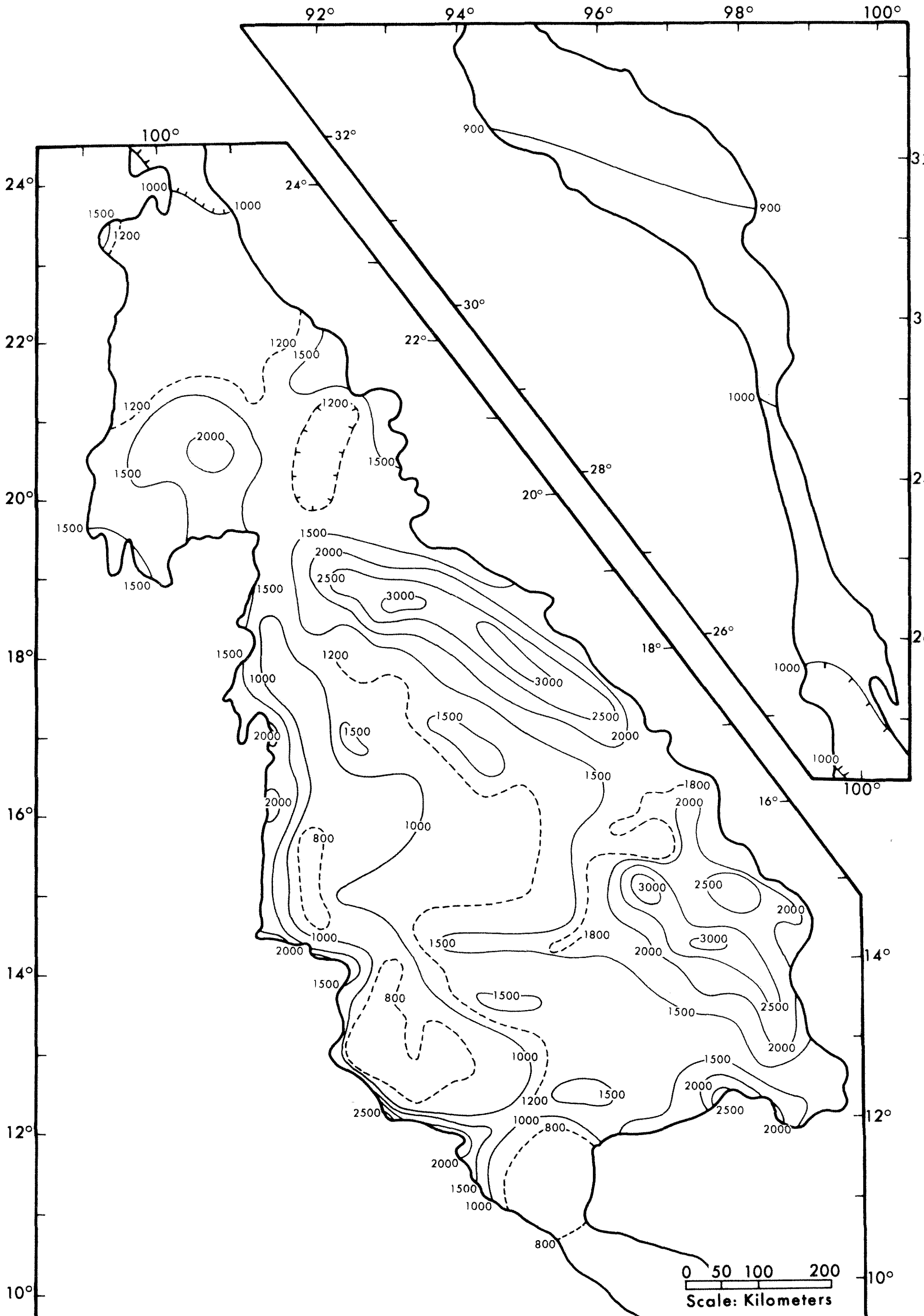

Figure 2-8. Mean southwest monsoon precipitation (mm) May through September

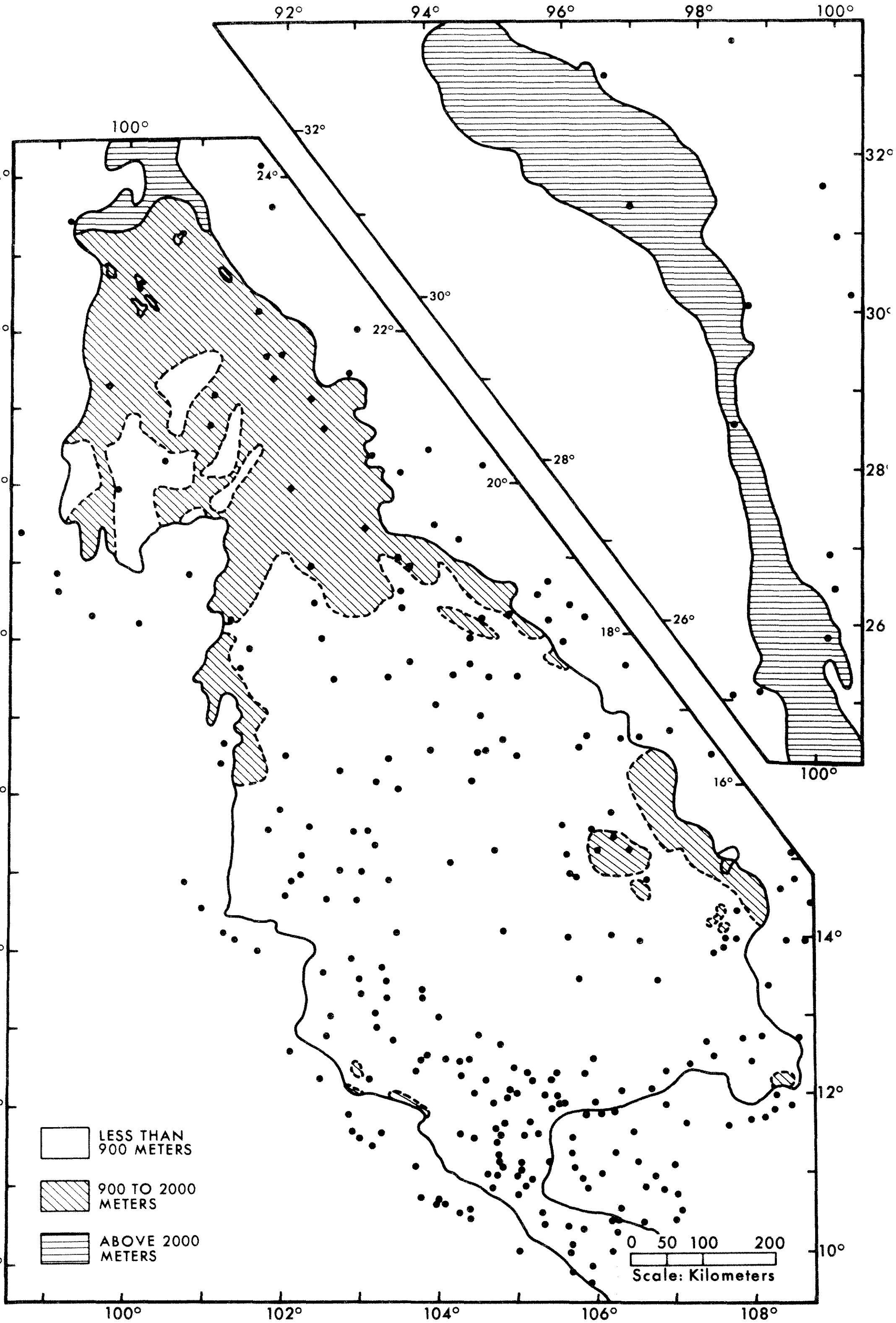

Figure 2-9. Generalized topography of the Mekong Basin with station locations

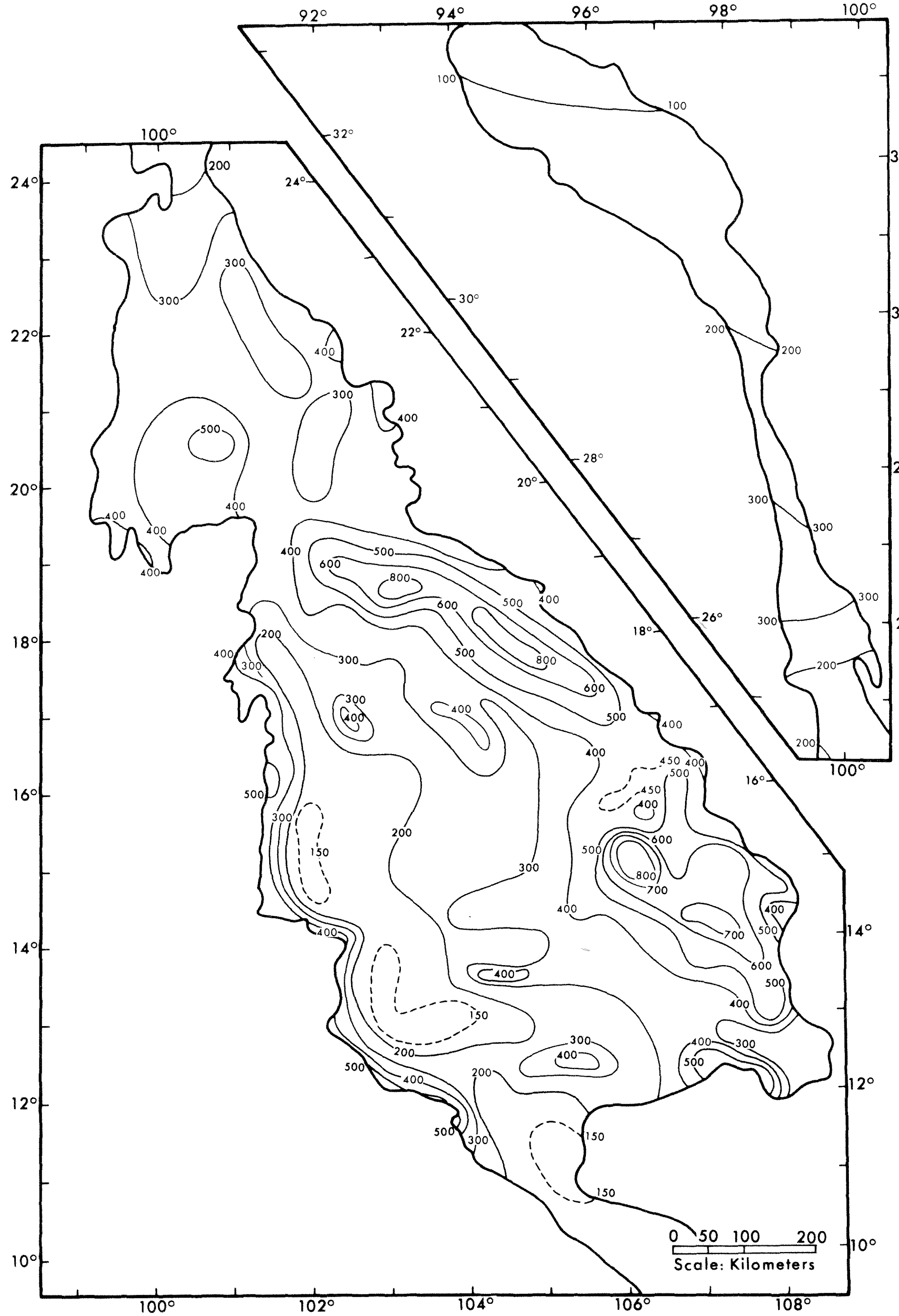

Figure 2-10. Mean August precipitation (mm)

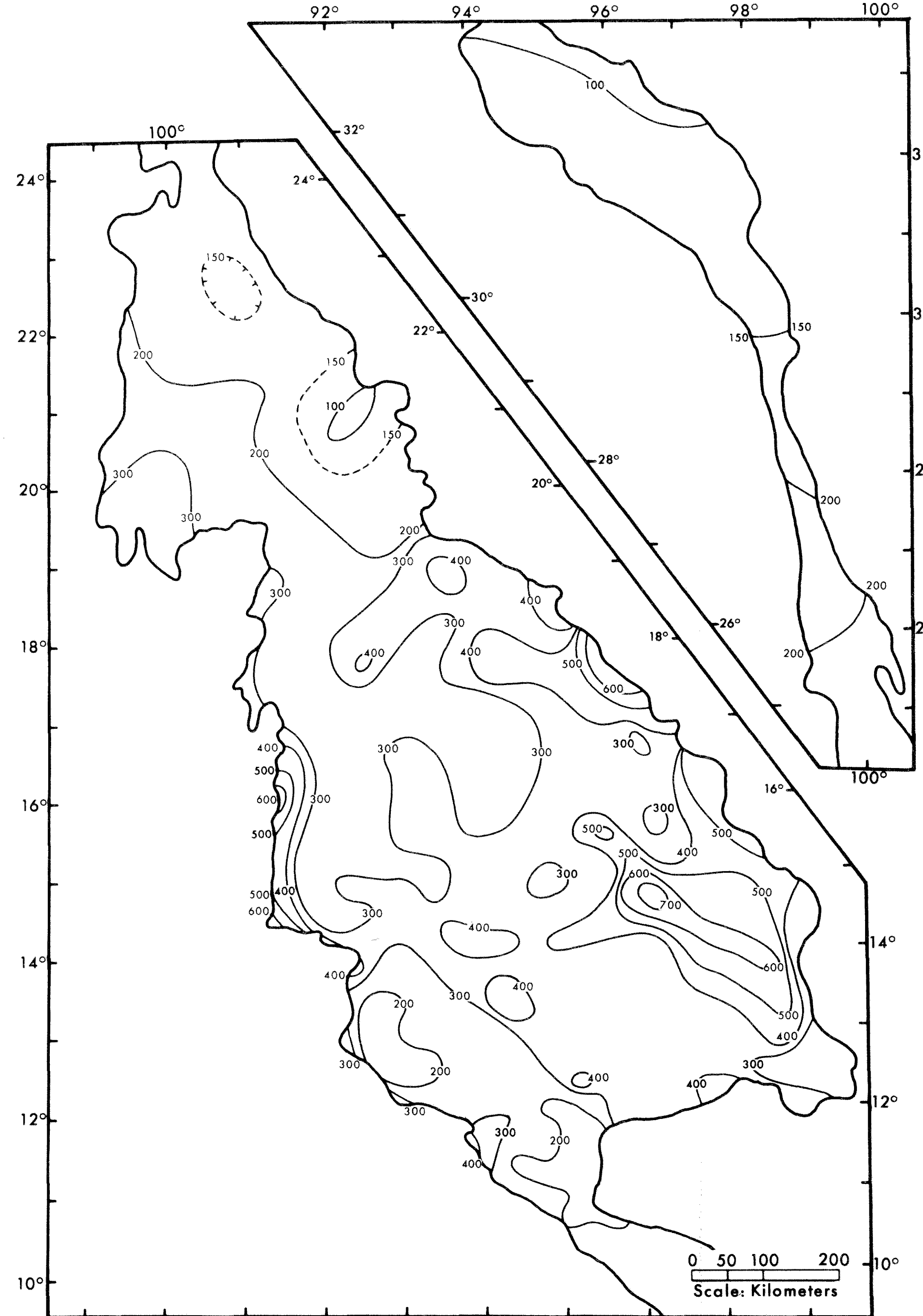

Figure 2-11. Mean September precipitation (mm)

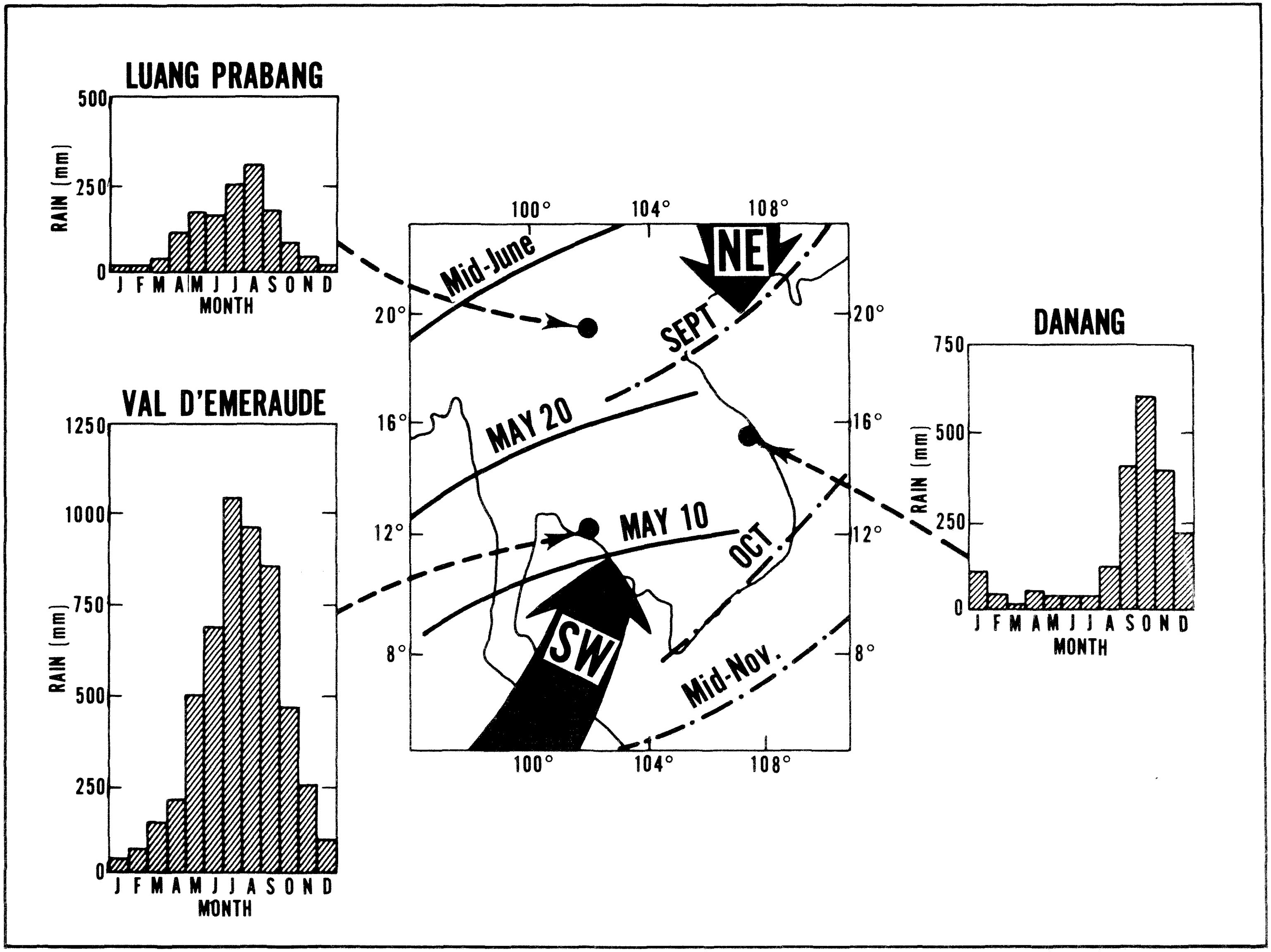

Figure 2-12. Seasonal distribution of rainfall and average dates of seasonal shift in winds

Chapter III

GENERALIZED ESTIMATES OF PMP OVER THE LOWER MEKONG DRAINAGE FOR AREAS FROM 5,000 TO 25,000 SQUARE KILOMETERS

Introduction

In this chapter estimates of probable maximum precipitation (PMP) are developed for durations up to three days over the Lower Mekong River drainage. The estimates are "generalized" in that, through an index map, PMP can be obtained for any selected subdrainage between 5,000 and 25,000 sq. km. in area.

It has been found that generalized PMP estimates are much more satisfactory than estimates developed on a project-by-project basis. The greatest difficulty in the latter approach is to maintain consistency in PMP values with respect to location of subbasins in the region (regional variation) and from one size area to another (areal variation). The main drawback to a generalized approach is the considerably more labor and time required to complete the study.

This chapter is divided into four main sections. Section A considers extreme typhoon rainfalls; section B gives the derivation of PMP; section C covers application of PMP to a project basin; section D makes some comparisons between PMP and other rainfall values.

Rainfall from two typhoons in sequence is a portion of the criteria developed for estimating the probable maximum flood at three major sites on the Mekong River (chapter V). The second storm in the sequence is of PMP magnitude and the prior storm is 50 or 65 percent of the second, depending on the time interval (3 or 4 days, respectively) between the two storm tracks. Chapter IV presents the evidence for the recommended magnitudes of the prior storm and the time intervals.

It is suggested that the antecedent storm also be used prior to the PMP for subbasins. Section C of this chapter gives directions on application of the prior storm rainfall.

A. Extreme Typhoon Rainfalls

Introduction

Examination of storm rainfalls of several days duration in the Mekong drainage shows that typhoons have produced the greatest areal depths. A typhoon is considered the PMP prototype for areas up to 200,000 sq. km.

Extreme typhoon rainfall of three kinds is discussed below. First, is record typhoon rainfall in the Mekong Basin; next, record world-wide point typhoon (hurricane) rainfall; and, finally, maximum rainfall in Atlantic hurricanes. The first and last categories are areal depths in the form of depth-duration-area arrays, hereafter abbreviated DDA values.

Record typhoon rainfalls in the Mekong

A survey of rainfall records in and near the Mekong drainage revealed two storms that stand out above all others for durations of one through three days. These were the rains from typhoon Tilda, September 21-25, 1964, and typhoon Vae, October 21-22, 1952. The Appendix shows storm tracks, isohyetal analyses and maximum depths over selected areas and durations for these storms. The greatest depths come from typhoon Tilda for most durations and areas. Typhoon Vae produced the greatest depths in 48 hours for areas from 3,000 to 100,000 km^2 and in 72 hours for areas of 20,000 to 100,000 km^2. Table 3-1 gives the greatest depths from these two storms.

World-wide extreme point rainfall from tropical storms

A summary of the world maximum 24-hr. typhoon* point rainfalls is shown in table 3-2.

Before evaluating the highest typhoon point rains, a few statements concerning orographic effects need to be made.

1. Forced lifting of the moist air in a typhoon by the terrain substantially increases the rainfall.

2. Since the winds diminish as a typhoon moves inland, terrain-produced increases in rainfall should be a maximum where steep slopes exist close to the water.

3. Formidable mountains (i.e., extending to high elevations without significant gaps) should produce the maximum orographic effects.

The maximum known typhoon point 24-hr. nonorographic rainfall in the Western Hemisphere is the Yankeetown, Florida value of 983 mm. For a Pacific Ocean typhoon, the maximum observed basically nonorographic value is the 1072 mm observed at Kadena Air Force Base, Okinawa on September 8, 1956. The ratio of this maximum-observed Pacific to maximum-observed Atlantic rain is 1.09. The true ratio of heaviest rainfall in the Pacific

*The terms hurricane and typhoon are considered synonymous, both meaning a severe tropical cyclone with surface winds of 65 knots or higher. For simplicity, in the remainder of the report, we will refer to hurricanes as typhoons.

typhoon to that in the Florida typhoon may be greater than this, since a survey for unofficial measurements was made in Florida but not Okinawa. It is improbable that the reporting station at Kadena Air Force Base actually sampled the heaviest rainfall.

The remaining values in table 3-2, on the Island of La Reunion, are larger than the Kadena Air Force Base 24-hr. rain by the following percentages: Cilaos 74 percent, Belouve 58 percent, and Aurere 48 percent. It is not unreasonable to ascribe these differences to effects of high mountains on the Island of La Reunion near the coast.

Point rainfall values are now compared for two typhoon-prone regions - the Vietnam coast and the south and southeast coast of the United States. Comparison of many maximum values provides a more stable statistic than does the comparison of single maxima only.

Table 3-3 summarizes record 24-hr. rains along the Vietnam coast north of latitude 15°N and table 3-4 the maximum rain along the south and southeast coast of the United States. Most of these rains are assumed to come from typhoons.

In interpreting these station rainfall data we need to keep in mind that many of the Vietnam stations are subject to orographic effects, while the United States stations are in relatively flat areas.

The mean of the Vietnam rainfall is approximately twenty percent greater than that for the United States data. The furthest we can go in interpreting this comparison is to conclude that no difference has been found in nonorographic typhoon 24-hr. rainfall at the Vietnam and United States coasts, the 20 percent excess at the Vietnam coast easily being accounted for by mountain effects.

North American maximum observed areal rainfall

DDA data from all typhoon-associated storms in North American were summarized to obtain highest values. These are listed in table 3-5. Eight of the nine storms providing these controlling values are in the United States, the remaining one in Mexico.

B. Derivation of PMP

Techniques developed for estimating PMP in one part of the world may not be appropriate in others. The hydrometeorological procedure applied generally in the U.S.A. is discussed below, followed by innovations in methods required for the interior Mekong drainage of Southeast Asia.

General method used in the United States

Methods that evolved over the years for estimating probable maximum precipitation were surveyed in a paper at the International Symposium on Floods and Their Computations, at Leningrad in 1967 (3-2). The customary procedures require the availability of certain data, including an adequate sample of storm rainfall on a volumetric basis in severe storms.

For nonorographic regions in the United States, the method of computing PMP for moderate size drainages has become quite standardized. Basic steps are: 1. Maximize areal rainfall depths of major storms for moisture by multiplying by the ratio of maximum moisture for the month and location of each storm to the moisture actually available in the storm. 2. Transpose maximized rain values of the storms that might be expected to occur over the project basin. Consider storm rainfalls for a range of sizes and durations. 3. Envelop the resulting rain depths by constructing smooth depth-area and depth-duration curves.

The moisture adjustment is an important storm maximization step in middle latitude regions such as the United States where dew points in observed storms may be several degrees or more below what is possible at the season and latitude of occurrence. However, when we focus our attention on intense storms in tropical regions, the importance of the moisture-maximizing step diminishes, since dew points tend to be continually high during the rainy season.

What has been said to this point applies to maximization of non-orographic rainfall. Where orographic effects are involved, special techniques must be applied, either through use of a model or by empirical rainfall-orography relations, or both.

Method for the Mekong

In the Mekong, unlike the southern and eastern coasts of the United States, extensive coastal plains are non-existent where typhoons are most frequent. Hence, most observed typhoon rains already possess orographic influences.

Depth-duration-area values for storms in Southeast Asia are scant. This necessitates bringing to bear storm experience from other areas and going beyond the usual procedures on storm transposition (3-2).

In a tropical region such as the Lower Mekong, moisture maximization during the southwest monsoon season is relatively meaningless since a plentiful supply of moisture is always available.

For the above reasons, derivation of typhoon PMP for the Mekong required:

(1) The liberal use of extreme rainfall from similar types of storms elsewhere.

(2) The abandonment of the important mid-latitude procedure of moisture adjustment of storms.

(3) The development of several adjustment procedures to take care of orography and basin location with respect to the coast.

Applicability of North American data

The role of the more plentiful North American precipitation data needs to be evaluated for its suitability in helping to set enveloping values along the Vietnam coast. Certain working assumptions and conclusions from typhoon literature help.

1. The assumption is made that the massiveness of a typhoon is related to its potential for heavy rains. By "massiveness" we mean the total kinetic energy of the storm viewed qualitatively, as indicated by the magnitude of winds and the area they cover.

2. The largest Pacific typhoons have greater massiveness than their Atlantic hurricane counterparts.

3. The largest China Sea typhoons are less massive than those of the western Pacific (Philippines and eastward).

4. It is concluded that the China Sea typhoon heavy-rainfall potential about equals the Atlantic hurricane potential (both less than that of western Pacific typhoons east of the Philippines). The point rainfall data comparisons cited (tables 3-3 and 3-4) as well as other factors, influence this conclusion. Therefore, it is assumed typhoon rainfall potential for coastal Vietnam, off the China Sea, is approximately equal to that in the U.S.A.

In the Southeastern United States and Southeast Asia, about the same surface dew points are characteristic of big storms, 23-24°C. Furthermore, typhoons frequently move slowly in both regions. Thus, a slowly moving typhoon can draw upon sufficient moisture in either region to produce comparable volumes of rainfall.

Speed of tropical cyclones in Southeast Asia and the United States. The most intense small-area rains from tropical storms in the United States are from the Yankeetown, Florida storm of September 3-7, 1950. This storm largely sets the level of PMP in the Mekong for areas up to 5000 km^2 for durations of 12 hours or more (table 3-5). It is thought that this is an extreme event, partly because the storm moved slowly and partly because it traced a loop very close to the rain center. While such a track has not been recorded over the Mekong drainage, this does not negate the possibility of such an occurrence.

Chin's tropical cyclone tracks for Southeast Asia (2-3) and Cry's tracks for the United States (3-3) were used to make comparative frequency distributions of the speed of tropical storms over land. In general, half of a daily movement had to be over land to be a case eligible for consideration.

Chin's tabulation of tracks produced 78 cases of tropical storms which met the criterion. A comparable number of cases along the Gulf Coast of the United States were selected from the most recent years of record.

The frequency distributions of the two sets of data are shown in figures 3-1 and 3-2. Median speeds are quite similar for the two regions. It was concluded that slow speeds are possible over Southeast Asia although they are more likely in the United States.

Nonorographic probable maximum precipitation (PMP) at the Vietnam coast

As pointed out above, DDA rainfall values in Southeast Asia are insufficient for defining enveloping relations for design purposes in the Mekong. Furthermore, it has been indicated, by a comparison with more abundant point rainfalls, that typhoon potential in the China Sea (therefore Vietnam coast) approximates that of North America as derived from Atlantic hurricanes. The enveloping DDA values for the Vietnam coast come, therefore, from an envelopment of all appropriately adjusted data, which include the relatively sparse Southeast Asia data and the more abundant North American data. These data, considered applicable to the Vietnam coast north of 15°N, are shown in figure 3-3 in the form of enveloping DDA curves.

The data of figure 3-3 have been adjusted for several different factors. Moisture maximization was used for the U.S. storms. All occurred north of latitude 29°N. The largest increase for this factor was 21 percent. An adjustment for distance-from-coast (to be discussed in later paragraphs) provides for normalizing the storms for differences in distance from the moisture source. This adjustment is used on all storms.

The remaining adjustments apply only to the Mekong storms and are discussed in following paragraphs. One adjustment is for intervening barriers between the moisture source and the storm rainfall. Adjustment for latitude of storm (south of 15°N) normalizes for varying potential (zero near the equator) with latitude. Adjustment for terrain at storm location accounts for local augmentation or depletion by nearby slopes. The barrier and slope adjustments do not apply to the U.S. storms because none of these particular storms occurred on slopes or were located behind barriers.

Adjustments shown on figure 3-3 for typhoons Tilda and Vae are the adjustments applied to the rainfall depths shown in table 3-1, which were obtained from measurements in the Mekong Basin. These adjustments are necessary to convert depths measured in the Basin to depths at the Vietnam coast where data were not available. They are the reciprocals of the adjustments obtained from figures 3-4 to 3-7.

The envelopes provide smooth transition from duration-to-duration as well as area-to-area. This accounts for some of the envelopment of the plotted data on figure 3-3.

Generalized PMP estimates for the Mekong Basin

Having assumed that the values of figure 3-3 represent nonorographic PMP off the Vietnam coast, the next step was to evaluate factors that are important in modifying this PMP for occurrence in the Mekong drainage. Distance from the coast, latitude of the particular location, mountain barriers to the east of the drainage, and adjustment for terrain within the basin are most important.

Distance-from-coast adjustment. This considers the general decrease in rainfall as the distance from the sea increases. It was originally developed for another study (3-4) from approximately 60 tropical storms in largely nonorographic regions of the United States. Equivalent data are not available in Southeast Asia but the relationship is considered transposable. It is nonorographic in nature and represents the decrease in rain-producing potential of tropical storms as their intensity and massiveness are reduced on moving inland away from their moisture source. Diminution with increased friction inland is also a factor in the relationship.

PMP values require an allowance for the multi-directional moisture source in the Mekong. Since the envisioned PMP typhoon would move in some westward direction, the distance from the Vietnam coast is of some consequence. However, during its movement across the Mekong Basin, moisture would normally be drawn in from the south also. This was allowed for by weighting the adjustment for distance-from-coast one-third from the south and two-thirds from the southeast through east. The weighted adjustment was applied to the drainage south of 17°N. Figure 3-4 shows the adopted distance-from-coast variation over the Lower Mekong.

Latitude adjustment. The potential for typhoon rainfall must decrease to zero near the equator. Full typhoon potential is considered reasonable northward from 15°. Watts (3-5) points out that no typhoons have been observed in Malaya. A Netherlands study (3-6) showed no typhoon south of 8°N latitude in Southeast Asia for the period 1910-1935. Gray (3-7), summarizing Southeast Asian tropical storms, shows the minimum latitude of hurricane force winds at about 4-5° near 150°E longitude. The minimum latitude of hurricane force winds is farther north in the China Sea area.

Arakawa (3-8) summarized the minimum central pressure of 561 typhoons by latitude and season. The increase in minimum central pressure from 15° to 10°N latitude is about 50 millibars. Perhaps more significant from Arakawa's summary are minimum pressures of only about 990 millibars at 5°N latitude. Arakawa's figure 6 indicates a slower rate of decrease in minimum pressure in the 15° to 10°N latitude zone than farther south. In a summary of tropical storms over the Indian Ocean, Koteswaram (3-9) shows one case of a storm within 6 degrees of the equator. In 1957-1958, unusual synoptic patterns permitted the occurrence of a rare typhoon at the Marshall Island atoll of Jaluit, at about 5°N latitude. This occurred on January 7, 1958 (3-10). Prior to this, no typhoon had affected the same area since 1905.

Such rare occurrences are the basis for postulating typhoon occurrences this far south as a limit for Southeast Asia. This is a maximizing step since the occurrences such as those at Jaluit are at a longitude much more prone to low-latitude intense typhoons than is the Southeast Asia area.

The October 1952 storm, typhoon "Vae," centered near 12°N in Cambodia and Thailand warns against too sharp a decrease in rain potential south of 15°N.

Summing up the conclusions on latitude variation for the area of Southeast Asia embracing the Mekong drainage and southward:

1. Typhoon rainfall potential near 5°N latitude should be zero.
2. Typhoon potential near 15°N latitude should be 100 percent.
3. Several indices (maximum 24-hr. rains, typhoon rainfall, and typhoon pressures) help in defining the change with latitude of typhoon rainfall potential.

These various points are incorporated into figure 3-5, expressed in percent of the full typhoon rainfall potential at 15°N latitude. For the span of 3° to 4° needed in the Mekong, it gives a downward adjustment for latitude of 2-1/2 percent per degree latitude. It is assumed that a greater rate of decrease prevails south of 10°N latitude so as to go to zero potential at 4 to 5°N in accordance with the data and literature notes discussed above.

The general sense of the adopted latitudinal variation in typhoon potential is supported in a recent study by Riehl (3-11) which shows that the flow is quasigeostrophic as close as 10 degrees to the equator so that the primary effects of a lack of coriolis force should be restricted to the area <u>closer</u> to the equator.

<u>Barrier adjustment</u>. The distance-from-coast adjustment already described is to allow for the fact that typhoons and tropical storms always weaken and eventually dissipate when they move from sea to land. It is a

nonorographic adjustment that applies to relatively flat terrain. We now consider the additional modification to the rainfall by the eastern mountains between the sea and the Mekong drainage. These mountains, or barriers, block the inflow of humid air from the sea and diminish the rainfall for long distances to the lee. The effectiveness of the blocking depends on the height of the barrier, the presence or absence of breaks in the mountain chain, and the wind direction.

In the discussion of the distance-from-coast adjustment the multi-directional aspect of the moisture source was considered. The same factor is important in the consideration of barriers to moisture inflow. Since the barriers to the east of the Mekong drainage are not fully effective in cutting off some low-level moisture (due to some bypassing of these barriers by inflow from the south or southwest), these barriers to the east of the basin are therefore reduced to one-half effectiveness during the occurrence of a typhoon.

Barrier heights were determined with the purpose in mind of estimating the broad-scale generalized effects on typhoon rainfall over fairly large areas. Elevation contours were generalized on a 1:2,000,000 scale topographic chart.

Usual hydrometeorological procedures are used to relate effective barrier heights to reductions in rainfall. The barrier height determines the loss of moisture in a sounding with a moist adiabatic vertical distribution of moisture. The ratio of the moisture above the height of the barrier, to the total moisture above sea level is the barrier adjustment.

Figure 3-6 shows the smooth barrier adjustments used in determining typhoon PMP for interior basins.

Adjustment for terrain within basin. Local windward slopes augment rainfall while moisture-bearing winds flow against them and, correspondingly, lee valleys receive decreased amounts. Rainfall in the important storms of October 1952 (Vae) and September 1964 (Tilda) gives some clues to such orographic effects.

The orographic intensification of rainfall in Tilda takes the form of a large rain center along the southwest-facing slopes in southwestern Laos near the Thailand border. At the same time an important concentration of rainfall over the Korat Plateau suggests that orographic effects were restricted to only a portion of the storm's duration.

The rainfall pattern for Vae showed the primary rainfall center along or in the vicinity of the southwest-facing slopes in southwestern Cambodia and the southeast tip of Thailand near the Gulf of Siam.

Since the center of a typhoon must pass close to a basin for highest rainfall it is reasonable with a required turning of the wind during the storm passage that orographic effects, similar to those of the southwest monsoon, be limited to a portion of the storm's duration.

Because of the importance of southwest flow, the southwest monsoon season mean rainfall chart (fig. 2-8) was used for guidance in developing a terrain adjustment chart. Ratios of high-elevation to low-elevation rainfalls on this chart are the primary indices to local orographic effects within the Mekong Basin. However, certain adjustments are needed in these ratios.

One adjustment concerns the removal of the frequency-of-rain factor. By "frequency-of-rain" we mean the bias that is introduced in southwest monsoon season rainfall by virtue of the greater number of days with rain at the higher elevations. For the short duration of PMP, the assumption is made that it will rain simultaneously at all elevations. A comparison of rainy-day amounts at high and low unsheltered elevations in the Mekong Basin suggests that the increase of rain with elevation on the southwest monsoon season map be reduced to about 0.6 of its value to be applicable for typhoon PMP.

A second adjustment of the monsoon season rainfall ratios involves consistency with the one-half effectiveness assumption adopted for the barrier adjustment. This implies that the southwest slopes are effective for only one-half of the storm duration. The rainfall-elevation variation thus becomes 0.3 of that on the southwest monsoon rainfall map. A rainfall value of 1200 mm on the monsoon season map is used as a base nonorographic value. Both areas of orographic increase and orographic decrease in precipitation are handled similarly. Figure 3-7 shows the final terrain adjustment chart.

Combined adjustment. A combined adjustment chart is shown in figure 3-8. This adjustment chart, in relation to the coastal Vietnam typhoon rainfall values equated to 100 percent, results from combining the adjustments of figures 3-4, 3-5, 3-6, and 3-7.

Generalized PMP map for 24 hr for 5000 sq km. The basic 5000-sq km 24-hr Vietnam coastal value from figure 3-3 was multiplied by the percentages of figure 3-8, to obtain a generalized map of 24-hr 5000-sq km PMP for the Lower Mekong Basin. This is shown in figure 3-9.

PMP for other size basins and other durations. The PMP values for basin sizes between 5000- and 25,000 sq km from figure 3-3 were expressed in percent of the PMP for 24 hr and 5000 sq km. These percentage DDA curves are shown in figure 3-10. The average 24-hr 5000-sq km value from figure 3-9 over any selected basin between 5000 and 25,000 sq km in the

Lower Mekong, multiplied by the "percent of 24-hr 5000 sq km PMP" at the area of the selected basin gives the desired basin PMP for 6, 12, 18, 24, 48 and 72 hours. A smooth depth-duration curve can be drawn through values for those durations to obtain PMP by 6-hr increments out to 3 days.

C. Application of PMP

Time distribution

Examination of hourly records of intense rains in the Mekong shows a large number of possible sequences of 6-hr increments during a storm period. Those associated with tropical storms, for example Tilda of September 1964, have rain bursts lasting up to 30 hours with the most intense rains near the center of the burst. Some stations had double bursts with a lull between them lasting for 6 to 18 hours.

Strictly speaking, to maintain PMP magnitudes, no lulls can be permitted in a sequence of 6-hr rain depths during the PMP storm. That is, the greatest, 2d greatest, etc., down to the 12th greatest (or lowest) 6-hr increment must be arranged in an ascending and descending sequence such that the highest increments always adjoin. The lowest 6-hr rain increment inserted between the greatest and 2d greatest 6-hr increments, for example, will not give 18-hr PMP.

We recommend sequences of 6-hr rain increments determined by applying the following steps. Results will essentially conform to the PMP requirement and at the same time be characteristic of the timing in major storms.

1. Group the four greatest 6-hr increments of the 72-hr PMP storm in a 24-hr sequence, the middle four increments in a 24-hr sequence, and the smallest four increments in a 24-hr sequence.

2. Arrange the three 24-hr sequences with the highest in the middle. The smallest 24-hr sequence may be at either end.

3. Within each 24-hr sequence, arrange the 6-hr increments so that the two greatest and the three greatest adjoin. The lowest 6-hr increment of each 24-hr sequence can be on either end.

Areal distribution

Isohyetal patterns for 6-hr rain increments in observed storms have a large variety of configurations. Some are simple concentric circles or ellipses, while others are complicated, with nearby centers of high and low rainfall.

We recommend an idealized elliptical pattern, figure 3-11, for the four heaviest 6-hr rain periods. (These isohyets cover far greater area than 25,000 sq km. Larger isohyets are used in typhoon rainfalls for Mekong drainages of chapter V.) For the remaining 48 hours of the storm, we suggest uniform distribution. Areas of isohyets, figure 3-11, are given in table 3-6.

Within a three-day period the isohyetal center of a major storm most often moves along with the storm's path. In the most extreme rainfall situations, the storm may become nearly stationary over a particular location. For the PMP storm, it is therefore considered not unreasonable to have the isohyetal center over the same location for a 24-hr period.

Thus far we have set the PMP volume and shape of isohyets. Next to consider are values for the isohyets given in figure 3-11. Innumerable sets of values would maintain the prescribed rainfall volume. These range from a set that gives almost uniform depth over an area to a very peaked distribution where the outer isohyet is near zero. We recommend a set fashioned after the most severe tropical storm rainfalls of the Mekong and North America. Particular attention was given to maximum 6-hr and 24-hr rains. For these durations, consistent depth-area curves were constructed for 5000-, 10,000-, 15,000-, and 25,000-km^2 areas based on average depth-area values of the most severe storms. With the 6- and 24-hr relations set, the 2d and 3d heaviest 6-hr depth-area curves were computed proportional to the PMP increments at standard-size areas. Figure 3-12 gives an example of adopted storm depth-area relations for key basin sizes and durations by dashed curves. Solid curves on this chart come from figure 3-3.

From the storm depth-area curves and the depth-duration-area array of PMP, nomograms were calculated that considerably reduce computations for the user. These are shown in figures 3-13a through 3-13d. Entering these with basin drainage area, isohyet values can be obtained as a percent of the particular 6-hr PMP increment.

<u>Summary of procedure for obtaining PMP</u>

From the foregoing, the following steps summarize a procedure for obtaining basin PMP:

A. Basin average PMP by 6-hr increments.

1. Determine average 24-hr 5000-km^2 value of PMP from figure 3-9 over the basin. An average of values from a grid is sufficient.

2. From figure 3-10 read percents of 24-hr 5000-km^2 rainfall for 6, 12, 18, 24, 48, and 72 hours for the area of the basin.

3. Multiply percents of step 2 by the 24-hr 5000-km^2 PMP from step 1 to give basin PMP.

4. Plot a smooth depth-duration curve from values in step 3, then read PMP by 6-hr intervals to 72 hours.

5. Obtain 6-hr incremental PMP by successive subtraction of the values in step 4.

B. Sequence of 6-hr PMP increments.

1. Group the four greatest 6-hr increments of A-5 in a 24-hr sequence, the middle four increments in a 24-hr sequence, and the smallest four increments in a 24-hr sequence.

2. Arrange the three 24-hr sequences with the highest in the middle. The smallest 24-hr sequence may be at either end.

3. Within each 24-hr sequence, arrange the 6-hr increments so that the two greatest and the three greatest adjoin. The lowest 6-hr increment in each sequence can be on either end.

C. Areal distribution.

1. Use the isohyetal pattern, figure 3-11, to distribute the four greatest 6-hr PMP increments. Center and orient the pattern over the basin so as to obtain the most critical hydrograph. Usually this will result from the greatest rain volume in the basin.

2. Enter figure 3-13a with the area of the basin on the vertical scale. Read percents of the first (highest) 6-hr incremental PMP on horizontal scale for each pattern storm isohyet, P through E. Multiply these percents by the highest 6-hr basin PMP of step A-5 to obtain isohyetal values in mm. Use figures 3-13b, 3-13c, and 3-13d, in a similar manner to obtain isohyetal values for the second, third, and fourth highest 6-hr. PMP increments, respectively. Areas of isohyets are given in table 3-6.

3. Assume uniform areal depths for the remaining 6-hr rain increments.

D. Prior typhoon rainfall

Chapter IV makes recommendations on the magnitude of a prior storm and on the time interval between it and the PMP storm. The magnitude is either 50 or 65 percent of the PMP, depending on the time interval, three or four days, respectively, that is adopted. Timing of the two typhoon storms following the recommended time intervals is illustrated in table 5-13. For the heaviest 1-day rain of the prior storm, 6-hr isohyetal labels of the PMP (see step C-1, -2, and -3) are multiplied by either 50 or 65 percent.

D. General Level of PMP

It is useful for the user of this report to have some perspective on the magnitude of the PMP. Comparison of PMP with storms of record is often used as a reference.

Highest observed rains in a region provide only the very lowest level that has to be exceeded by PMP. A number of items need to be considered in judging the adequacy of the observational level. First, is the length of record. Naturally the longer the record is, the better is the chance for recording a greater storm. Next, is the number of observing stations. The greater the station density, the greater the opportunity for sampling the most intense portion of a storm. As the drainage size under consideration becomes smaller, the more important station density becomes. A related factor is the sampling area size. The larger a climatologically homogeneous region over which a particular storm type can occur, the greater the opportunity for recording an extreme event.

Another consideration is storm frequency. Near windward-facing slopes, the ever-present triggering and lifting of air masses produce more frequent rains than are observed in a relatively flat region. Thus, observed amounts in rugged mountainous regions would be expected to come closer to PMP than would amounts in relatively flat regions.

PMP compared to maximum observed areal rainfall

The available records of daily rainfall for stations in the Lower Mekong drainage[1] were surveyed, with the objective of finding the most intense 5000 and 25,000 km^2 3-day rain depths. First, the dates of maximum 1-, 2-, and 3-day totals for the period of record at each station were summarized. Dates of all 1-day and 3-day totals greater than 150 and 200 mm, respectively, were also extracted. Maps were plotted and isohyets drawn for the storm periods of greatest rainfall. Average depths for 5000- and 25,000-km^2 areas were computed. The 13 cases with highest areal depths are given in table 3-7 along with 3-day PMP for each location and the ratios of observed to PMP. Storm locations and ratios of observed to PMP are plotted on figure 3-14. The ratios for 5000 km^2 range from 0.26 to 0.58 (average 0.40); for 25,000 km^2 they range from 0.25 to 0.56 (average 0.41). Many of the storms are near the mountainous region of Thailand and Laos. This is a region of southwest-facing slopes, where monsoon season rainfall is relatively high and storms are more frequent. Locations of the record storms depend to some degree on distribution of reporting stations. The more dense observation network near Kratie could account for two storms in this relatively flat terrain.

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[1]Data compiled by the U. S. Corps of Engineers, from records obtained by the Mekong Committee for the Governments of Laos, Thailand, Cambodia and Vietnam, for 122 stations with an average of 14 years of record.

Some perspective on the magnitude of the observed to PMP ratios is obtained by comparison with similar ratios for the West Coast drainage of the United States (3-12, 3-13). A fairly complete record of major storms is available from about the year 1900 over much of the drainage. For areas of approximately 2600 km^2, seven storms have had more than one-half of the estimated PMP for one duration or more. Some of these storms included supplementary rainfall measurements obtained from surveys after the storm events. Such measurements tend to be higher than those at regular reporting stations and therefore give a higher ratio of observed to PMP. Most of these record storms are on or near steep mountain slopes, where highest ratios are expected.

PMP compared to computed 100-yr areal rainfall

For those stations in the Mekong with 10 or more years of daily record, 100-yr return-period rainfalls were estimated from the series of maximum 1- and 3-day rains for each year. The Gumbel frequency distribution was used. Figures 3-15 and 3-16 show the 100-yr values for 1 and 3 days, respectively. Isolines were drawn to these data, as shown. To compare with PMP, an average areal reduction from station to 5000 km^2 of 0.80 (based on the previously discussed 13 storms) was used to obtain estimates of 5000 km^2 depths. PMP for 1 and 3 days over 5000 km^2 areas was then computed from this report and compared with observed values on a one-degree grid. Results are shown in figures 3-17 and 3-18.

The ratios of 100-yr to PMP for 1 day, figure 3-17, range from 0.23 to 0.54 and average 0.36. For 3 days, figure 3-18, the ratios vary from 0.28 to 0.69 and average 0.43. Larger ratios generally are near upslope areas with smaller ratios in low-elevation, relatively flat regions.

Table 3-1

ENVELOPING RAIN DEPTHS FROM TYPHOON TILDA (SEPT. 21-25, 1964) AND TYPHOON VAE (OCT. 21-22, 1952)

Area	Duration (hr)					
(km^2)	6	12	24	36	48	72
	Average Depth (mm)					
1000	165	282	385	412	427	470
2000	130	240	352	380	395	438
3000	112	219	336	364	378[1]	420
5000	100	200	315	345	370[1]	396
10,000	90	179	283	315	355[1]	362
20,000	75	155	245	278	332[1]	*
30,000	70	140	222	252	315[1]	*
50,000	62	119	186	216	287[1]	*
100,000	50	83	123	150	225[1]	*
200,000	35	59	82	104	130	170
300,000	28	45	65	81	100	130

Notes:

All values from Tilda except those marked with a superscript 1.
*Vae 48-hr depth greater than Tilda 72 hr.

Table 3-2

WORLD MAXIMUM 24-HOUR TYPHOON POINT RAINFALL

Station	Date	Amount (mm)	Duration (hr)
Yankeetown, Fla. U.S.A.	Sept. 5-6, 1950	983	24
Kadena AF Base, Okinawa	Sept. 8, 1956	965	18
Kadena AF Base, Okinawa	Sept. 8, 1956	1059	21
Kadena AF Base, Okinawa	Sept. 8, 1956	1072	24
Cilaos, La Reunion (3-1)	Mar. 15-16, 1952	1870	24
Belouve, La Reunion (3-1)	Feb. 27-28, 1964	1689	24
Aurere, La Reunion (3-1)	Apr. 7-8, 1958	1583	24

Table 3-3

MAXIMUM 24-HOUR RAINS ALONG THE VIETNAM COAST

Station		Years of Record	Maximum 24-hr Rain (mm)
Quang Noai		44	490
Da Nang		35	333
Hue Pitu Bai		48	424
Hue		31	432
Quang Tri		42	353
Dong Hoi		50	341
Vinh		37	485
Thanh Hoa		37	333
Nam Dinh		43	351
Phu Lien		34	490
Haiphong		31	256
Mong Cai		45	386
	Mean	40	389

Table 3-4

MAXIMUM 24-HOUR RAINS ALONG THE SOUTH AND SOUTHEAST COAST OF THE UNITED STATES

Station Name		Years of Record	Maximum 24-hr Rain (mm)
1	Brownsville, Tex.	80	303
2	Corpus Christi, Tex.	74	210
3	Victoria, Tex.	64	218
4	Houston, Tex.	52	275
5	Galveston, Tex.	90	364
6	Port Arthur, Tex.	45	451
7	Lake Charles, La.	23	407
8	New Orleans, La.	90	356
9	Mobile, Ala.	71	339
10	Pensacola, Fla.	71	334
11	Apalachicola, Fla.	39	297
12	Tampa, Fla.	71	308
13	Fort Myers, Fla.	71	297
14	Sand Key, Fla.	20	249
15	Key West, Fla.	71	505
16	Miami, Fla.	51	384
17	Miami AP, Fla.	26	320
18	West Palm Beach, Fla.	23	387
19	Jupiter, Fla.	73	335
20	Orlando, Fla.	21	246
21	Daytona Beach, Fla.	39	326
22	Jacksonville, Fla.	71	258
23	Savannah, Ga.	73	291
24	Charleston, S. C.	91	268
25	Wilmington, N. C.	91	242
26	Cape Hatteras, N. C.	87	379
	Mean	61	325

Table 3-5

HIGHEST OBSERVED TYPHOON AND DECADENT TYPHOON RAINFALLS IN NORTH AMERICA (mm)

Area	Duration (hr)					
(km^2)	6	12	24	36	48	72
1000	414(1)	640(6)	848(6)	902(6)	930(6)	965(6)
2000	361(1)	602(6)	800(6)	859(6)	884(6)	917(6)
3000	328(1)	554(6)	748(6)	810(6)	841(6)	871(6)
5000	284(1)	462(6)	643(6)	706(6)	739(6)	767(6)
10,000	229(1)	325(1)	455(6)	523(8)	572(8)	655(8)
20,000	170(2)	224(5)	323(8)	417(8)	475(8)	572(8)
30,000	135(2)	183(5)	267(8)	366(8)	424(8)	523(8)
50,000	104(2)	142(7)	208(8)	302(8)	358(8)	455(8)
100,000	69(2)	107(7)	160(3)	213(9)	277(9)	356(9)
200,000	38(3)	74(3)	114(3)	157(5)	203(9)	279(9)
300,000	28(4)	56(4)	89(4)	122(5)	150(5)	208(5)

Numbers in parentheses refer to storms as follows:

Storm No.	Storm Assignment Number	Rainfall Center	Storm Date
1	GM 4-12	Thrall, Texas	Sept. 8-10, 1921
2	GM 5-6	Bebe, Texas	June 27-July 4, 1936
3	SA 2-15	Darlington, S. C.	Sept. 16-19, 1928
4	GM 5-8	Hillsboro, Texas	Sept. 25-28, 1936
5	GM 1-19	Bonifay, Fla.	July 5-10, 1916
6	SA 5-8	Yankeetown, Fla.	Sept. 3-7, 1950
7	SA 4-23	Bay Minette, Ala.	Sept. 17-21, 1926
8	GM 3-4	Hearne, Texas	June 27-July 1, 1899
9	SW 3-24	Sombreretillo, Mex.	Sept. 19-26, 1967

Table 3-6

ISOHYETAL AREAS

(For storm pattern of figure 3-11)

Isohyet	Isohyet Area (km^2)
P	20
A	260
B	2260
C	11,170
D	29,690
E	56,420
F	103,730
G	139,650
H	184,160
I	245,170

Table 3-1

COMPARISON OF HIGHEST OBSERVED 3-DAY AREAL RAINFALL WITH 3-DAY PMP

Storm No.	Date	Approximate Location of Center Lat.	Long.	Obs. 5000 km^2 depth (mm)	5000 km^2 PMP (mm)	Ratio: Obs./PMP	Obs. 25,000 km^2 depth (mm)	25,000 km^2 PMP (mm)	Ratio: Obs./PMP
1	9/24-26/38	12°16'	105°58'	254	796	.32	191	567	.34
2	8/26-28/42	12°15'	105°32'	234	772	.30	139	550	.25
3	7/21-23/43	18°15'	104°43'	229	875	.26	176	623	.28
4	6/16-18/53	16°40'	105°00'	246	744	.33	235	530	.44
5	9/13-15/54	17°28'	103°28'	230	625	.37	200	445	.45
6	9/26-28/59	14°44'	102°10'	285	600	.47	216	427	.51
7	8/16-18/60	17°34'	104°36'	475	812	.58	225	578	.39
8	8/19-21/61	17°30'	104°20'	294	748	.39	247	532	.46
9	6/15-17/62	17°30'	104°20'	405	748	.54	224	532	.42
10	8/1-3/62	16°57'	104°44'	229	750	.30	195	534	.36
11	9/15-17/62	15°59'	102°28'	240	538	.45	214	383	.56
12	9/23-25/64	16°00'	103°45'	396	800	.49	317	570	.56
13	8/1-3/66	17°54'	104°12'	310	850	.36	184	605	.30

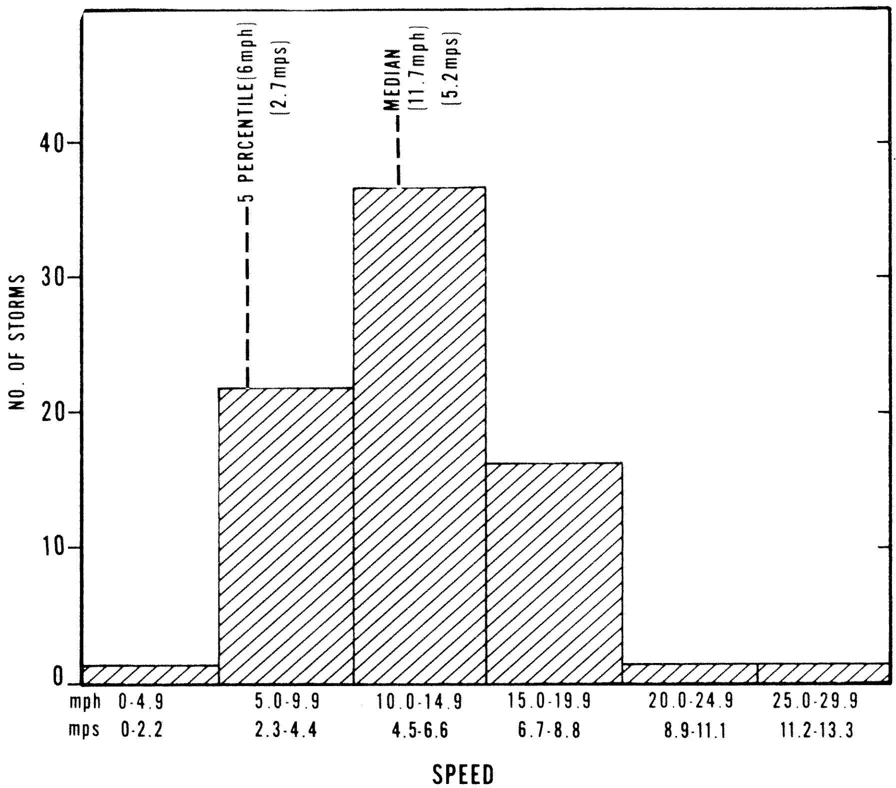

Figure 3-1. Frequency distribution of speed of storms at Vietnam coast

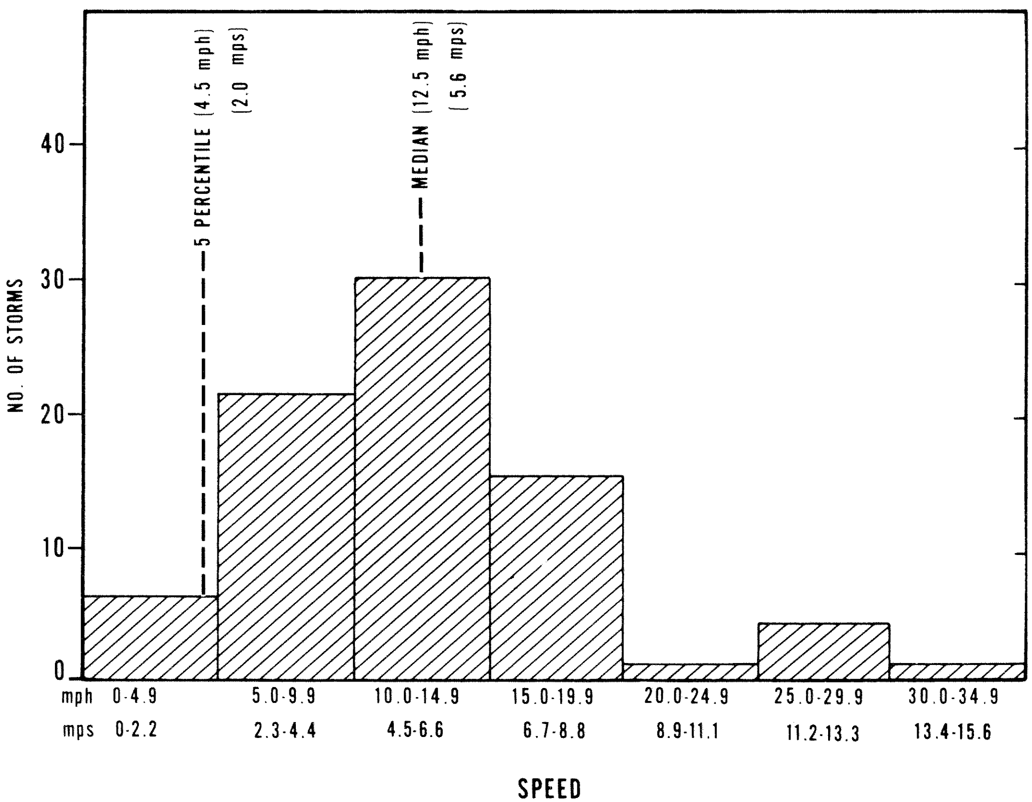

Figure 3-2. Frequency distribution of speed of storms at coast of Gulf of Mexico

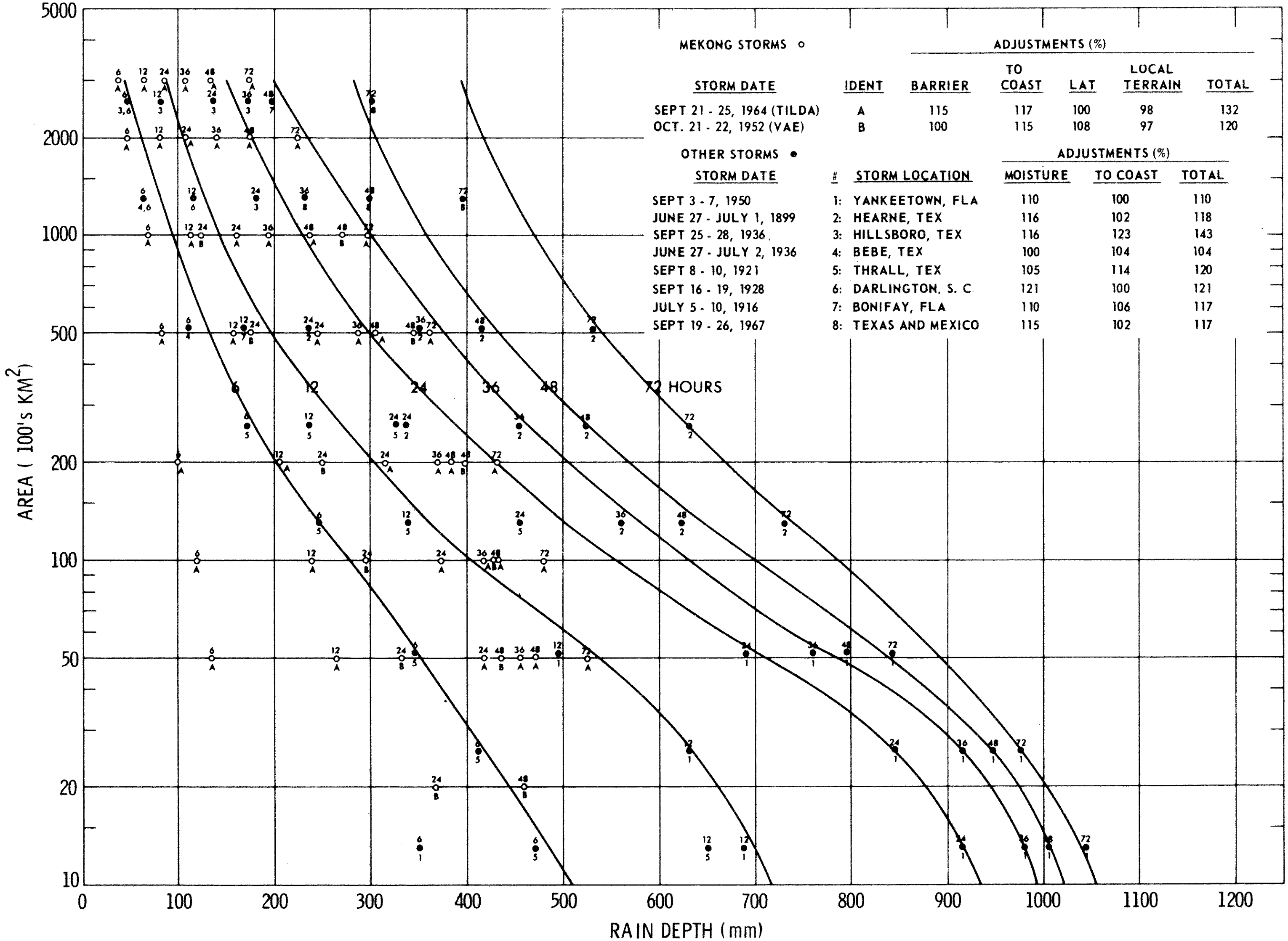

Figure 3-3. Enveloping depth-area curves for the Vietnam coast

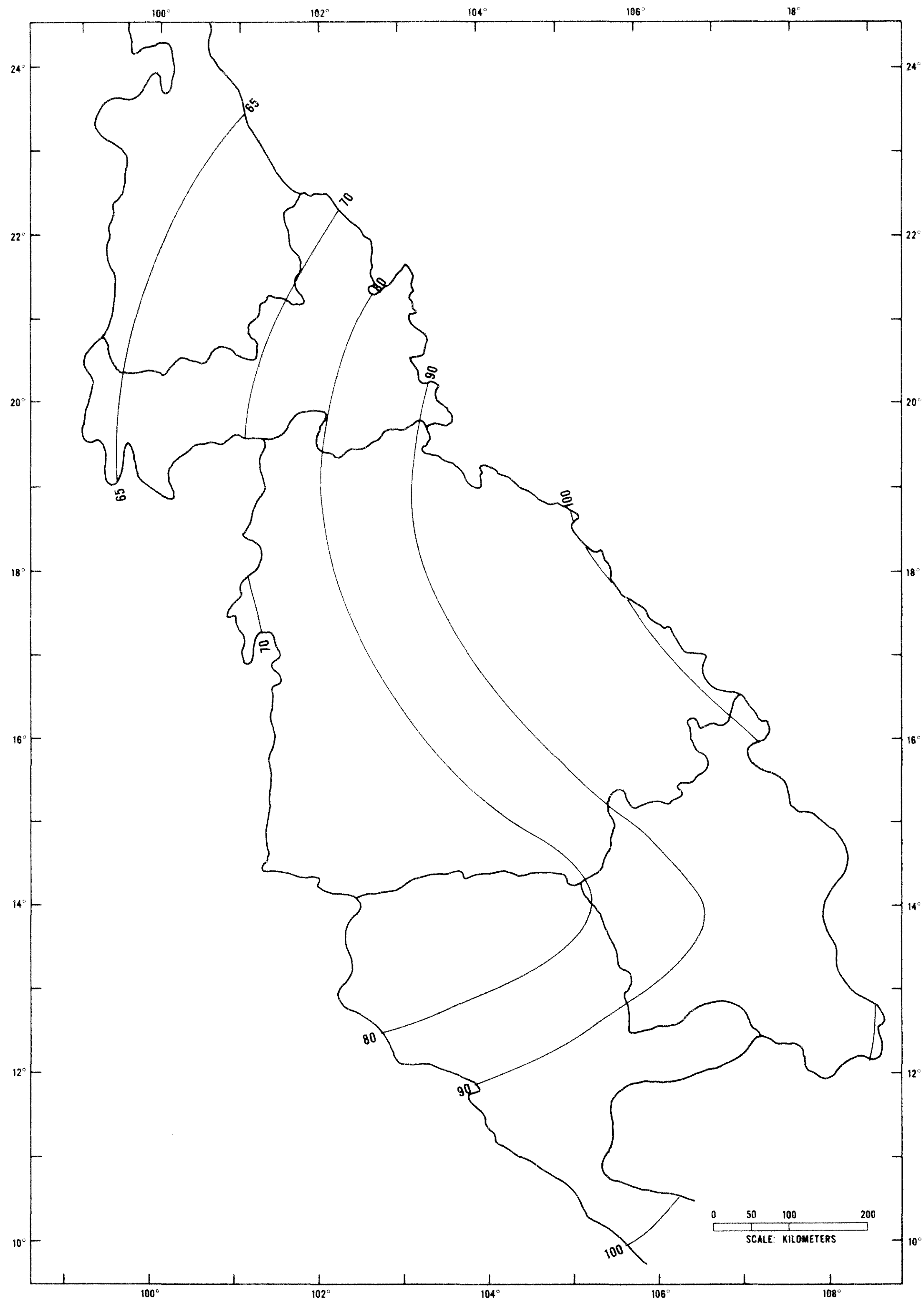

Figure 3-4. Distance-from-coast adjustment of typhoon rainfall (percent of coastal values)

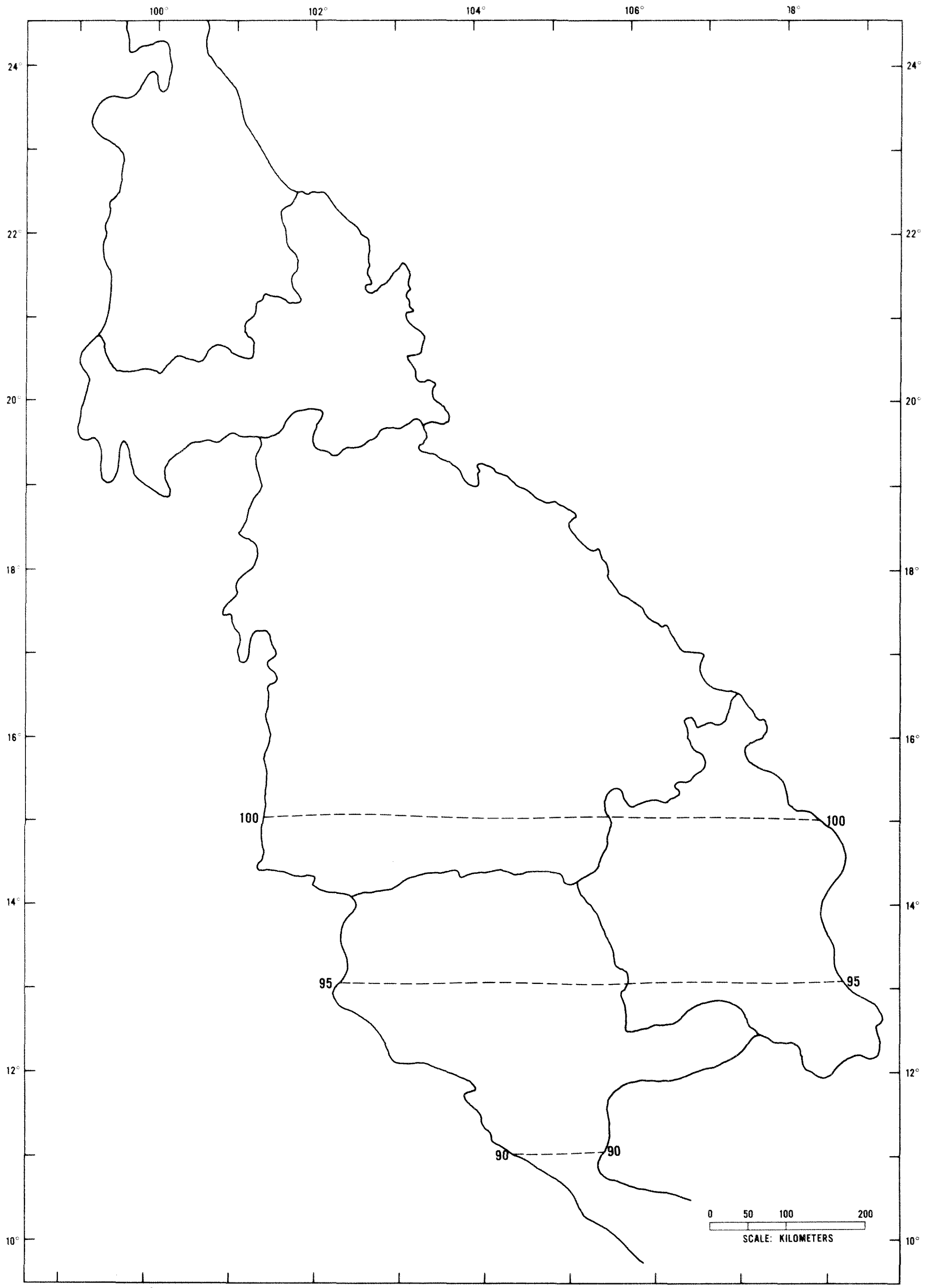

Figure 3-5. Latitude adjustment of typhoon rainfall (percent of values at 15°N)

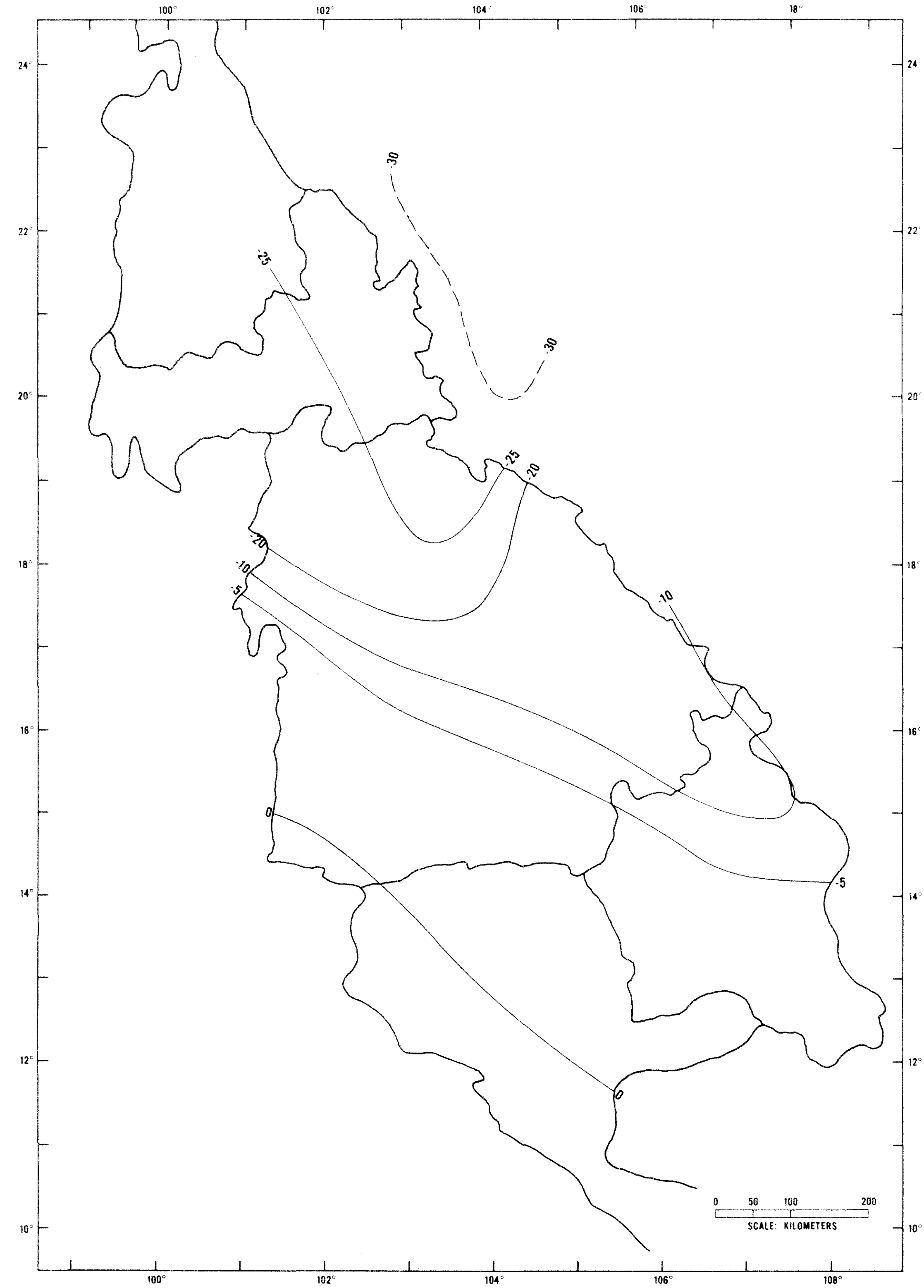

Figure 3-6. Barrier adjustment of typhoon rainfall (percent decrease)

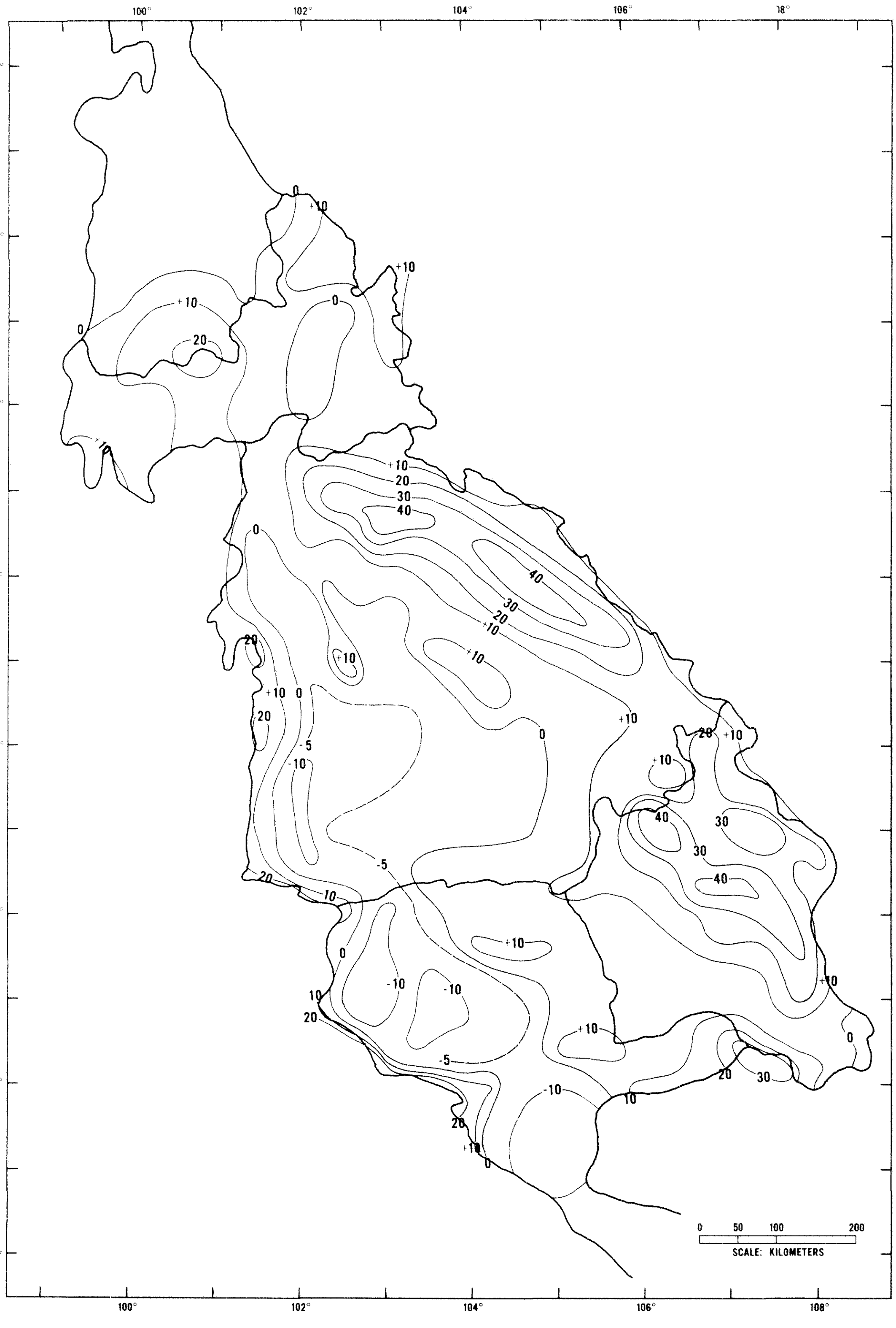

Figure 3-7. Adjustment of rainfall for terrain within basin (percent increase or decrease in values compared to those at low elevation, relatively flat terrain)

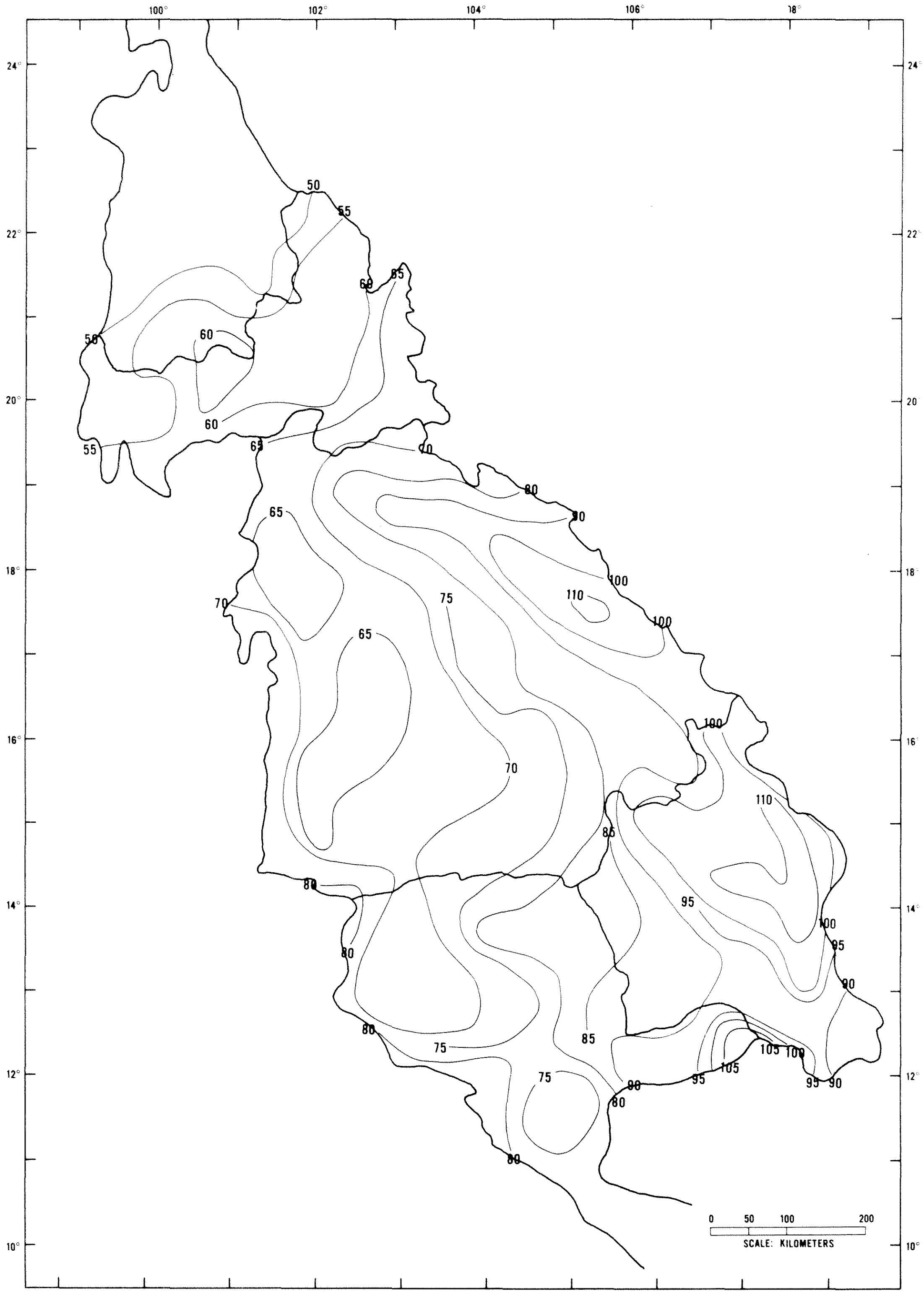

Figure 3-8. Total adjustment (percent) of coastal typhoon rainfall (combined adjustments of figures 3-4 thru 3-7)

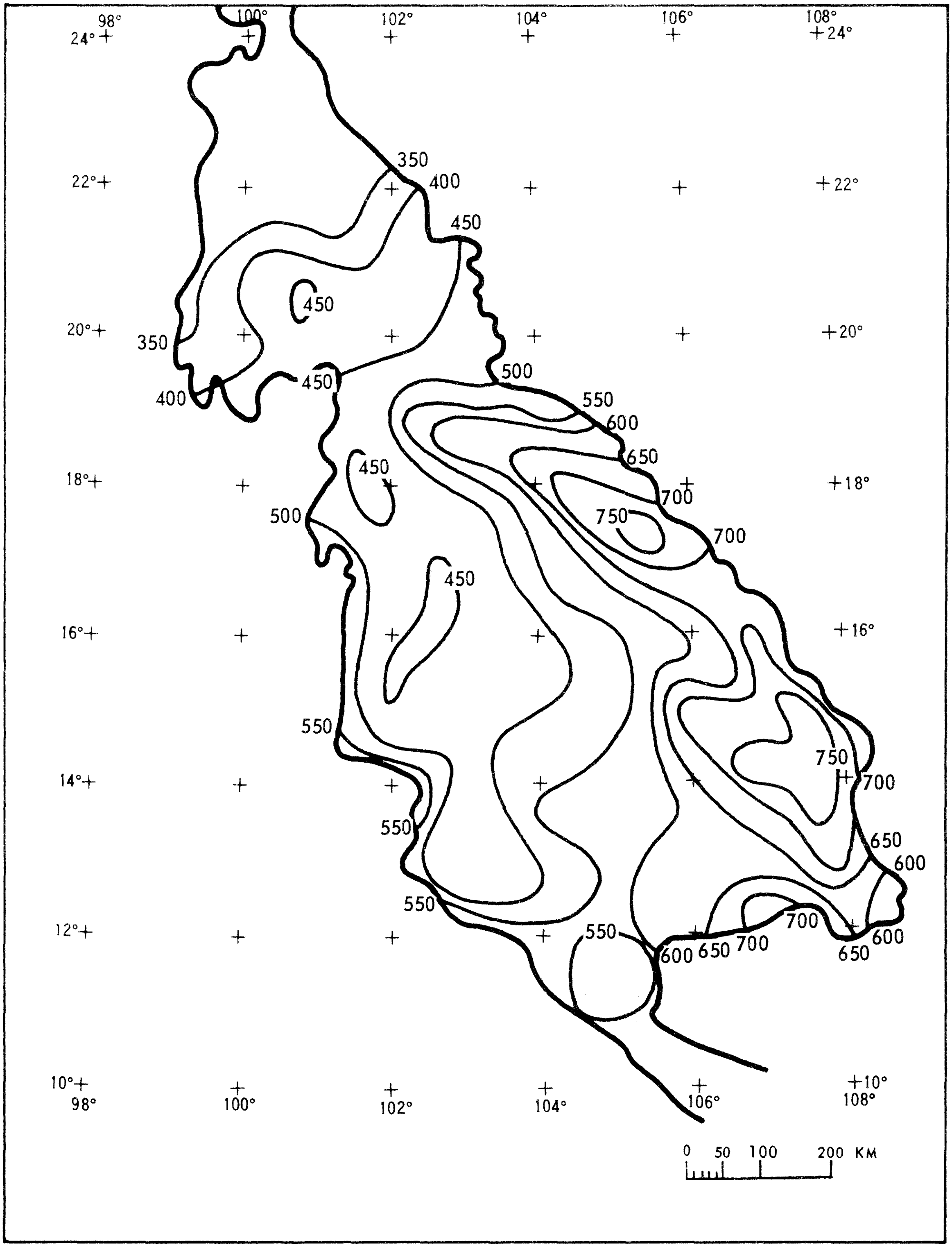

Figure 3-9. 24-hr 5000-km^2 PMP (mm)

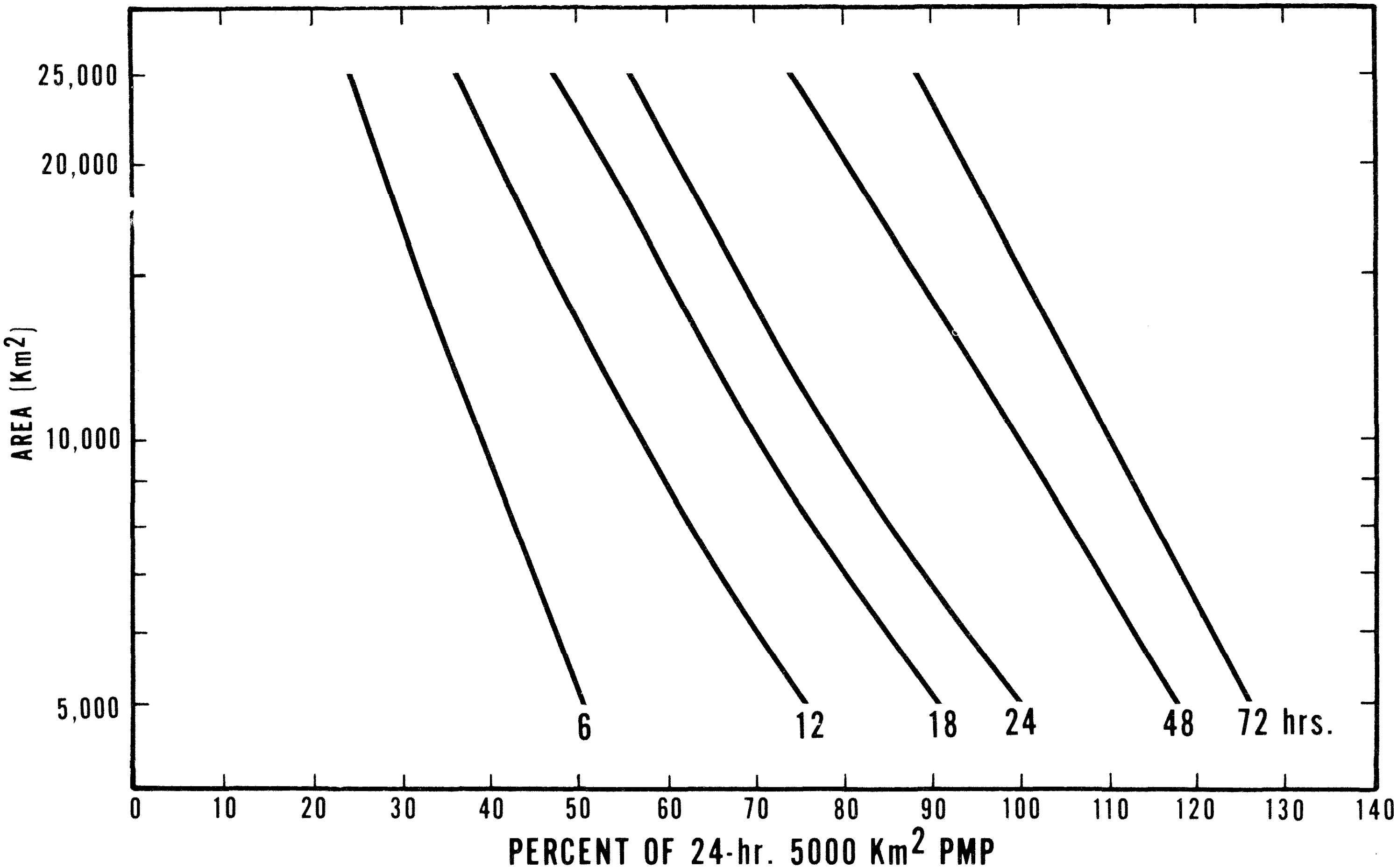

Figure 3-10. Depth-duration-area values of PMP in percent of 24-hr 5000 km^2 PMP (mm)

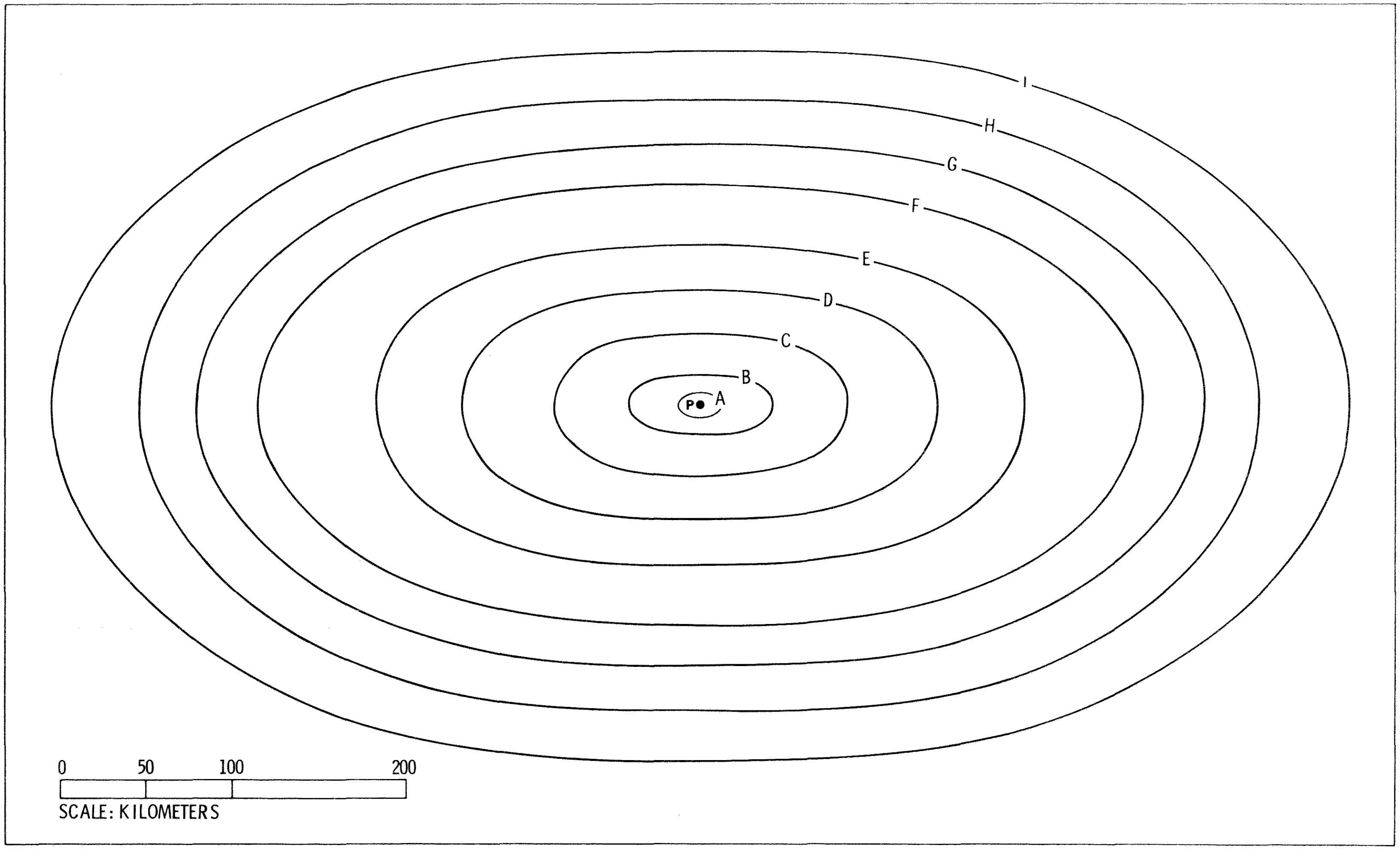

Figure 3-11. Isohyetal pattern for distribution of heaviest 1-day typhoon rain

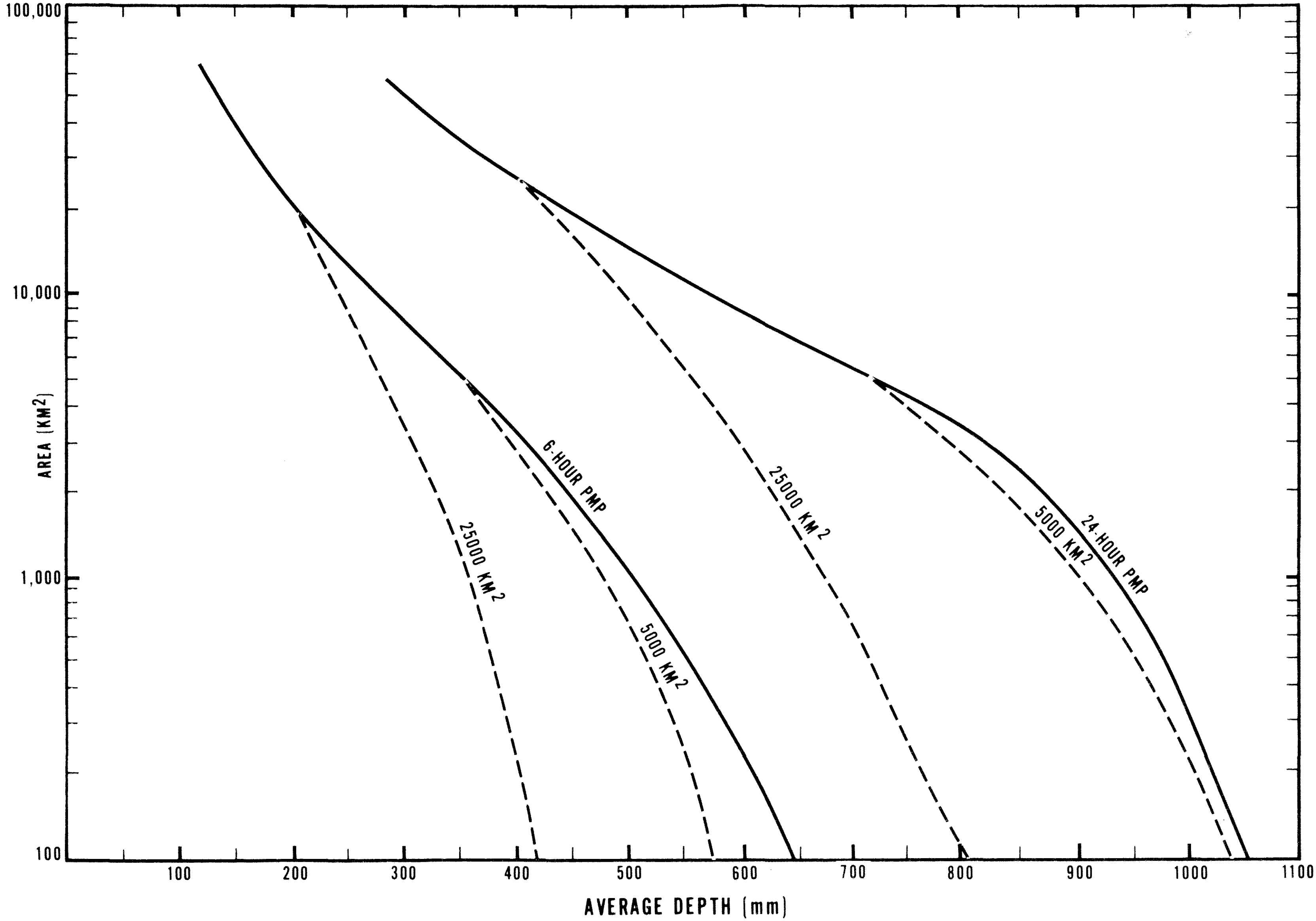

Figure 3-12. PMP (solid lines) and key depth-area curves typical of major storms

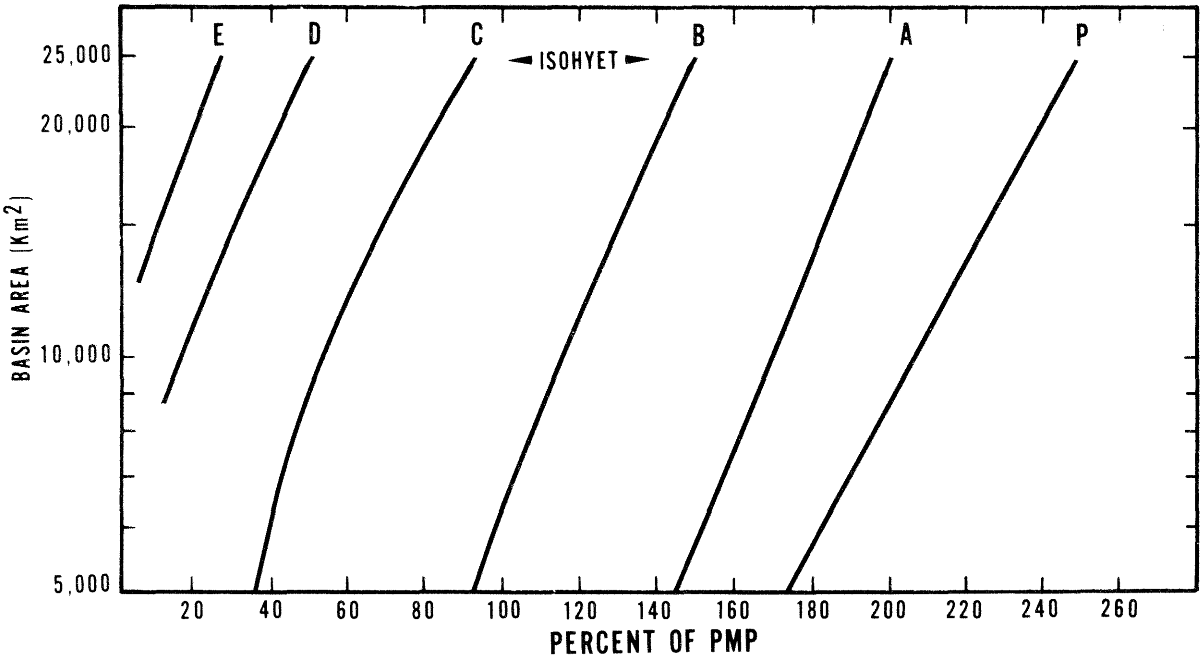

Figure 3-13a. Nomogram for isohyet values, 1st (highest) 6-hr PMP increment

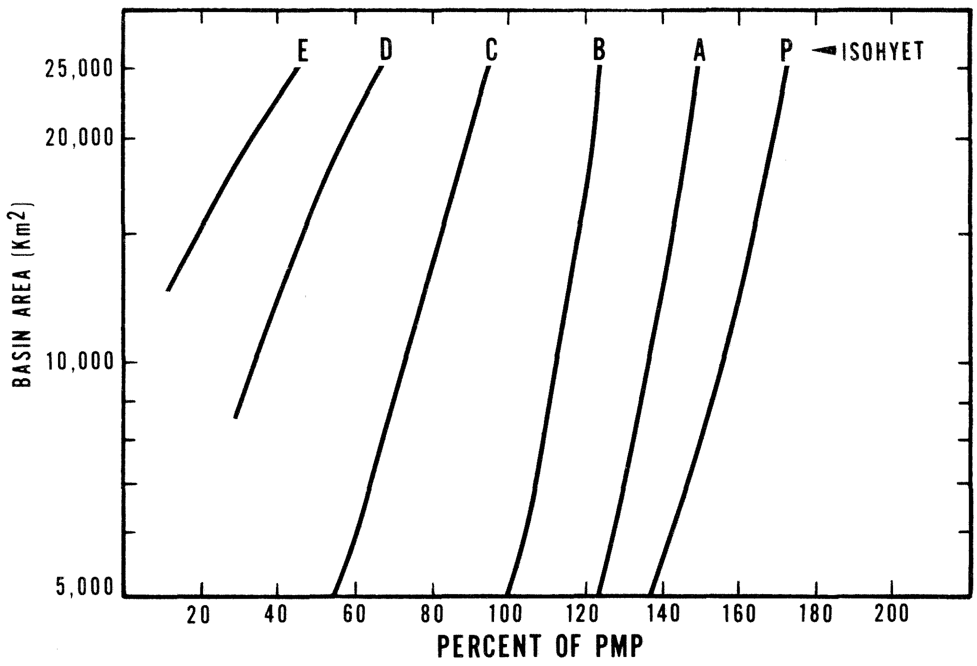

Figure 3-13b. Nomogram for isohyet values, 2d 6-hr PMP increment

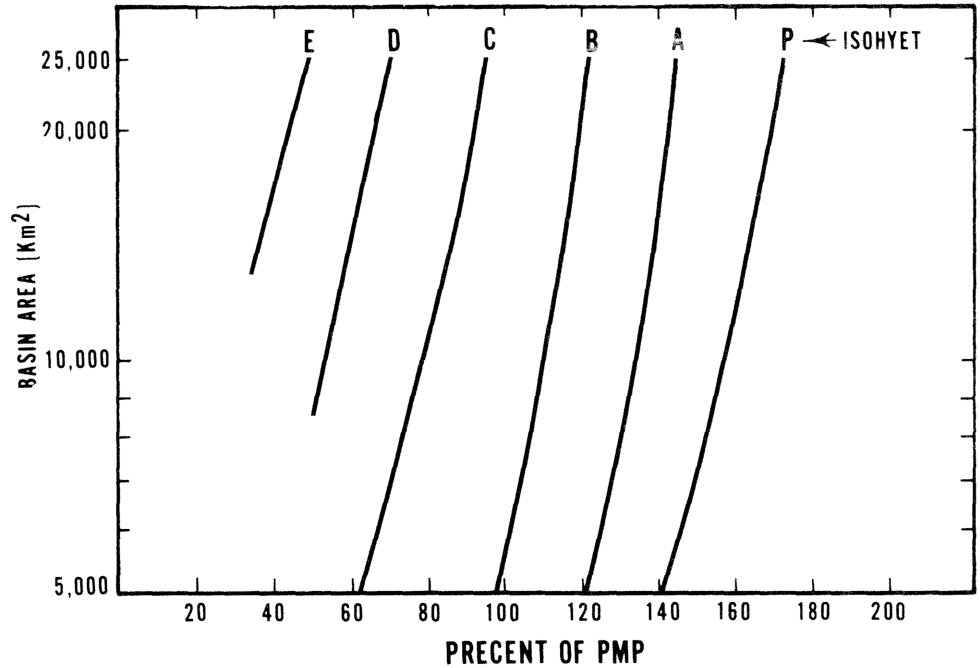

Figure 3-13c. Nomogram for isohyet values 3d 6-hr PMP increment

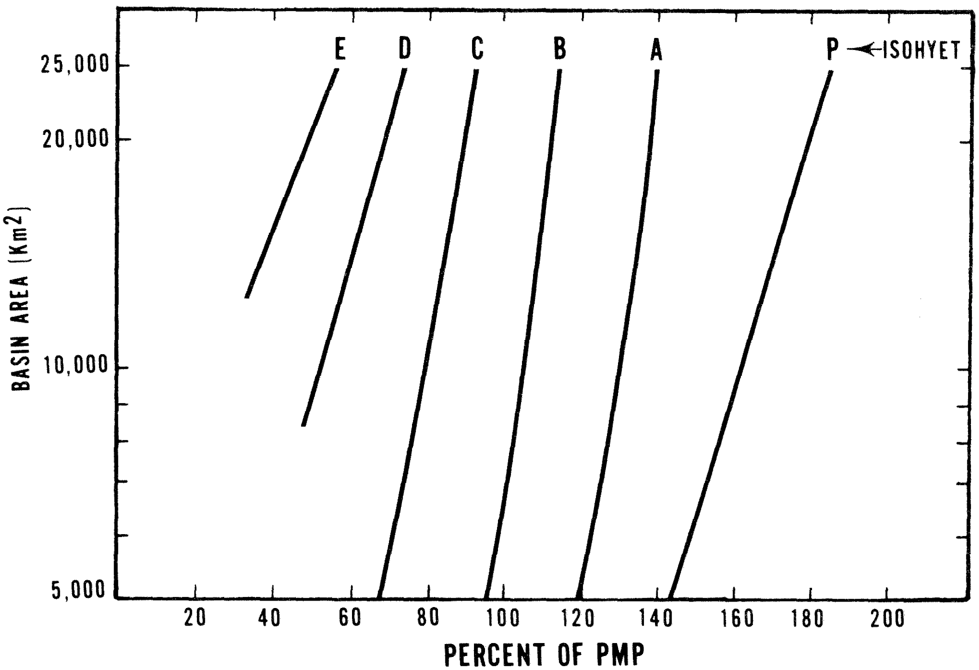

Figure 3-13d. Nomogram for isohyet values, 4th 6-hr PMP increment

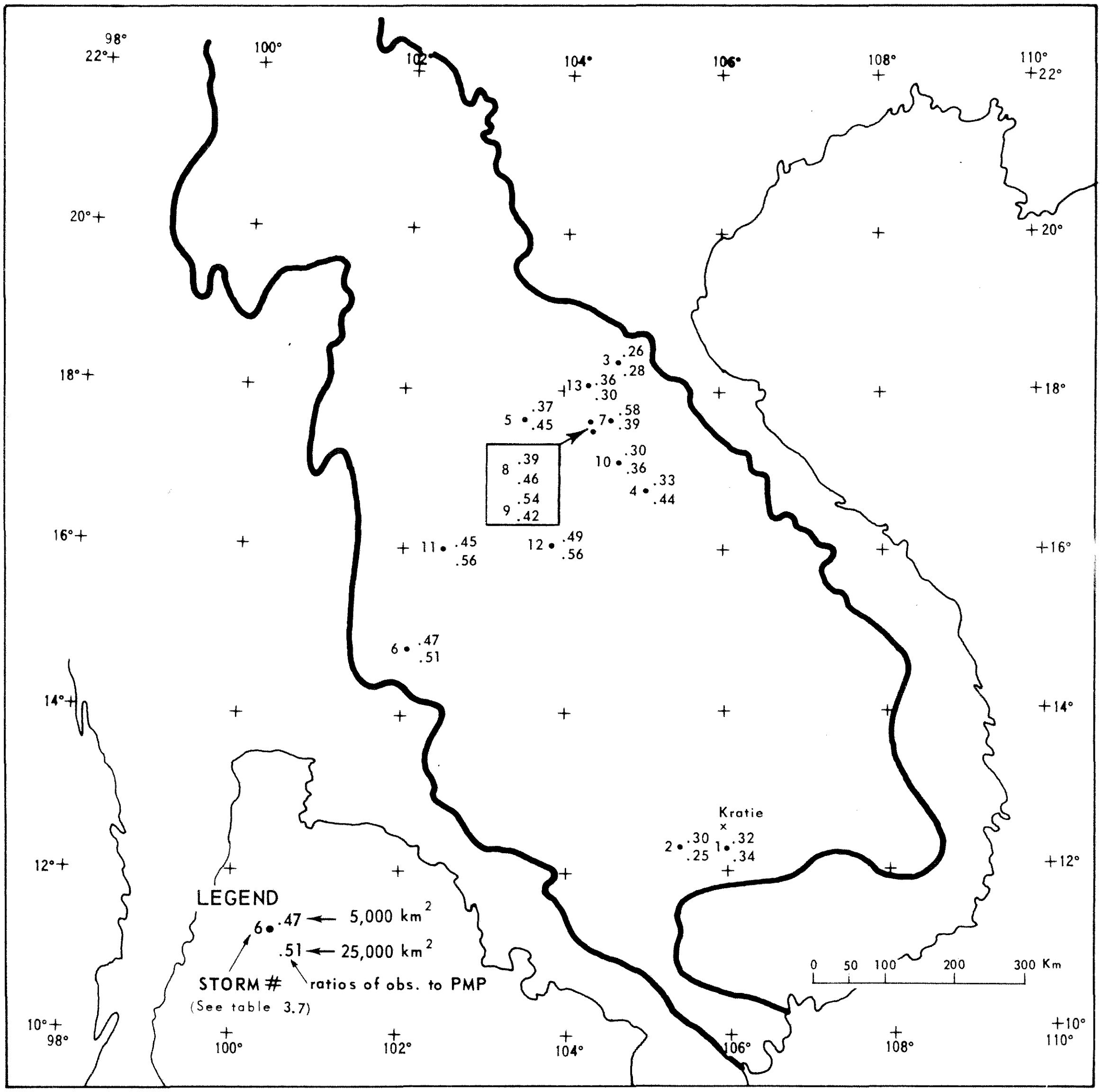

Figure 3-14. Ratios of observed 3-day rain to PMP for 5000-km^2 and 25,000-km^2 areas

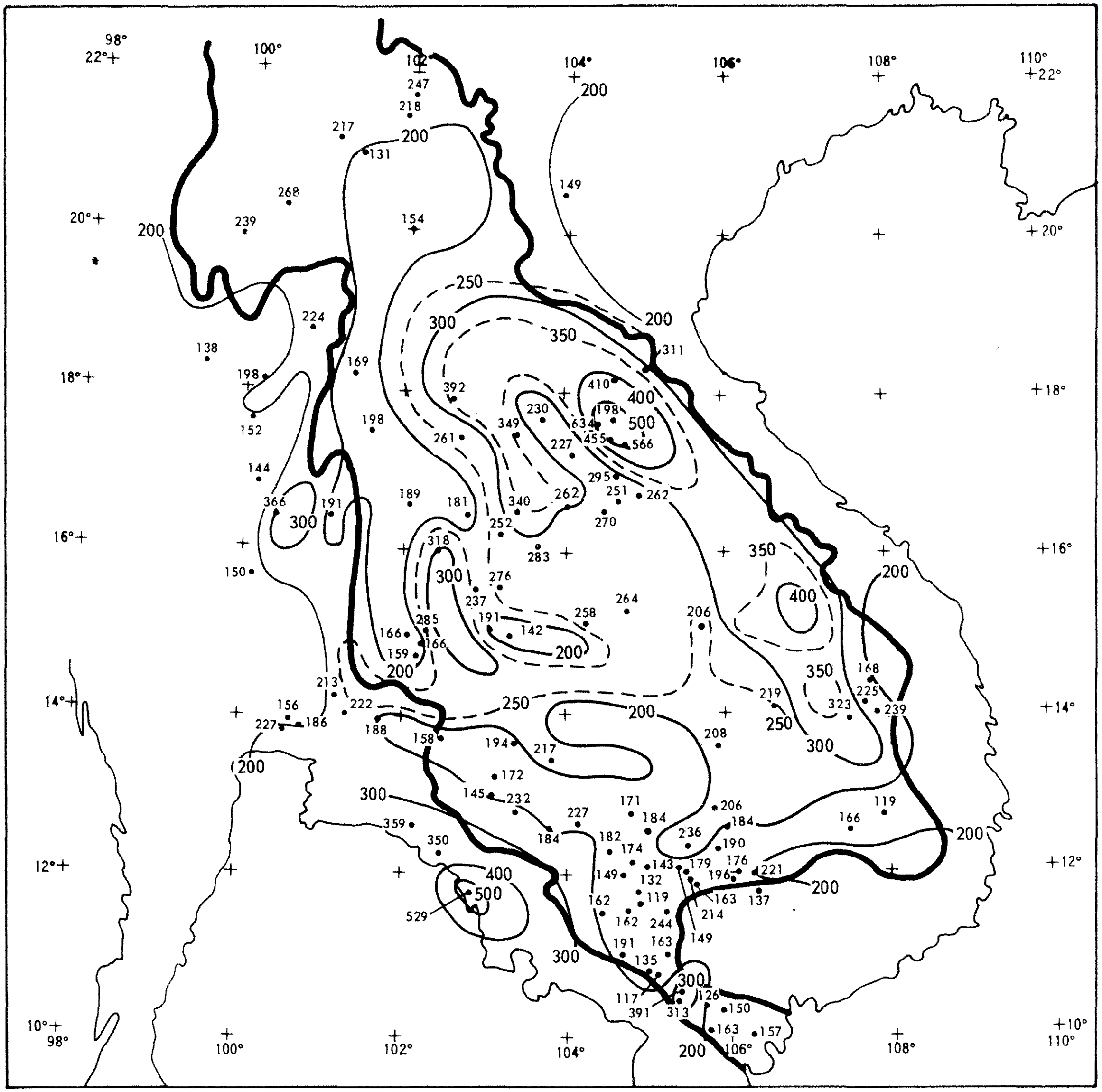

Figure 3-15. 100-year 1-day station rainfall (mm)

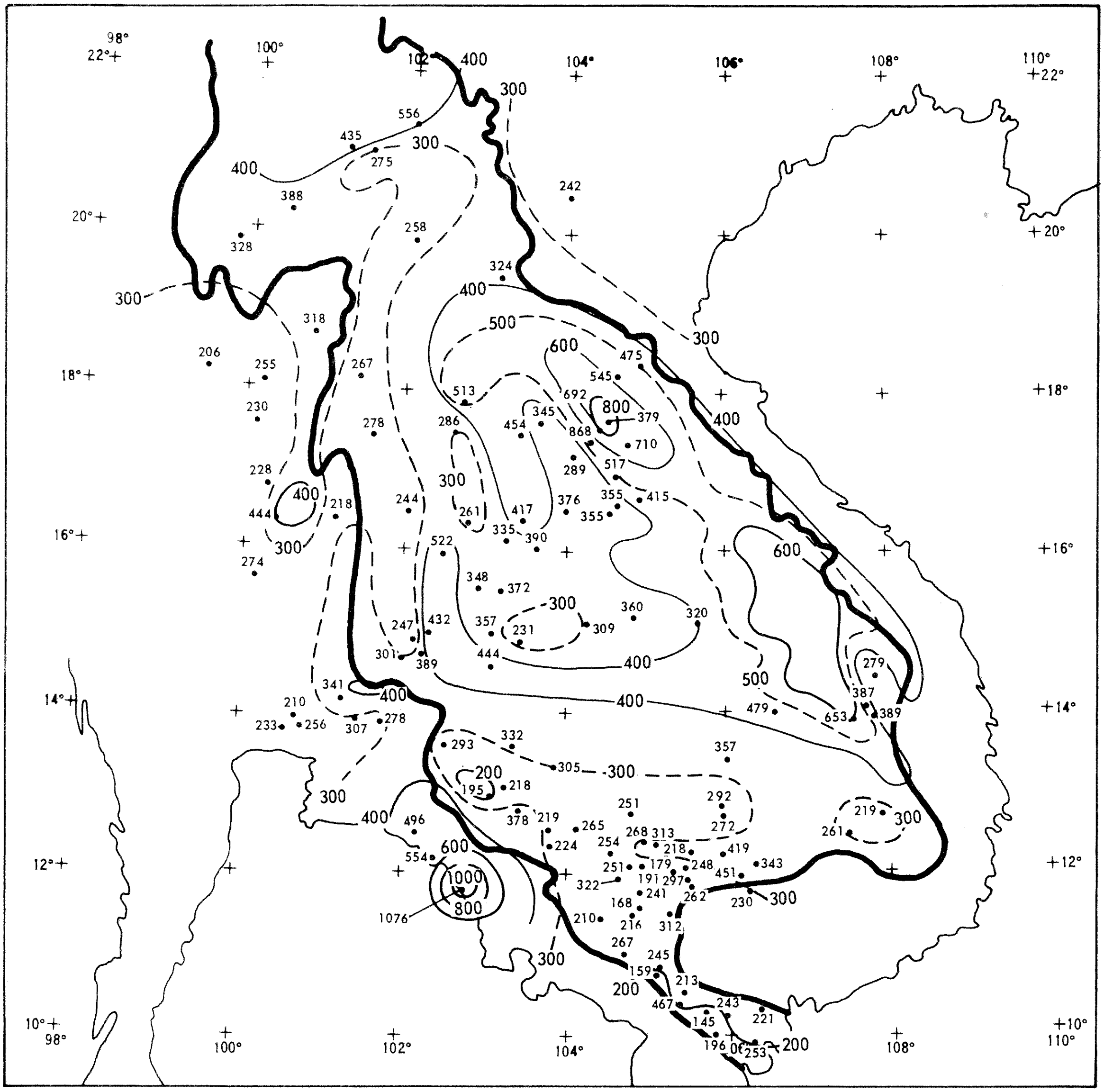

Figure 3-16. 100-year 3-day station rainfall (mm)

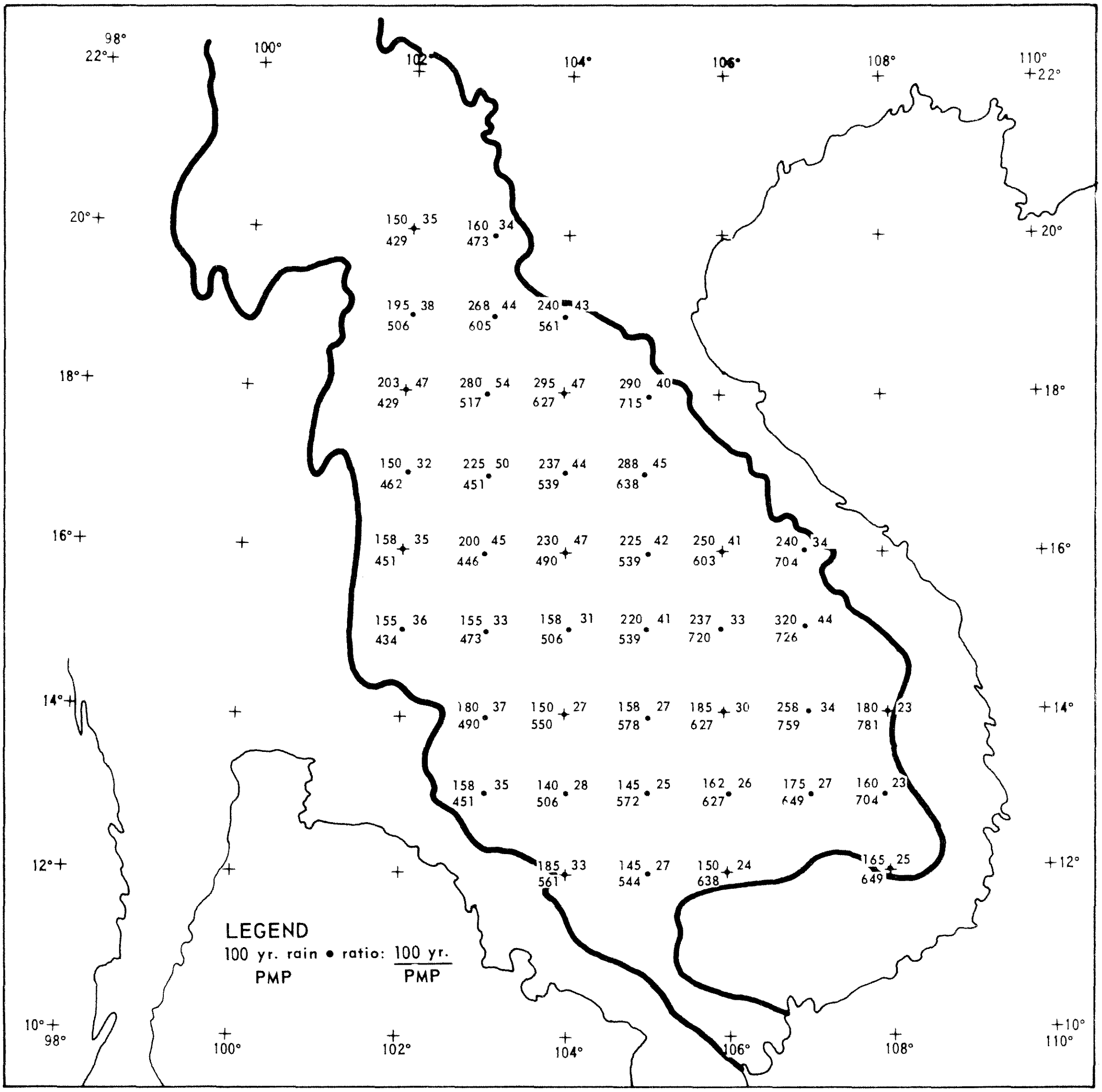

Figure 3-17. Comparison of 100-yr 1-day rainfall (5000 km^2) with PMP

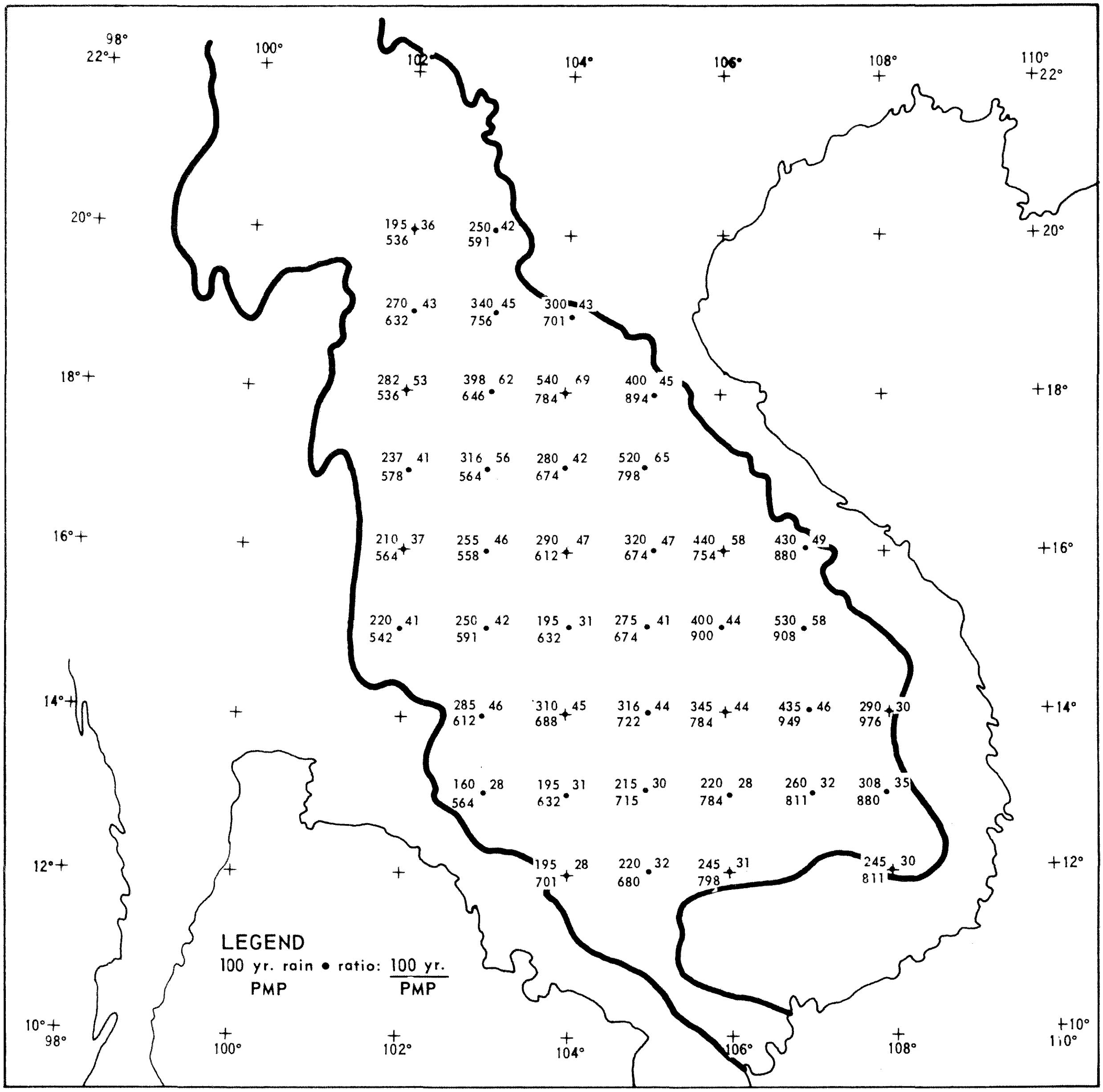

Figure 3-18. Comparison of 100-yr 3-day rainfall (5000 km^2) with PMP

Chapter IV

STORM ANTECEDENT TO THE PMP

Introduction

In developing a critical flood hydrograph from a probable maximum precipitation storm, the initial height of the streamflow is a necessary consideration. A critical antecedent storm prior to the PMP storm can be used to help set this height. The larger the drainage area, the more probable it is to have a sequence of two storms. A close sequence of two storms is particularly important in development of criteria for estimating the probable maximum flood at three sites on the Mekong River (chapter V).

In this section, available data are analyzed to determine the magnitude of an antecedent storm and the time interval between it and the PMP storm.

Intervals between typhoons

Tropical storms are most frequent late in the monsoon season when streamflows are already high and the soil wet. In this situation, then, the greatest threat for high flows on the Mekong River appears to be a succession of tropical storms in September. Storms in close succession are much more common in Southeast Asia than in North America. Study of storm tracks (described below) shows that after a tropical storm passes at latitudes between Luang Prabang and Pakse there is a 1 percent probability of another storm passing with the center within 500 km of the first within 2 days, a 10 percent probability within 4 days and a 20 percent probability within 6 days.

Chin's (2-3) summary of Southeast Asia tropical storms for the period 1884-1953 was used for evaluating intervals between tropical storms. From the track charts in the summary, all instances were tabulated of storms crossing the 110th meridian between 10° and 25°N, that is, across the line shown at 110E on figure 2-2. All crossings of this meridian were westward, i.e., toward the Vietnam coast. There were 115 cases during the 70 years in which intervals of 10 days or less were observed between successive storms. Table 4-1 summarizes the 115 cases by intervals and distance between storms.

The following pertinent conclusions follow from the frequency tabulations of table 4-1.

1. The most frequent interval was 5 days.
2. 14 percent of the cases had intervals of 3 days or less, one-quarter of which (i.e., 4 cases) were occurrences within 111 kilometers of each other.
3. Four cases had intervals of 1 day or less.

Within the Mekong Basin, two of the heaviest typhoon rainfalls of record occurred in a sequence of three storms. Typhoon Tilda's extreme rains, September 21-25, 1964, were preceded by typhoon Violet by about 7 days. A third storm of this sequence developed not far off the coast on September 25.

The rains of October 21-22, 1952, came from one of four tropical storms that crossed the coast in the last half of that month. The average interval between storms was 4 days.

The relative magnitude of the successive storms was not a parameter in the above study. In application, however, the adopted interval needs to be evaluated concomitantly with adopted relative magnitude of storms. The latter is now discussed, followed by an explanation of the recommended criteria.

Rainfall magnitude of successive typhoons

To estimate rainfall potential when two severe typhoons occur, separated by a short interval, is difficult. The presence of one typhoon places no known physical limit on the rainfall of another, say, three days later. We derive empirical guidance from past occurrences of successive typhoon rainfall. The heavier the rain, the more pertinent to the PMP case. Successive light typhoon rainfalls have little bearing on the problem.

Maximum depth-duration-area values obtained from pairs of typhoons that have occurred in a close sequence are used as guides to the rain magnitude of a typhoon antecedent to the PMP typhoon. Such systematic analyses for pairs of typhoons have not been made for the Mekong region. However, there is some information on pairs of typhoons. A quite severe typhoon preceded the Tilda rains of September 21-25, 1964 (Appendix). The prior storm, typhoon Violet, crossed the Vietnam coast the morning of the 15th, moving in a northwest direction. Tilda crossed the coast the morning of the 22d, moving in a direction a little south of west, about 200 km farther north.

An isohyetal map was constructed of Violet's rainfall in the Mekong Basin. Here, rainfall centers of over 190 mm were observed between September 14-17. The ratios of Violet's rains to Tilda's September 21-25 rains, are given in table 4-2. For 6 hours the ratios vary from 0.57 to 0.90. For 48 hours they range from 0.53 to 0.74.

Turning to the United States, where many hurricane and tropical storm rainfalls have been summarized in the form of maximum depth-duration-area values, heavy rain-producing tropical storms with more than 250-mm rainfalls over 51,800 square kilometers (20,000 sq. mi.) and 72 hours duration (4-1) were selected (only 214 mm in one storm). Table 4-3 lists the storms.

Of the storms in table 4-3, only one involved the occurrence of another hurricane within the span of a few days. The first of the pair, July 5-10, 1916, with rain center in northwest Florida, was followed by a hurricane rainfall, July 13-17, 1916, centered at Altapass in the mountains of North Carolina. The 51,800-km^2 72-hr rainfall centered at Altapass, N. C. was 214 mm compared to the 356-mm Florida center (table 4-3), or 0.6 of the first storm.

If the threshold of 250 mm is lowered somewhat, we find an excellent pair of storms for assessing the successive storm problem. This was a pair of hurricanes that occurred along the East Coast of the United States in August 1955, with the rains of each stretching over a distance of nearly 1000 km. Since this sequence of storms affected such a large area, depth-duration-area rainfall values were determined for two separate areas of concentrated rainfall - one centered near 35°N latitude, the other near 42°N latitude. A comparison of the 51,800 km^2 72-hr rains in the two storms at both locations shows that rains of the smaller storm were 0.64 and 0.85 of the larger.

The time between the significant rainfall of the two storms discussed above was approximately 3 days.

Recommended interval and magnitude

Summarizing what we have deduced from the record concerning intervals between typhoons and their rain magnitudes:

1. Storms approaching the Vietnam coast in close succession are much more common than in North America. The most frequent interval between pairs is 5 days. After a tropical storm passage there is a 6-percent probability that another storm will pass within 500 km within 2 days.

2. Evidence on typhoon rainfall magnitudes in the Mekong is based on a limited period of record. Notwithstanding, typhoon Tilda produced rains approaching known world records for some long durations and large areas. Rains from typhoon Violet, preceding Tilda, gave rains approaching Tilda's for some durations.

3. Longer records in North America (where storms are far less frequent) show that, for couplets, one of which gave major rains, the other in the pair has produced up to 0.7 of the greater rain.

In consideration of the evidence, the following sequences and magnitudes of typhoon rainfalls have been adopted for the Mekong Basin.

1. A 3-day interval between storm tracks, with the first or prior storm 50 percent of the 3-day typhoon PMP.

2. A 4-day interval between storm tracks, with the first or prior storm 65 percent of the 3-day typhoon PMP.

A unique feature of a part of this study, namely development of maximum flood peak for sites on the main stem of the Mekong (chapter V) is that the couplet of typhoon rains need not occur over the same sub-area. Indeed, a significant displacement of the storm center may produce a more critical hydrograph.

The recommended time distribution of 3-day rainfall in a typhoon, is to place the heaviest 1-day rain in the middle of the 3-day period (chapter III, section C). This distribution gives one-day interval between the ending of the prior storm and PMP storm with a 4-day track separation. For the 3-day track separation the first day of the PMP storm follows the last day of the prior storm with no intervening days. Table 5-13 gives an example of the two sequences for a beginning date of September 15.

Table 4-1

FREQUENCY DISTRIBUTION OF INTERVALS BETWEEN TROPICAL STORMS

Distance Between Tropical Storms (Degrees of Latitude)*	Interval (Days) 0	1	2	3	4	5	6	7	8	9	10	Total
0-0.50		1		1	2	5	2	1		3	1	16
.51-1.00		1		1	1	2	2	1	2	1	3	14
1.01-1.50			2	1	2	4	1	1	1	3	1	16
1.51-2.00				2	1	2	2	3	4			14
2.01-2.50					5	1	1	2	2			11
2.51-3.00				1	2	3			2	1		9
3.01-3.50					1	1	1			3	2	8
3.51-4.00					1	1		2		1	1	6
4.01-5.00		1	1		1	2					1	6
5.01-6.00			1		1	1			1		1	5
6.01-7.00							1		1	1		3
7.01-8.00					1				1	1		3
8.01-9.00	1			1		1						3
9.01-10.00				1								1
Sums	1	3	4	8	18	23	10	10	14	14	10	115

*The distance is measured perpendicular to the track of the storm that crosses the 110th meridian first. A "degree of latitude" as used here follows common practice in meteorology and is a unit of length on the earth's surface (in any direction) equal to 60 nautical miles (111 km).

Table 4-2

RATIOS OF MEKONG RAINS FROM TYPHOON VIOLET TO THOSE OF TYPHOON TILDA

Area km^2	Duration (hr) 6	12	24	36	48
1000	.68	.46	.46	.52	.53
2000	.75	.49	.47	.52	.55
5000	.82	.52	.48	.53	.55
10,000	.84	.54	.50	.54	.56
50,000	.85	.61	.59	.62	.62
100,000	.90	.67	.73	.75	.69
200,000	.57	.59	.71	.77	.74

Table 4-3

U. S. HURRICANES PRODUCING EXCEPTIONALLY LARGE RAINFALL VOLUMES

Date	51,800-sq. km. 72-hr rainfall (mm)
Aug. 16-21, 1915	313
July 5-10, 1916	356
July 13-17, 1916	214
Sept. 17-21, 1926	261
Sept. 23-28, 1929	267
July 22-27, 1933	315
Sept. 14-18, 1936	264
Aug. 6-9, 1940	320
Sept. 1-7, 1950	343
Sept. 19-26, 1967	470

Chapter V

RAINFALL ESTIMATES FOR PROBABLE MAXIMUM FLOOD AT THREE MAJOR DAM SITES ON THE MEKONG RIVER

The objective of this chapter is to provide rainfall estimates that will produce the probable maximum flood at sites on the main stem of the Mekong River. The three sites and total drainage areas above them are:

Luang Prabang, Laos: 262,000 sq km
Pakse, Laos: 539,000 sq km
Kratie, Cambodia: 646,000 sq km

The drainage areas are shown on figure 1-1.

Approach to the problem

There are important reasons why the usual methods of estimating probable maximum precipitation (PMP) cannot be used alone for estimating the probable maximum flood for the large drainages above sites on the main stem of the Mekong River. Most previous estimates of PMP are for smaller drainages, up to approximately 50,000 km^2, and three days has been a satisfactory longest duration. When larger drainage areas are involved, a succession of lesser storms in strategic positions could result in more critical hydrographs than a single 3-day PMP storm. Hydrologic tests of several different sequences of rainstorms with varying placements and time intervals between the storms in sequence can then be used to select the maximum flood. Development of a computerized hydrologic model of the Mekong by the North Pacific Division of the Corps of Engineers allows flexibility in testing various rainfall combinations and selecting the most critical.

The general procedure for rainfall data used in computing the flood hydrograph is briefly summarized as follows: Rainfalls of selected return periods for May through September, for the drainage above a dam site, are used to build up a fairly rare high-flood hydrograph. At the time this hydrograph is near a peak, rainfall from a pair of critically-placed typhoons, the second one of PMP magnitude for 1 to 3 days duration, is superimposed.

The presentation then can be separated into three main parts. Starting with the available data, station rainfall frequencies for long durations are developed in section A. Using mean rainfall maps of chapter II, the station statistics are transformed to areal rainfall frequencies in section B. Section C then prescribes combinations of areal rainfall frequencies with sequences of two critically-placed typhoon rainfalls that were developed in chapters III and IV.

A. Station Rainfall Frequencies

The objective of this section is to derive frequency distributions of monthly and seasonal rainfalls at stations. We first select an appropriate mathematical form of the frequency distribution. The mean rainfall from chapter II, and one additional parameter will then define the frequency distribution for a particular month or season and station. The selected frequency distribution is the log-normal. The standard deviation of the logarithm of rainfall is, in essence, the second defining parameter. This parameter is converted to an equivalent parameter for convenience, namely the ratio of 100-yr rainfall to mean rainfall. A geographical variation of this ratio is sought but not found.

These point statistics are converted to areal statistics in section B.

The work described in this chapter requires fitting not only monthly and seasonal rainfalls but also streamflow to a standard mathematically-defined probability distribution. For optimum compatibility the same frequency distribution should be used for both rainfall and streamflow. The log-normal distribution was selected for both rainfall and streamflow after tests with several distributions described in this chapter.

Theoretical frequency distributions

Discussion of probability distributions for meteorological and hydrologic analysis is found in papers by Thom (5-1), Remenieras (3-1), Chow (5-2), and Benson (5-3) as well as in standard texts on statistics. Benson's paper summarizes the recommendations of an interagency committee of the U. S. Government on uniform streamflow frequency analysis by departments of that government (5-4). From these papers, theoretical frequency distributions of a continuous variable include the following:

Normal (Gaussian)
Log-normal (Galton, Pearson Type III with zero skew)
Gumbel (Pearson Type I)
Log-Gumbel (Frechet, Pearson Type II)
2-parameter gamma
Pearson Type III
Log-Pearson Type III
Hazen

The Gumbel and log-Gumbel distributions are bypassed on the grounds that they are extreme value distributions, more applicable to the series of maximum daily values each year than to a series of monthly values. The heavier the rainfall and the longer the time unit, the more nearly normal is the distribution of a series of rainfalls (5-1, p. 18). The skewness of the data is judged insufficient to warrant the general form of the Pearson Type III or log-Pearson Type III. Selected for trial fits are the log-normal, which is a particular case of the log-Pearson Type III with a skew coefficient of zero, the normal distribution, and the 2-parameter gamma.

Tests of three distributions

Fit of distributions to highest observed values. For this test, frequency curves were computed using the log-normal, normal, and gamma distributions for the rainfalls at selected stations in the Mekong Basin. Values read from these curves were then compared with the 5 highest observed values at each station. The basis for this test is the assumption that if one of the three distributions consistently comes closest to reproducing the 5 highest observed values it would likewise give the best estimate of the "true" rare rainfall--such as the 100-yr return-period value.

Stations selected for testing are fairly well distributed over the Lower Mekong. While long records are most suitable for testing, an attempt was made to include stations at higher elevations. The 15 selected stations are underlined on figure 5-1. The length of rainfall records varies from 15 to 54 years, averaging 37. Rainfall periods tested were August, September, May through August and May through September.

For each station's rainfall, the normal, log-normal, and gamma frequency distribution curves were computed from readily available computer programs.* The curves were then plotted on frequency charts, along with the 5 highest observed rainfall values at their appropriate plotting positions (assigned frequency). The differences between the observed rains and values read from the frequency curve at the plotting positions were summed. Table 5-1 shows individual differences (for each of the 5 highest observed values) at Phong Saly and Pakse, Thailand.

A summary of the differences for each station is given in table 5-2. Comparisons between the 3 distributions with respect to reproducing the 5 highest rains can be made from the summaries near the end of the table.

The log-normal distribution gave least error (total differences) for August and September rains, while the normal distribution gave the greatest. However for both of the long periods, May-August and May-September, the log-normal has the greatest error, the gamma the least in the first period and the normal the least for the second period.

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*Some difficulty was found in computing the gamma frequency distribution. Where the argument of the gamma function for a particular set of data exceeds a value of 40, frequency values could not be computed. This affected 2 stations for the May-August period and 5 for the May-September period.

Distribution of the errors, plus or minus, is also of interest. The last portion of table 5-2 gives a count of the number of stations where the total of the 5 differences is biased toward the positive (observed higher than computed) and the number of stations where the bias is negative. The log-normal appears to have the least bias and the normal the most. For example, the computed August and September rains from the normal distribution had a positive bias at each of the 15 stations, while the log-normal gave a positive total to 8 and 5 of the 15 stations for these two months, respectively.

In summary, the log-normal distribution showed least error for two periods, and least bias for the four periods.

Frequency estimates based on 1/2 of data. Another test of the three distributions was to compare computed return-period rainfalls using all the data with those using one-half of it. This test provides one measure of the suitability of each distribution as a basis for extrapolating beyond the period of record. While the longest-record stations would be the best for this test, readily available data for the same 15 stations of the earlier test were used.

In general, one-half of the rainfalls, obtained by selecting every other chronological value, quite well reproduce 100-yr return-period values based on all the data. This applies to all three distributions, as shown in table 5-3 where the ratios of 100-yr values using one-half the data to 100-yr values using all the data are summarized. Differences in reproducing the 100-yr value by the three distributions are small. The average ratio for the 15 stations (fewer for the gamma distribution) and the 4 periods departs the least from a ratio of 1.00 for the normal (1.005) and the most for the gamma (0.985) with the log-normal average in between (0.990). The gamma distribution shows the most bias, towards lower 100-yr values, using 1/2 the data. Of the 45 gamma cases, 30 have a ratio less than 1.00.

Choice of frequency distribution. The differences among the three distributions tested are small. The log-normal appeared to have slight advantages in both convenience and goodness of fit to the data in the above tests and was selected as the analysis method for this investigation.

Computation of station rainfall frequencies

Using a log-normal computer program, station-rainfall frequency values were determined for more than 70 stations with 15 or more years of record in the Mekong Basin or to the west in Thailand. The added non-Mekong data gives 19 stations with close to 50 years of record. Locations of stations, along with lengths of record are given in figure 5-1. Outside of Thailand the rainfall records are considerably shorter, averaging 24 years, and are not contemporaneous. Rainfall frequencies were computed for August, September, May through August and May through September; the latter period approximating the normal southwest monsoon rainy season.

Removal of "outliers." Comparisons of computed rain frequencies with the data, showed that one or two "outliers" (extremely high or low observed values) have a great effect on the results. An example is shown in figure 5-2, the frequency plot and computed frequencies for 47 September rains at Chaiyaphum, Thailand. Computations leaving out the two lowest values, 8 and 22 mm, reduced the computed 100-yr return rainfall from 1104 mm to 660 mm. Plots of the September rains for these two low years on maps and comparison with contemporaneous values at nearest stations indicated the low values could be erroneous.

The decision was made to drop low extremes from all stations if they were less than half the next lowest. This is arbitrary, but we believe it eliminates some errors in the data. Extremely low values, even if correct, have too much effect on the computed magnitude of rare frequencies. Beard (5-5, para. 4.07) recognized this and describes a procedure for discounting the effects of low values in frequency analysis of streamflow data. Extremes on the high side are more difficult to exclude, even if they are high in comparison with adjacent stations. An unusually heavy local rain at a station could result in a large difference between adjacent stations. Out of 75 stations with 15 or more years of record (average length 35 years) 26 September values were dropped; 3 high and 23 low extremes. For May-August, there are 71 stations with 15 or more years of record, of which 7 low and 4 high extremes were dropped. It is recognized that this tends to lower frequency values extrapolated beyond the period of record. Attempts to find a geographic variation in 100-yr rainfalls or 100-yr to mean rainfall ratios were the primary reason for dropping extremes. Some outstanding 100-yr values that could not be explained meteorologically, topographically or otherwise, were thus brought more into line with surrounding values.

Lack of geographical variation. Maps of ratios of computed 100-yr to mean station rains did not show consistent variations with features of the terrain or other factors such as latitude or distance from the coastline. Lower rainfall ratios of 100-yr to mean would be expected on or near mountain slopes where topographic control can result in large rainfall values every year. Such regional variations in the ratios are found in North America. This was not evident for the Mekong. In particular localities, such as in the adjoining Mae Nam Chao Phraya drainage of west Thailand, the data indicated somewhat higher ratios of 100-yr to mean on or near slopes than in the relatively flat valley. Data in the Mekong indicated no general organized pattern.

Station average 100-yr to mean rainfall ratios. Lacking a definite geographical pattern, a generalized procedure was used to obtain station average 100-yr to mean rainfall ratios. Computed station 100-yr values were plotted against station mean rains for each duration considered. Figures 5-3 through 5-6 display the respective plots for May through August, May through September, August and September rainfalls. The average of the ratios of 100-yr to mean station rainfall was computed for each set. In addition, the average ratio was computed after both the 100-yr and mean rainfall values for each station were weighted by the number of years of record. These and the adopted ratios are tabulated in table 5-4.

2-yr to mean rainfall ratios. Accepting the log-normal distribution, the distribution of rainfall is slightly skewed, with the median (2-yr value) less than the mean of a series of annual values. Mean ratios of median to mean were calculated from the 70 station frequency distributions and are listed in table 5-5. These range from 0.92 for September to 0.97 for the May-September season. For monthly streamflows the ratio of median to mean averaged 0.98 for several gages on the Mekong (August and September).

The rainfall ratios are adjusted to areal values in the next section of the chapter and are used to derive 2-yr values from mean values.

B. Areal Rainfall Frequencies

A first step to deriving areal rainfall frequencies was to divide the Mekong drainage above Kratie into six subbasins, each with a stream gage at the lower end of the subbasin, figure 5-7. The three dam sites under study, Kratie (Sambor), Pakse, and Luang Prabang, are at the lower ends of three of these subbasins. Monthly and seasonal rainfall frequencies over five of the subbasins are derived by statistical reduction of the generalized point ratios of 100-yr to mean rainfall from section A of this chapter. Frequencies of rainfall averaged over a combination of subbasins, for example, the entire drainage from Chiang Saen to Kratie, are also derived by a repeated application of the same statistical procedure.

Rainfall correlation-distance relations

Areal rainfall frequencies may be calculated from point rainfall frequencies if we can describe the correlation of rainfall at pairs of stations within the area as a function of the distance between the stations. Here we derive such correlation-distance curves empirically, figures 5-8 and 5-9. The statistical reduction procedures to which the curves are applied are explained in later paragraphs.

Monthly correlation-distance relation. The curve of figure 5-8 is an empirical average of the correlation of monthly rainfalls during the monsoon season at pairs of stations in the portion of the Mekong Basin making the largest contributions to streamflow. The correlation decreases from 1.0 at zero distance to about 0.2 at several hundred kilometers. The curve is derived as follows.

August and September rainfalls and logarithms of rainfall at two long-record stations, Chiang Rai and Ubon Ratchathani, Thailand (fig. 5-1 shows locations) were correlated with corresponding data for other selected stations out to several hundred kilometers. Priority was given to longer record stations. Various plots of the correlation coefficients showed:

1. Correlation decreases with distances between stations.
2. Log correlations average higher than correlations of rainfall.
3. No difference between August and September.
4. No definite difference between the Chiang Rai set and the Ubon Ratchathani set.
5. A geographical pattern with somewhat higher correlations to the north and east of the key stations than to the south and west.

The geographical pattern is interpreted as indicating higher association of rainfall at equal distances in the mountainous regions than in the lowlands of Thailand. This is not surprising. A possible explanation is that, in the mountains, the rainfall is more related to the direction and strength of the general wind flow, while random elements are more influential in the lowlands. In view of this, to establish a correlation-distance relation applicable to the subbasins of figure 5-7, a NW-SE line was constructed through each of the two key stations. Log correlations between stations north of this line and the key station are listed in table 5-6. The averages of the August and September correlations are also listed. These averages are plotted against distance in figure 5-8, for both stations, and a curve fitted by eye. 90-percent confidence bands, indicated by vertical lines thru the points on figure 5-8, are placed around the correlation coefficients from chart I of (5-6). The sum of the number of years of record for August and for September is the sample size for this operation.

The composite eye-fitted curve is adopted for all evaluations of R (defined after equation (9)) for periods of one month.

Seasonal correlation-distance relation. Seasonal rainfalls at pairs of stations in the Mekong region are less well correlated than monthly rainfalls. Table 5-6 shows a comparison.

Correlations of the logarithm of the total rainfall for the period May through August are not significantly altered by adding September to the season, table 5-6. Correlations for the May-August and May-September periods are therefore averaged in the table to obtain a degree of smoothing. These seasonal correlations average 46 percent of the monthly correlations. To obtain the seasonal correlation-distance relation, the monthly curve is reduced to 46 percent of its magnitude from about 150 kilometers out and smoothed into 1.0 at zero distance, figure 5-9.

Correlation method

The correlation method of estimating return-period rainfalls over subbasins makes use of the theory of the variance of means, expressed as follows:

$$\sigma_A^2 = \left\{ \sum_{K=1}^{K=N} \sum_{L=1}^{L=N} \sigma_K \, \sigma_L \, r_{K,L} \right\} \frac{1}{N^2} \qquad (1)$$

In our application here we interpret σ_A^2 as the variance of the logarithm of mean rainfall at N stations; 1 through N are the serial numbers of the stations; σ_K and σ_L are the standard deviations of the logarithms of the individual station rainfalls and $r_{K,L}$ is the linear correlation coefficient between the logarithm of the rainfall at station K and at station L.

Example of variance of mean of three station values. Expansion of equation (1) for N=3 is now given as an illustration.

$\sigma_1, \sigma_2, \sigma_3$ = standard deviation of values at stations 1, 2, and 3.

σ_A = standard deviation of mean of three station values.

σ_A^2 = variance of mean of three station values.

$r_{1,2}$ = linear correlation coefficient between values at station 1 and station 2.

Expanding (1),

$$\sigma_A^2 = \frac{1}{9} \Big\{ \sigma_1\sigma_1 r_{1,1} + \sigma_1\sigma_2 r_{1,2} + \sigma_1\sigma_3 r_{1,3} + \sigma_2\sigma_1 r_{2,1} + \sigma_2\sigma_2 r_{2,2} + \sigma_2\sigma_3 r_{2,3} + \sigma_3\sigma_1 r_{3,1} + \sigma_3\sigma_2 r_{3,2} + \sigma_3\sigma_3 r_{3,3} \Big\} \qquad (2)$$

But since $r_{1,1} = 1.0$; $r_{2,2} = 1.0$; $r_{3,3} = 1.0$;

$r_{1,2} = r_{2,1}$, etc.,

(2) becomes

$$\sigma_A^{\ 2} = \frac{1}{9}\left\{\sigma_1^{\ 2} + \sigma_2^{\ 2} + \sigma_3^{\ 2}\right.$$

$$\left. +2(\sigma_1\sigma_2 r_{1,2} + \sigma_1\sigma_3 r_{1,3} + \sigma_2\sigma_3 r_{2,3})\right\} \qquad (3)$$

<u>Standardizing for subbasins.</u> To estimate return-period rainfalls for the subbasins of about 100,000 km^2 or less (fig. 5-7) by application of equation (1), the procedure is as follows. The subbasin is treated as if it were a square divided into 16 equal subsquares shown schematically in figure 5-10. Each square is considered as a "station." Applying equation (1), N=16, and there are 256 terms within the bracket on the right side of the equation. To simplify this, we first assume that the standard deviation of the logarithm of individual station rainfall, σ_K or σ_L, is sufficiently uniform throughout the subbasin that we may substitute a mean value. Thus equation (1) becomes

$$\sigma_A^{\ 2} = \frac{\sigma_S^{\ 2}}{N^2}\left\{\sum_{K=1}^{K=N}\ \sum_{L=1}^{L=N} r_{K,L}\right\} \qquad (4)$$

where σ_S is the average of the individual station standard deviations of logarithm of rainfall, as estimated from the available data. This is accepted as an approximation to σ for subsquares.

The second simplifying assumption is that r is a function of distance between centers of subsquares only, and may be scaled from figure 5-8 or 5-9. Thus, of the 256 r's, those pertaining to equal distances may be grouped as single terms. This grouping leads to

$$\sigma_A^{\ 2} = \frac{\sigma_S^{\ 2}}{Q^4}\left\{4\sum_{K=1}^{K=Q-1}\ \sum_{L=1}^{L=Q-1} KLr_{\sqrt{(Q-K)^2 + (Q-L)^2}\,\Delta}\right.$$

$$\left. + 4\sum_{L=1}^{L=Q-1} QLr_{\sqrt{(Q-L)^2}\,\Delta} + Qr_0\right\} \qquad (5)$$

Here, Q is the number of subsquares along one side of the square subbasin (Q=4 in the example above), and Δ is the length of the edge of a subsquare:

$$\Delta = \sqrt{A}/Q \qquad (6)$$

The subscript to r refers to distance on the empirical correlation decay relationship. r_0 is the value of correlation coefficient at distance 0 and is identically equal to 1.0.

The correlation r, changes rapidly at short distances (figs. 5-8 and 5-9). For added precision at short distances the middle term on the right side of equation (5) is separated as follows:

$$4 \sum_{L=1}^{L=Q-1} QLr_{(Q-L)\Delta} = 4 \sum_{L=1}^{L=Q-2} QLr_{(Q-L)\Delta} + 4Q(Q-1)r_{\Delta} \qquad (7)$$

Here r_{Δ} is the correlation of rainfall between adjacent subsquares. These are divided into quarter squares, figure 5-11, and r_{Δ} assigned the average value of the 16 correlations that can be formed between the 4 quarter squares of one subsquare and the 4 quarter-squares of its neighbor. This gives

$$r_{\Delta} = \frac{2}{16} \left\{ r_{0.5\Delta} + r_{\sqrt{0.5}\Delta} + 2r_{\Delta} + r_{1.5\Delta} + 2r_{\sqrt{1.25}\Delta} + r_{\sqrt{2.5}\Delta} \right\} \qquad (8)$$

For Q=4, substituting (8) in (7) and (7) in (5), and averaging certain terms, equation (5) becomes

$$\sigma_A^{\;2} = \frac{\sigma_S^{\;2}}{64} \left\{ r_{4.24\Delta} + 18r_{3.04\Delta} + 20r_{2.14\Delta} + 11r_{1.43\Delta} + 4r_{1.06\Delta} + 3.8r_{0.71\Delta} + 4.6r_{0.50\Delta} + 1.6 \right\} \qquad (9)$$

For convenience, we symbolize 1/64 times the expression within the brackets of equation (9) by R. This is a mean weighted correlation coefficient.

Thus

$$\sigma_A^{\;2} = \sigma_S^{\;2} R; \quad \sigma_A = \sigma_S \sqrt{R} \qquad (10)$$

<u>Frequency equation</u>. Before applying equation (10) we transform σ for convenience. Here we will treat "100-yr" or .01 probability values of a variate. The same procedure applies at any probability level. Chow's (5-2) generalized frequency equation is

(11)

where z is any variable treated statistically, the bar indicates the mean value over the series of items, and the subscript 100 indicates the "100-yr" or .01 probability value of z, if z is an annual series. K_{100} is a frequency factor depending on the form of the frequency distribution assumed. In our application we assume that the logarithm of rainfall, y, is distributed normally for any station (section A of chapter). Therefore,

$$y_{100} = \bar{y} + K_{100}\,\sigma_y \qquad (12)$$

where K_{100} is the appropriate value from tables for the normal distribution. The same equation applies to the logarithm of subbasin average rainfall

$$(y_{100})_A = \bar{y}_A + K_{100}\,(\sigma_y)_A \qquad (13)$$

where the subscript A indicates subbasin values. Averaging equation (12) over the subbasin

$$\overline{y_{100}}^{A} = \bar{\bar{y}}^{A} + K_{100}\,\overline{\sigma_y}^{A} \qquad (14)$$

Here $\overline{\quad\quad}^{A}$ symbolizes averaging over area and $\overline{\quad\quad}$ averaging over a series of items (i.e., over time).

But $\overline{\sigma_y}^{A}$ is σ_S of equation (10). Substituting (10) in (14),

$$\overline{y_{100}}^{A} = \bar{\bar{y}}^{A} + K_{100}\left\{\frac{\sigma_A}{\sqrt{R}}\right\} \qquad (15)$$

where σ_A is the same as $(\sigma_y)_A$. Eliminating this between (15) and (13),

$$(y_{100})_A = \bar{y}^{A} + K_{100}\left\{\frac{\overline{y_{100}}^{A} - \bar{\bar{y}}^{A}}{K_{100}}\right\}\sqrt{R} \qquad (16)$$

At this point we revert to the rainfall, x, instead of logarithm of rainfall, y, and (16) becomes

$$\log(x_{100})_A = \log \bar{x}^{\,A} + \sqrt{R}\left\{\overline{\log x_{100}}^{\,A} - \overline{\overline{\log x}}^{\,A}\right\} \tag{17}$$

Tests with the particular data in use show that substitution of $\log \bar{x}$ for $\overline{\log x}$ on the average produces an error of 1.5% and substituting $\log \bar{x}^A$ for $\overline{\log x}^{\,A}$ gives a smaller error. With these approximations (17) becomes

$$\log\ (x_{100})_A = \log \bar{x}_A + \sqrt{R}\left\{\log \overline{x_{100}}^{\,A} - \log \bar{x}^{\,A}\right\} \tag{18}$$

which may also be written

$$\frac{(x_{100})_A}{\bar{x}_A} = \left\{\frac{\overline{x_{100}}^{\,A}}{\bar{x}^{\,A}}\right\}^{\sqrt{R}} \tag{19}$$

or approximately,

$$\frac{(x_{100})_A}{\bar{x}_A} = \overline{\left\{\frac{x_{100}}{\bar{x}}\right\}}^{\,A\ \sqrt{R}} \tag{20}$$

Equation (20) is the calculating formula in this study to derive basin 100-yr values from station data. The corresponding formula applies to other frequency levels. We also use

$$\frac{(x_2)_A}{\bar{x}_A} = \overline{\left\{\frac{x_2}{\bar{x}}\right\}}^{\,A\ \sqrt{R}} \tag{21}$$

to calculate 2-yr or median basin rainfall.

<u>Rainfall frequencies for individual subbasins</u>

2-Yr and mean rainfalls are listed for several time periods in table 5-7 for the following subbasins (fig. 5-7): A. Pakse to Kratie; B. Thakhek and Ubon Ratchathani to Pakse; C. Above Ubon Ratchathani; D. Luang Prabang to Thakhek; E. Chiang Saen to Luang Prabang; F. Above

Chiang Saen. 100-yr rainfalls are listed for all except the last subbasin. Also listed are the ratios of 2-yr and 100-yr values to the mean. In the procedure described below, the ratios are derived first and, multiplied by the means, yield the 2-yr and 100-yr values.

Mean rainfall, $(\bar{x})_A$. Mean subbasin rainfalls in table 5-7 are scaled from figures 2-8, 2-10, and 2-11. The May-July values are obtained by subtracting September and August from May-September totals.

2-yr rainfall, $(x_2)_A$. Having accepted that the logarithm of rainfall tends to be normally distributed, the frequency distribution of rainfall itself tends to be skewed, with median, or 2-yr, value slightly less than the mean. That is, $(x_2)_A \,/\, \bar{x}_A$ is slightly less than 1.0. Values of this ratio are calculated from equation (21) and listed in table 5-5 for several time periods for a standardized 100,000 km^2 basin.

In this application of equation (21), the weighted correlation coefficient, R, is calculated as defined after equation (9), with the respective r's scaled from the curves of figure 5-9 (upper curve for August and September, lower curve for combinations of months). $\overline{x_2/\,\bar{x}}^{A}$ is the average of $x_2/\,\bar{x}$ at 70 stations, as explained in section A of this chapter.

The 2-yr/mean ratios from table 5-5 are carried over to tables 5-7 and 5-8, with subjective smoothing and adjustment to other basin sizes.

Multiplication of the mean by the 2-yr/mean ratio on each line of tables 5-7 and 5-8 yields the 2-yr value.

100-yr rainfall, $(x_{100})_A$. 100-yr rainfalls are calculated for the various subbasins in table 5-7 by application of equation (20) in the same manner as explained above for 2-yr values. Here $\overline{x_{100}/\,\bar{x}}^{A} = 2.5$ for August, 2.6 for September, 1.8 for May-August, and 1.7 for May-September, from section A.

These ratios are derived entirely from Lower Basin data and are therefore not applied to the Upper Basin in Mainland China where there is no assurance climatological factors are the same.

Alternate to rainfall frequencies for drainage above Chiang Saen

Chapter II discussed the scanty and unrepresentative rainfall records that were available for the Mekong drainage above Chiang Saen, Thailand. The drainage area above Chiang Saen is 189,000 km^2 or approximately 70 percent of the drainage above the Luang Prabang site. Mean rainfall isohyets in this area on figures 2-8, 2-10, and 2-11 are related to apparent runoff as well as other factors (chapter II). There is insufficient information to develop rainfall frequency distributions.

It is recommended therefore that seasonal rainfall values for this drainage be selected such that the resulting flow will be high before the beginning of the typhoon rainfall. Consistency can be maintained by comparisons between rainfall and runoff data for the drainage between Chiang Saen and Luang Prabang.

Rainfall frequencies for combinations of subbasins

Contiguous subbasins may be combined by the correlation method. For example, rainfall frequencies for the total drainage from Thakhek to Kratie may be derived by combining frequencies from Thakhek to Pakse with frequencies from Pakse to Kratie. Such frequencies were developed for several combinations of subbasins and are listed in table 5-8.

For these combinations, we use streamflow correlations for the specific subbasins involved during the high-runoff season in substitution for rainfall correlations. This is thought to be the best index available of the rainfall association. The sparsity of rainfall stations in the most critical areas may be noted from figure 5-1. Runoff variation is necessarily closely related to rainfall variation where total percentage of runoff is high. Table 5-9 is a list of streamflow correlations, computed from discharge data furnished by the Corps of Engineers for the months of August and September. To obtain the first correlation in the table, for example, each August discharge at Pakse is subtracted from each corresponding August discharge at Kratie, thus obtaining an index of the runoff (and therefore rainfall) from Pakse to Kratie. This is correlated with the similar differences obtained by subtracting Thakhek and Ubon Ratchathani monthly flows from Pakse monthly flows (correlation of logs). No lag or adjustment is made for transit time from the upper to the lower gage.

In combining subbasins they are weighted by their contribution to mean rainfall volume. Equation (1) becomes for a combination of N subbasins:

$$\sigma_c^{\,2} = \frac{\sum_{K=1}^{K=N} \sum_{L=1}^{L=N} \sigma_K \sigma_L \, r_{KL} \, \bar{x}_K \, A_K \, \bar{x}_L \, A_L}{\sum_{K=1}^{K=N} \sum_{L=1}^{L=N} \bar{x}_K A_K \, \bar{x}_L \, A_L} \qquad (22)$$

where $\sigma_c^{\,2}$ is the variance of the logarithm of mean rainfall over the subbasin combination, $\bar{x}$ the mean rainfall over a subbasin, and A the area of the subbasin.

Replacing the σ's by log $(x_{100}/\bar{x})$ as before, from Chow's frequency equation, (12), and from y = log x, (22) becomes

$$\left\{\log\left\{\frac{x_{100}}{\bar{x}}\right\}_c\right\}^2 = \frac{\sum_{K=1}^{K=N}\sum_{L=1}^{L=N} \log\left\{\frac{x_{100}}{\bar{x}}\right\}_K \log\left\{\frac{x_{100}}{\bar{x}}\right\}_L r_{KL}\,\bar{x}_K A_K \bar{x}_L A_L}{\sum_{K=1}^{K=N}\sum_{L=1}^{L=N}\bar{x}_K A_K \bar{x}_L A_L} \qquad (23)$$

This is the calculating equation for the subbasin combination 100-yr-to-mean ratio. The r's are taken directly from table 5-9. The average of August correlations and September correlations is used for all time periods, the scatter being considered due to random variation rather than true seasonal trend. All other needed data for equation (23) are found in table 5-7.

Seasonal correlations, e.g., May through September, are not calculated for runoff. Runoff is a less stable index of rainfall during the early part of the monsoon season when soil is dry than during the late wet-soil period.

The possible range of 2-yr values is so slight that the above somewhat complex calculation is not warranted. 2-yr-to-mean ratios are estimated from table 5-5 for the larger areas and the 2-yr values based on these estimates.

Rainfall frequency graphs. Rainfall frequencies for the various Lower Mekong subbasins and combinations are portrayed in graphical form in figures 5-12 to 5-15. These are useful to obtain frequency values for return periods other than two years and 100 years. The graphs are constructed by plotting the 2-yr and 100-yr values from tables 5-7 and 5-8 on log-normal probability paper and connecting with straight lines.

Check on correlation method from station averages

A direct method of determining subbasin average rainfall frequencies is to average the station rains for each year of record, and then compute frequencies based on such averages. This method would be preferable, provided there were sufficient concurrent station rainfalls to determine subbasin averages. The Mekong does not have such a sufficiency. But an attempt was made with what data there are to give a check on the subbasin frequencies derived through the correlation procedure.

Some subbasins are so short of concurrent rainfall records that no areal frequencies could be attempted. For example, the drainage between

Pakse and Kratie sites has only 7 concurrent years of record for 4 stations. On the other hand, the drainage above Ubon Ratchathani has 6 stations, well distributed, with 40 or more concurrent years; or 7 stations with 24 years. Table 5-10 compares 100-yr-to-mean rain ratios determined through station correlations with ratios computed directly for 4 subbasins. August, September, May through August and May through September are the periods considered.

Conclusion. Recognizing the lack of sufficient areal coverage of data, the results support the ratios computed thru the correlation method. Of the 14 comparisons, the largest difference is about 8 percent. Average difference is about 3 percent, with no bias towards lower or higher ratios by either method.

C. Application of Criteria

Introduction

Having determined rainfall frequencies for the Lower Mekong and various subbasins above each of the three main stem sites, probable maximum precipitation, for durations up to three days (chapter III), and an antecedent storm (chapter IV), what is now needed is a sequence of these rain events that will give the critical peak hydrograph.

The search here is for the rainfall combination that will most readily produce the probable maximum flood peak. This means that we combine rainfall events according to the following hierarchy:

Influence of rainfall event on flood peak	Recurrence interval of rainfall event
great influence	probable maximum or very rare
moderate influence	rare
slight influence	normal
negligible influence	neglect

The influence of different rainfall events is determined by hydrologic trial and is not known *a priori*. Exhaustive study of all possibilities was not made. But, sufficient hydrologic trials were run (by the Corps of Engineers) to establish the following hierarchy of influence on peak flow at the dam sites:

Greatest influence	3-day typhoon rain immediately above dam site.
Strong influence	a. Prior typhoon upstream. b. Prior basin rainfall for several weeks.
Less influence	Earlier monsoon-season basin rainfall.
Negligible influence	Prior dry season base flow.

Following these guide lines, it is concluded that the rainfall leading to the probable maximum flood can be approximated by a combination of:

a. Probable maximum typhoon rainfall immediately above dam site.

b. Lesser antecedent typhoon rainfall upstream, at shortest reasonable time interval prior to this.

c. 100-yr monthly rainfall for the month preceding or encompassing the typhoons, broken down into daily increments. This rainfall rate also pertains outside the typhoon rain area during the typhoons and all areas on a no-typhoon day between the typhoons.

d. Normal monsoon-season rainfall over all areas preceding this month. A transition period of intermediate recurrence interval between "c" and "d" might be used.

A third typhoon and early monsoon-season rainfall greater than normal are both possibilities. However, the influence of either on the flood peak is insufficient to warrant this compounding of probabilities. If judgment were to dictate more severe criteria for the probable maximum flood, it would be more significant to make changes higher in the "influence hierarchy" listed above. Within these decisions, details of rainfall sequences should be modified for different hydrologic trials, and the combination of details producing the most critical hydrograph selected. As illustration, two specific detailed sequences are outlined below.

Basic sequences of rain events

Two basic sequences of rain events are called pattern 1 and pattern 2. Differences between the two demonstrate some of the variation that can be obtained within the developed criteria.

Pattern 1:	a.	May 1-July 31:	Normal rainfall.
	b.	August 1-31:	10- to 20-yr August rainfall, divided into daily increments.
	c.	September 1-30:	100-yr September rainfall plus 2 typhoons occurring near the middle of the month.
Pattern 2:	a.	May 1-August 15:	Normal rainfall.
	b.	August 16-September 14:	100-yr rainfall plus 2 typhoons occurring near the middle of September.

Application of patterns 1 and 2. A tabular format of rainfall depths conforming to the two patterns for each of the three sites is shown in tables 5-11 and 5-12. Sources of rainfall depths are given in the tables.

Areal distribution of seasonal rain

Mean May-September, August and September rainfall maps are given in figures 2-8, 2-10, and 2-11. These can be used to distribute the rainfall volumes of tables 5-11 and 5-12. May-July rainfall may be patterned after the May-September map. Multiplying the isohyetal values on the mean map by the 2-yr to mean or 100-yr to mean ratios (from tables 5-7 and 5-8 for May-July and September) will give the areally distributed rainfall directly. It would be desirable to check rainfall volumes determined in this manner and make adjustments, if necessary, to maintain specified rain volumes.

Time distribution of seasonal rain

Curves showing daily percents of May 1-July 31 and May 1-August 16 rain totals are shown in figure 5-16. These are based on normal distribution of seasonal rain totals at stations in the Mekong. If grouping of daily values into more realistic storm periods of 3 to 5 days has an important effect on the hydrograph, such grouping can be made but still maintaining the total rainfall volume for the season.

For August or September rainfalls, divide by 31 or 30 days to obtain daily rains. Again, grouping into storm bursts is permissible.

Flood peak from typhoon rainfall

Chapter III develops typhoon PMP for 3 days duration for occurrence in any subarea of the Lower Mekong. Chapter IV discusses the magnitude of a prior storm, the time interval between it and the PMP, and recommends two sequences of the two typhoons, one allowing the storms to occur closer together in time, in which case the prior storm is less than in the other sequence. Table 5-13 lists the two sequences on a time scale. Both sequences begin September 15.

Location of typhoon PMP. Generally, the typhoon PMP would be most critical for peak flow if located immediately above the dam site. Figure 5-17 shows isohyets for the heaviest day of PMP in these suggested locations for the 3 dam sites. Derivation of the isohyetal values on this figure is given in the following paragraphs.

PMP storm depths. For the maximum 1-day rainfall, the elliptical isohyetal pattern, figure 3-11, is recommended. Isohyetal values were developed for the Vietnam coast PMP by constructing isohyetal profiles, and making use of the storm depth-area curve for 24 hours of figure 3-12. The resulting Vietnam coast isohyet values are shown in table 5-14.

For each location of the typhoon shown on figure 5-17, the average adjustment to coastal PMP was obtained from figure 3-8. This adjustment, shown on table 5-15, times the isohyetal labels of table 5-14 will give 1-day PMP isohyet values for each of the three locations. Isohyetal values shown on figure 5-17 were determined by this procedure.

The adjusted 1-day isohyetal pattern is used over the selected subbasin and surrounding areas until the isohyets blend in with the 1-day proportion of the 100-yr September rainfall. PMP for the remaining 2 days can then cover the same area as the heaviest day of PMP.

The maximum 1-day rain accounts for approximately 50 percent of the 3-day PMP. It follows that areal distribution is more important for this day of rain than for the remaining 2 rain days. Shifting of storm centers and randomness in distribution of the lighter rain amounts results in little consistency of the areal variation from one record storm to another. It is recommended therefore that uniform average depths be used for the two lighter rain days. This procedure has been used previously for large basin PMP studies, such as for the Susquehanna River of Eastern U.S.A. (5-7).

Rains for the 2d and 3d heaviest rain days for each subbasin are given in table 5-15. These values have been adjusted for the subbasin location.

Location of prior typhoon rain. Location of the prior typhoon rain that in combination with typhoon PMP will produce the highest flow is dependent upon stream travel time and other hydrologic characteristics of the basin. Suggested placements for first hydrologic trials are listed in table 5-16.

Prior typhoon storm depths. For a selected location of the prior storm, the average combined typhoon adjustment from figure 3-8 is determined. This adjustment, in percent, times the 50 or 65 percent factor, depending on whether 3 or 4 days track separation is being used, is the ratio by which the isohyetal values of table 5-14 are multiplied to obtain the heaviest 1-day rain of the prior storm. The remaining 2 days of rain are obtained by multiplying 130 mm and 110 mm by the last-mentioned ratio above. As with the PMP, use the isohyetal pattern until it blends with the 1-day proportion of the 100-yr September rain. The 2d and 3d day average rains cover the same area.

Time distribution. For a 3-day typhoon, it is most common for the heaviest 1-day rain to occur in the middle of the storm, with lighter rains on the adjacent days. This is the pattern recommended for both typhoons, as illustrated on table 5-13.

Table 5-1

EXAMPLES OF DIFFERENCES BETWEEN 5 HIGHEST OBSERVED RAINS AND RAINS COMPUTED FROM 3 FREQUENCY DISTRIBUTIONS

Phong Saly (20 years)

(rainfall mm)

Plotting Position	Aug.							Sept.						
	O	N	d	LN	d	G	d	O	N	d	LN	d	G	d
f*														
.952	767	589	178	600	167	580	187	367	300	67	362	5	323	44
.904	528	541	-13	538	-10	528	0	324	270	54	295	29	277	47
.857	514	513	1	500	14	498	16	261	250	11	257	4	250	11
.809	438	486	-48	469	-31	471	-33	203	236	-33	232	-29	232	-29
.761	416	467	-51	447	-31	453	-37	191	222	-31	212	-21	214	-23
Σ+			179		181		203			132		38		102
Σ-			-112		-72		-70			-64		-50		-52
Abs			291		253		273			196		88		154

Plotting Position	May-Aug.							May-Sept.						
	O	N	d	LN	d	G	d	O	N	d	LN	d	G	d
f*														
.952	1799	1560	239	1580	219	1560	239	2014	1775	239	1790	224	1765	249
.904	1690	1468	222	1470	220	1465	225	2002	1673	329	1665	337	1648	354
.857	1338	1410	-72	1400	-62	1400	-62	1477	1602	-125	1590	-113	1573	-96
.809	1310	1355	-45	1335	-25	1348	-38	1378	1545	-167	1520	-142	1515	-137
.761	1214	1316	-102	1290	-76	1310	-96	1374	1502	-128	1475	-101	1472	-98
Σ+			461		439		464			568		561		603
Σ-			-219		-163		-196			-420		-356		-331
Abs			680		602		660			988		917		934

Pakse (26 years)

(rainfall mm)

	Aug.							Sept.						
	O	N	d	LN	d	G	d	O	N	d	LN	d	G	d
.960	872	804	68	940	-68	867	5	778	700	78	840	-62	750	28
.920	736	745	-9	818	-82	776	60	749	644	105	715	34	644	5
.880	733	699	34	736	-3	715	18	671	604	67	640	31	614	57
.840	676	667	9	680	-4	671	5	525	572	-47	587	-62	576	49
.800	667	639	28	640	27	635	32	493	550	-57	550	-57	542	51
Σ+			139		27		120			250		65		190
Σ-			-9		-157		0			-104		-181		0
Abs			148		184		120			354		246		190

	May-Aug.							May-Sept.						
	O	N	d	LN	d	G	d	O	N	d	LN	d	G	d
.960	1791	1905	-114	2210	-419	2055	-264	2284	2407	-123	2680	-396	2525	-241
.920	1791	1785	6	1990	-199	1875	-84	2282	2275	7	2425	-143	2333	-51
.880	1768	1705	63	1830	-62	1760	8	2242	2173	69	2280	-38	2215	27
.840	1670	1648	22	1730	-60	1680	-10	2224	2100	124	2170	54	2125	99
.800	1562	1595	-33	1640	-78	1610	-48	1997	2023	-26	2070	-73	2040	43
Σ+			91		0		8			200		54		169
Σ-			-147		-818		-406			-149		-650		-292
Abs			238		818		414			349		704		461

O: observed
N: normal distribution
LN: log-normal distribution
G: gamma distribution
d: difference between observed and computed values. Where minus (-), computed value is higher.

$*f = \frac{m}{N+1}$ where: f = assigned frequency; m = rank of datum; N = number of data.

Table 5-2

SUMMARY OF DIFFERENCES BETWEEN FIVE HIGHEST OBSERVED AND COMPUTED RAINS

Station		August			September			May-August			May-September		
		Nd	LNd	Gd	Nd	LNd	Gd	Nd	LNd	Gd	Nd	LNd	Gd
		Rainfall (mm)											
Vientiane	+	123	0	34	377	160	310	247	206	55	170	34	-
	-	0	75	14	0	0	0	215	469	264	8	95	-
	Abs	123	75	48	377	160	310	462	675	319	178	129	-
Phongsaly	+	179	181	203	132	38	102	461	439	464	568	561	603
	-	112	72	70	64	50	52	219	163	196	420	356	331
	Abs	291	253	273	196	88	154	680	602	660	988	917	934
Kontum	+	176	132	172	42	23	80	29	214	-	134	113	-
	-	55	32	25	35	159	29	169	133	-	13	0	-
	Abs	231	164	197	77	182	109	198	347	-	147	113	-
Chiang Rai	+	179	13	75	236	25	135	476	261	326	380	243	305
	-	0	87	17	0	37	0	0	0	0	0	49	0
	Abs	179	100	92	236	62	135	476	261	326	380	292	305
Battambang	+	147	70	130	271	52	182	137	135	-	213	121	-
	-	0	0	0	0	15	0	0	0	-	0	0	-
	Abs	147	70	130	271	67	182	137	135	-	213	121	-
Kratie	+	208	25	111	197	110	149	72	27	22	176	166	126
	-	0	129	4	0	55	3	28	324	202	79	174	166
	Abs	208	154	115	197	165	152	100	351	224	255	340	292
Pakse	+	139	27	120	250	65	190	91	0	8	200	54	169
	-	9	157	0	104	181	0	147	818	406	149	650	292
	Abs	148	184	120	354	246	190	238	818	414	349	704	461
Attopeu	+	315	145	279	73	7	18	447	498	523	563	698	659
	-	0	32	0	56	154	70	0	89	19	0	21	0
	Abs	315	177	279	129	161	88	447	587	542	563	719	659
Luang Prabang	+	102	0	13	188	0	71	243	0	107	5	0	0
	-	30	339	119	0	236	33	38	211	49	178	804	483
	Abs	132	339	132	188	236	104	281	211	156	183	804	483
Nape	+	207	249	192	371	280	424	310	78	308	482	362	-
	-	0	0	0	19	0	0	21	404	61	143	174	-
	Abs	207	249	192	390	280	424	331	482	369	625	536	-
Sakon Nakon	+	498	244	405	735	228	587	1481	1657	1617	2227	2450	2423
	-	31	42	29	0	12	0	432	200	249	1055	636	537
	Abs	529	286	434	735	240	587	1913	1857	1866	3282	3086	2960

Table 5-2 (Continued)

SUMMARY OF DIFFERENCES BETWEEN FIVE HIGHEST OBSERVED AND COMPUTED RAINS

Station		August Nd	August LNd	August Gd	September Nd	September LNd	September Gd	May-August Nd	May-August LNd	May-August Gd	May-September Nd	May-September LNd	May-September Gd
							Rainfall (mm)						
Khon Koen	+	197	47	129	186	27	77	440	400	420	19	0	0
	-	7	72	8	0	82	0	49	57	44	35	537	246
	Abs	204	119	137	186	109	77	489	457	464	54	537	246
Loei	+	617	518	625	160	31	112	1385	1517	1592	1451	1385	1480
	-	67	107	43	0	137	20	200	115	145	481	351	382
	Abs	684	625	668	160	168	132	1585	1632	1737	1932	1736	1862
Chaiyaphum	+	298	205	271	162	43	169	187	21	132	245	0	79
	-	47	67	32	0	60	0	7	16	10	0	231	23
	Abs	345	272	303	162	103	169	194	37	142	245	231	102
Surin	+	131	35	90	130	0	65	194	9	74	323	119	-
	-	9	167	66	18	327	123	0	45	8	0	0	-
	Abs	140	202	156	148	327	188	194	54	82	323	119	-
Summation of differences								(13 stations)			(10 stations)		
	+	3516	1891	2849	3510	1089	2671	6034	5113	5648	5834	5557	5844
	-	367	1378	427	296	1505	330	1356	2911	1653	2397	3809	2460
	Abs	3883	3269	3276	3806	2594	3001	7390	8024	7301	8231	9366	8304
Count of number of stations with total positive and negative bias													
	+ bias	15	8	14	15	5	13	12	7	10	8	5	6
	- bias	0	7	1	0	10	2	1	6	3	2	5	4

Nd: difference between observed and computed from normal distribution
LNd: difference between observed and computed from log-normal distribution
Gd: difference between observed and computed gamma distribution

+ : Observed higher than computed
- : Observed lower than computed
Abs: Absolute (total) differences

Table 5-3

COMPARISON OF 100-YEAR VALUES BASED ON HALF THE DATA AND ALL DATA

	Aug.			Sept.			May-Aug.			May-Sept.		
Station	N	LN	G	N	LN	G	N	LN	G	N	LN	G
100-yr value computed from 1/2 the data ÷ 100-yr value computed from all data.												
Vientiane	1.08	1.18	1.09	1.13	1.23	1.15	1.00	1.07	0.99	1.02	1.02	-
Phong Saly	1.10	1.11	1.10	0.92	0.82	0.87	0.97	0.97	0.96	0.99	0.97	0.97
Kontum	1.04	0.94	0.98	1.07	1.20	-	1.03	1.01	-	0.94	0.92	-
Chiang Rai	0.95	0.95	0.95	0.99	0.92	0.96	1.03	1.04	1.03	1.02	1.03	1.02
Battambang	1.02	1.06	1.03	0.94	0.92	0.93	0.96	0.96	-	1.02	1.03	-
Kratie	0.86	0.88	0.88	0.96	0.88	0.91	0.95	0.95	0.94	0.96	0.97	-
Pakse	1.03	0.93	0.88	1.02	0.91	0.97	0.98	0.84	0.89	0.93	0.83	-
Attopeu	1.03	1.12	-	1.05	0.89	0.96	1.05	1.07	-	1.08	1.11	-
Luang Prabang	0.99	0.97	0.97	1.10	1.02	1.04	1.01	0.94	0.97	0.97	0.94	0.93
Nape	0.87	0.83	0.84	1.04	1.00	0.91	1.00	0.99	0.98	1.08	1.11	-
Sakon Nakhon	0.93	0.97	0.93	0.95	0.88	0.95	1.11	1.12	1.13	1.10	1.09	1.10
Khon Kaen	1.10	1.05	1.07	1.08	1.11	1.09	0.90	0.90	-	0.97	0.90	-
Loei	1.07	1.05	1.05	0.90	0.83	0.87	1.10	1.05	1.06	0.85	0.85	0.87
Chaiyaphum	1.17	1.25	1.19	0.97	0.98	0.96	1.06	1.08	1.06	1.03	1.06	0.98
Surin	0.96	0.89	0.93	0.97	0.94	0.95	0.97	0.95	0.96	0.95	0.93	-
Average ratio	1.01	1.01	0.99	1.01	0.97	0.97	1.01	1.00	1.00	0.99	0.98	0.98
Number of stations where ratio is greater than 1.00	9	7	6	7	5	3	9	7	4	7	7	2

N: normal distribution
LN: log-normal distribution
G: gamma distribution

Table 5-4

RATIOS OF 100-YEAR TO MEAN RAINFALL

Period	Average of Station Ratios $\frac{1}{N}\frac{\Sigma X_{100}}{\overline{X}}$	Average Weighted by Years of Record $\frac{\Sigma X_{100}\, Y}{\Sigma\, \overline{X}\, Y}$	Adopted Ratio	Number of Stations
May-August	1.74	1.72	1.8	71
May-September	1.64	1.66	1.7	71
August	2.48	2.47	2.5	71
September	2.55	2.59	2.6	75

X_{100} = 100-year rainfall

$\overline{X}$ = mean rainfall

N = number of stations

Y = years of record at a station

Table 5-5

RATIO OF MEDIAN RAINFALL (x_2) TO MEAN RAINFALL ($\overline{x}$)

Period	Station Average* $x_2 / \overline{\overline{x}}$	100,000 km^2 $\sqrt{R}$	100,000 km^2 $(x_2)_A / \overline{x}_A$
August	0.94	.665	.96
September	0.92	.665	.94
May-August	0.96	.51	.98
May-September	0.97	.51	.98

*Average of 70 stations.

Table 5-6

CORRELATIONS OF LOGS OF STATION RAINFALLS

Chiang Rai, Thailand, vs.	Correlation: Monthly Aug.	Correlation: Monthly Sept.	Correlation: Monthly Avg.	Correlation: Seasonal May thru Aug.	Correlation: Seasonal May thru Sept.	Correlation: Seasonal Avg.	Years of Record Aug.	Years of Record Sept.	Years of Record May thru Aug.	Years of Record May thru Sept.
Stung Treng, Cambodia	.00	.06	.03	-.19	-.18	-.18	38	38	36	36
Attopeu, Laos	-.33	.62	.15	.24	.45	.34	18	18	16	16
Houei Sai, Laos	.37	.43	.40	.25	.24	.24	30	30	29	28
Luang Prabang, Laos	.20	.01	.11	.28	.23	.26	46	47	44	44
Nape, Laos	.36	.15	.26	.22	.06	.14	22	22	20	22
Pakse, Laos	-.09	.31	.11	-.19	-.26	-.22	23	26	23	23
Phong Saly, Laos	.32	.32	.32	.07	.21	.14	20	26	20	20
Vientiane, Laos	.28	.19	.23	.06	.12	.09	44	45	44	44
Xiangkhoang, Laos	.16	.37	.27	.08	.14	.11	23	22	19	19
Mukdahan, Thailand	.12	.01	.07	-.20	-.21	-.20	29	27	27	27
Nakhon (Sakon Nakhon), Thailand	.14	.27	.22	.14	.29	.22	50	49	46	46
Nan, Thailand	.31	.34	.33	.26	.11	.18	52	52	51	51
Roi Et, Thailand	.05	.40	.23	.03	.06	.04	53	53	53	53
Ubon Ratchathani, Thailand	-.02	.30	.14	-.03	.02	-.01	54	50	53	50
Udon Thani, Thailand	.31	.36	.34	.15	.17	.16	53	53	51	51
Kontum, Viet Nam	-.13	.05	.03	-.21	-.11	-.16	19	18	15	15
Mean			.20			.07				

Table 5-6 (Continued)

CORRELATIONS OF LOGS OF STATION RAINFALLS

	Correlation						Years of Record			
	Monthly			Seasonal						
Ubon Ratchathani, Thailand vs.	Aug.	Sept.	Avg.	May thru Aug.	May thru Sept.	Avg.	Aug.	Sept.	May thru Aug.	May thru Sept.
Veunesai (Virachei), Cambodia	.38	.50	.44	.00	.16	.08	26	24	24	24
Stung Treng, Cambodia	.28	.38	.33	.34	.20	.27	38	37	36	36
Attopeu, Laos	.48	.16	.32	.40	.28	.34	18	17	16	16
Luang Prabang, Laos	.14	-.12	.01	-.02	-.16	-.09	46	45	44	44
Nape, Laos	.40	.12	.26	.11	.35	.23	20	20	20	20
Pakse, Laos	.60	.71	.66	.52	.61	.56	23	26	23	23
Phong Saly, Laos	.18	.33	.26	.36	.29	.32	20	20	20	19
Vientiane, Laos	.15	.10	.13	-.29	-.16	-.22	44	43	44	43
Xiangkhoang, Laos	.14	.01	.08	.06	.00	.03	23	21	19	18
Chiang Rai, Thailand	-.02	.30	.14	-.03	.02	-.01	54	50	53	50
Khon Kaen, Thailand	.13	.35	.24	-.22	-.08	-.15	51	50	49	47
Loei, Thailand	.09	.35	.22	.09	-.00	.04	53	51	51	50
Mukdahan, Thailand	.63	.36	.50	.50	.47	.48	30	28	29	28
Nakhon (Sakon Nakhon), Thailand	.12	.26	.19	.17	.18	.18	51	48	48	47
Roi Et, Thailand	.39	.52	.46	.25	.33	.29	54	52	55	52
Surin, Thailand	.41	.50	.46	.28	.18	.23	55	52	54	52
Udon Thani, Thailand	.18	.12	.15	.20	.16	.18	54	52	53	52
Kontum, Viet Nam	.55	-.21	.17	-.05	-.31	-.18	20	18	15	15
Mean			.28			.15				
Overall mean (both stations)			.24			.11				

Table 5-7

RAINFALL FREQUENCIES OVER MEKONG SUBBASINS (mm)

		Area km^2	May-July Mean	2/M	2-Yr
A.	Pakse to Kratie	101,000	970	.98	950
B.	Thakhek and Ubon Ratchathani to Pakse	68,000	890	.97	865
C.	Above Ubon Ratchathani	104,000	630	.98	620
D.	Luang Prabang Thakhek	105,000	1145	.98	1120
E.	Chiang Saen to Luang Prabang	79,000	870	.97	845
*F.	Above Chiang Saen	189,000	580	.99	575

	August					September				
	Mean	2/M	2-Yr	100/M	100-Yr	Mean	2/M	2-Yr	100/M	100-Yr
A.	470	.95	445	1.84	865	450	.95	430	1.89	850
B.	400	.94	375	1.90	760	360	.94	340	1.95	700
C.	240	.95	230	1.84	440	310	.95	295	1.89	585
D.	435	.95	415	1.84	800	300	.95	285	1.89	565
E.	360	.94	340	1.88	675	210	.94	195	1.93	405
F.	235	.96	225			155	.96	150		

	Mean	2/M	2-Yr	100/M	100-Yr	Mean	2/M	2-Yr	100/M	100-Yr
A.	1440	.98	1410	1.35	1945	1890	.98	1850	1.31	2475
B.	1290	.97	1250	1.37	1780	1650	.97	1600	1.34	2210
C.	870	.98	850	1.35	1175	1180	.98	1155	1.31	1545
D.	1580	.98	1550	1.35	2135	1880	.98	1840	1.31	2465
E.	1230	.97	1195	1.37	1685	1440	.97	1395	1.33	1915
F.	815	.99	805			970	.99	960		

2/M -- ratio of 2-yr to mean
100/M -- ratio of 100-yr to mean
*Values estimated for this subbasin.

Table 5-8

RAINFALL FREQUENCIES OVER COMBINATIONS OF MEKONG SUBBASINS (mm)

	Area km^2	May-July Mean	May-July 2/M	May-July 2-Yr
A+B+C+D+E (above Kratie)	457,000	905	.99	895
B+C+D+E (above lower Pakse site)	356,000	885	.98	865
B+D+E (above upper Pakse site)	252,000	990	.98	970
*E+F (above Luang Prabang)	268,000	665	.98	650

	August					September				
	Mean	2/M	2-Yr	100/M	100-Yr	Mean	2/M	2-Yr	100/M	100-Yr
A+B+C+D+E	380	.99	375	1.49	565	330	.99	325	1.52	500
B+C+D+E	355	.98	350	1.52	540	295	.98	290	1.55	455
B+D+E	400	.97	390	1.55	620	290	.97	280	1.58	460
*E+F	270	.97	265	1.51	400	170	.97	165	1.59	270

	May-August					May-September				
	Mean	2/M	2-Yr	100/M	100-Yr	Mean	2/M	2-Yr	100/M	100-Yr
A+B+C+D+E	1285	1.00	1285	1.18	1515	1615	1.00	1615	1.16	1875
B+C+D+E	1240	.99	1230	1.20	1490	1535	.99	1520	1.18	1810
B+D+E	1390	.98	1360	1.22	1695	1680	.98	1645	1.20	2015
*E+F	935	.98	920			1110	.98	1085		

2/M -- ratio of 2-yr to mean
100/M -- ratio of 100-yr to mean
*Values estimated for this combination

Table 5-9

SUBBASIN STREAMFLOW CORRELATIONS

MEKONG RIVER

Subbasins	Correlation of Logs			Years of Record	
	Aug	Sept	Avg	Aug	Sept
A vs. B	.71	.47	.59	18	19
C	.42	.25	.34	18	19
D	.22	.00	.11	17	17
B+C	.62	.50	.56	25	26
B+C+D	.59	.19	.39	17	17
B+D	.56	.15	.36	16	16
B+C+D+E+F	.43	.26	.35	25	26
D+E+F	.15	-.05	.05	25	26
E+F	.17	-.24	-.03	18	17
B vs. D	.29	.18	.24	16	17
D+E+F	.13	.15	.14	18	20
E+F	.25	-.18	.04	16	17
B+C vs. D	.29	.16	.22	17	18
D+E+F	.08	.19	.14	25	27
E+F	.07	-.13	-.03	17	18
B+C+D vs. E+F	.18	.13	.15	18	18
B+D vs. C	.56	.35	.45	17	17
C vs. D	.39	.11	.25	17	17
E+F	.55	-.03	.29	17	17
D vs. E+F	.25	.32	.28	18	18

Subbasins

A. Pakse to Kratie
B. Thakhek and Ubon Ratchathani to Pakse
C. Above Ubon Ratchathani
D. Luang Prabang to Thakhek
E. Chiang Saen to Luang Prabang
F. Above Chiang Saen

Table 5-10

COMPARISON OF SUBBASIN 100-YR TO MEAN RAIN RATIOS BY TWO METHODS

	Month or Season								For Method B	
	Aug		Sept		May-Aug		May-Sept			
Subbasin*	A	B	A	B	A	B	A	B	No. of Sta.	Yrs. of Record
	$(x_{100})_A / \bar{x}_A$									
Above Ubon Ratchathani (C)	1.84	1.92	1.89	1.90	1.35	1.33	1.31	1.30	6	44
Luang Prabang to Thakhek (D)	1.84	1.80	1.89	2.00	1.35	1.31	1.31	1.29	5	30
Chiang Saen to Luang Prabang (E)	1.88	1.73	1.93	2.02	1.37	1.43	1.33	1.36	3	28
Chiang Saen to Thakhek (D+E)	1.65	1.68	1.76	1.71	-	-	-	-	6	23

A -- correlation method
B -- direct average method
* see figure 5-7

Table 5-11

PATTERN 1 SEQUENCE OF RAINFALL EVENTS EXCLUDING TYPHOONS

	Drainage Basin		
	Chiang Saen to Luang Prabang Site (79,000 km^2)	Chiang Saen to Pakse Site (252,000 km^2)	Chiang Saen to Sambor Site (457,000 km^2)
a. May 1-July 31 2-yr rainfall (mm)	845	970	895
		(from tables 5-7 and 5-8)	
b. August 20-yr rainfall (mm)	550	540	500
		(from figure 5-12)	
c. September 100-yr rainfall (mm)	405	460	500
		(from tables 5-7 and 5-8)	

Table 5-12

PATTERN 2 SEQUENCE OF RAINFALL EVENTS EXCLUDING TYPHOONS

	Drainage Basin		
	Chiang Saen to Luang Prabang Site ($79,000\ km^2$)	Chiang Saen to Pakse Site ($252,000\ km^2$)	Chiang Saen to Sambor Site ($457,000\ km^2$)
a. May 1-Aug. 15 2-yr rainfall (mm)	1015	1165	1082
	(May 1-July 31 2-yr values plus 1/2 of August 2-yr from tables 5-7 and 5-8)		
b. Aug. 16-Sept. 14 100-yr rainfall (mm)	540	540	532
	(Average of 100-yr values for August and September from tables 5-7 and 5-8)		

Table 5-13

SEQUENCES OF TYPHOON RAINFALLS

3-Day Track Separation

Prior storm, 50% factor	Sept.	15 - 2d heaviest day
		16 - heaviest day
	3 days	17 - 3d heaviest day
PMP storm, 100% factor		18 - 3d heaviest day
		19 - heaviest day
		20 - 2d heaviest day

4-Day Track Separation

Prior storm, 65% factor	Sept.	15 - 2d heaviest day
		16 - heaviest day
	4 days	17 - 3d heaviest day
		18 - normal rain
PMP storm, 100% factor		19 - 2d or 3d heaviest day
		20 - heaviest day
		21 - 3d or 2d heaviest day

Table 5-14

ISOHYETAL LABELS FOR COASTAL PMP

Isohyet (See fig. 3-11)	Isohyet Value (mm)	Isohyet Area km^2
B	541	2260
C	366	11,170
D	234	29,690
E	173	56,420
F	135	103,730
G	119	139,650
H	109	184,160
I	102	245,170

Table 5-15

ADJUSTMENTS FOR TYPHOON PMP IN SUBBASINS ABOVE THE DAM SITES

Dam Site	Subbasin	Combined Typhoon Adjustment (from fig. 3-8) (%)	Adjusted PMP* for 2d and 3d Heaviest Rain Day 2d day (mm)	3d day (mm)
Luang Prabang	Drainage from Lat. 24°N to Luang Prabang	55	72	61
Pakse	Luang Prabang to Pakse	82	107	90
Sambor	Pakse to Sambor	93	121	102

*Adjustment times 130 mm and 110 mm, respectively.

Table 5-16

SUGGESTED LOCATIONS OF PRIOR STORM FOR FIRST HYDROLOGIC TESTS

Dam site:		
Luang Prabang	Pakse	Sambor
	Prior storm location	
Drainage between 24°N Lat. and Luang Prabang	Same as for Luang Prabang site	Drainage between Luang Prabang and Pakse

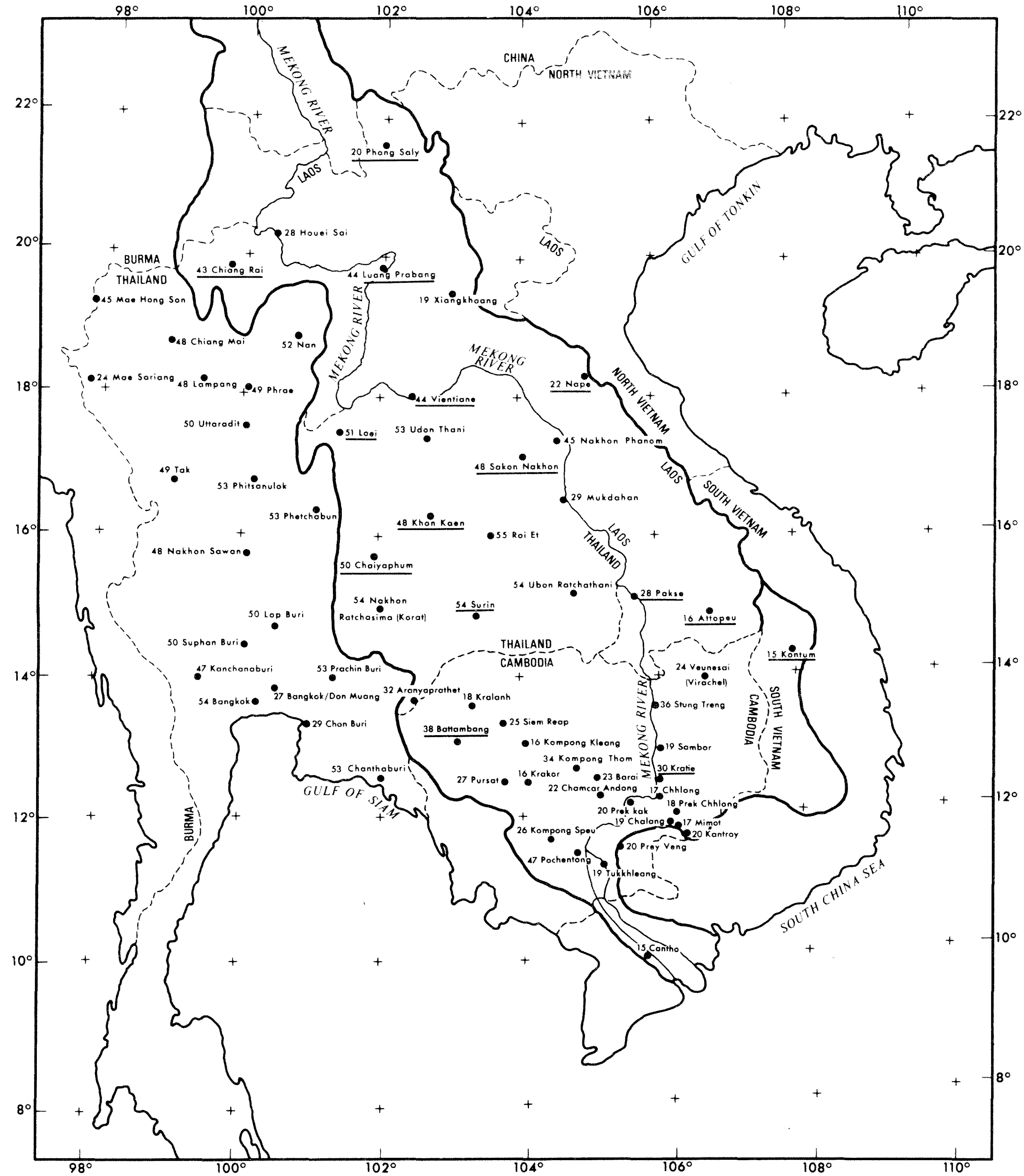


Figure 5-1. Rainfall stations with 15 or more years of record. All stations used for analysis of 100 yr to mean rainfall ratios (fig. 5-3 to 5-6). Stations underlined used for tests of frequency distributions (tables 5-1 to 5-3). Numbers are years of record.

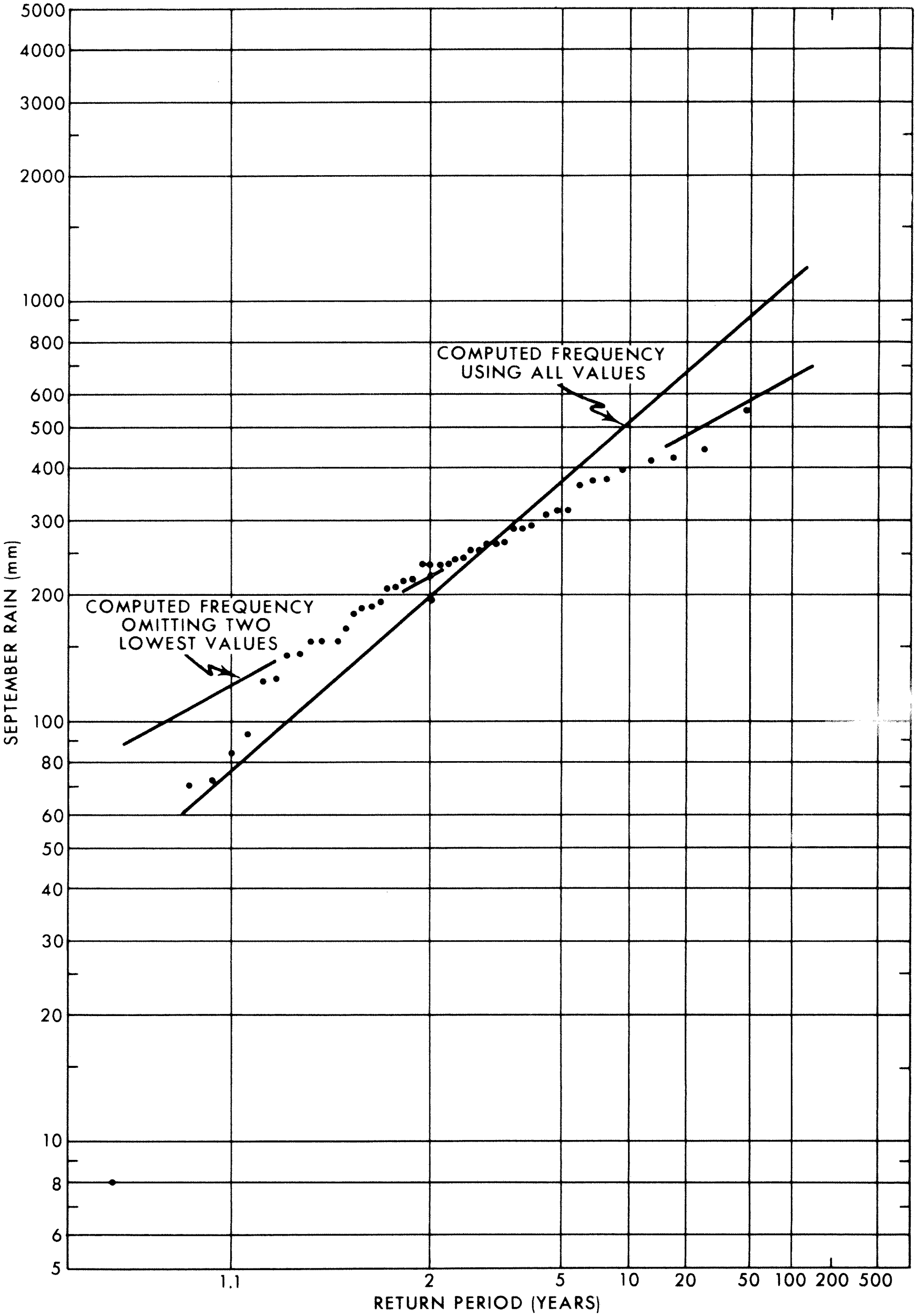


Figure 5-2. Effect of deleting two lowest observations (Chaiyaphum, Thailand)

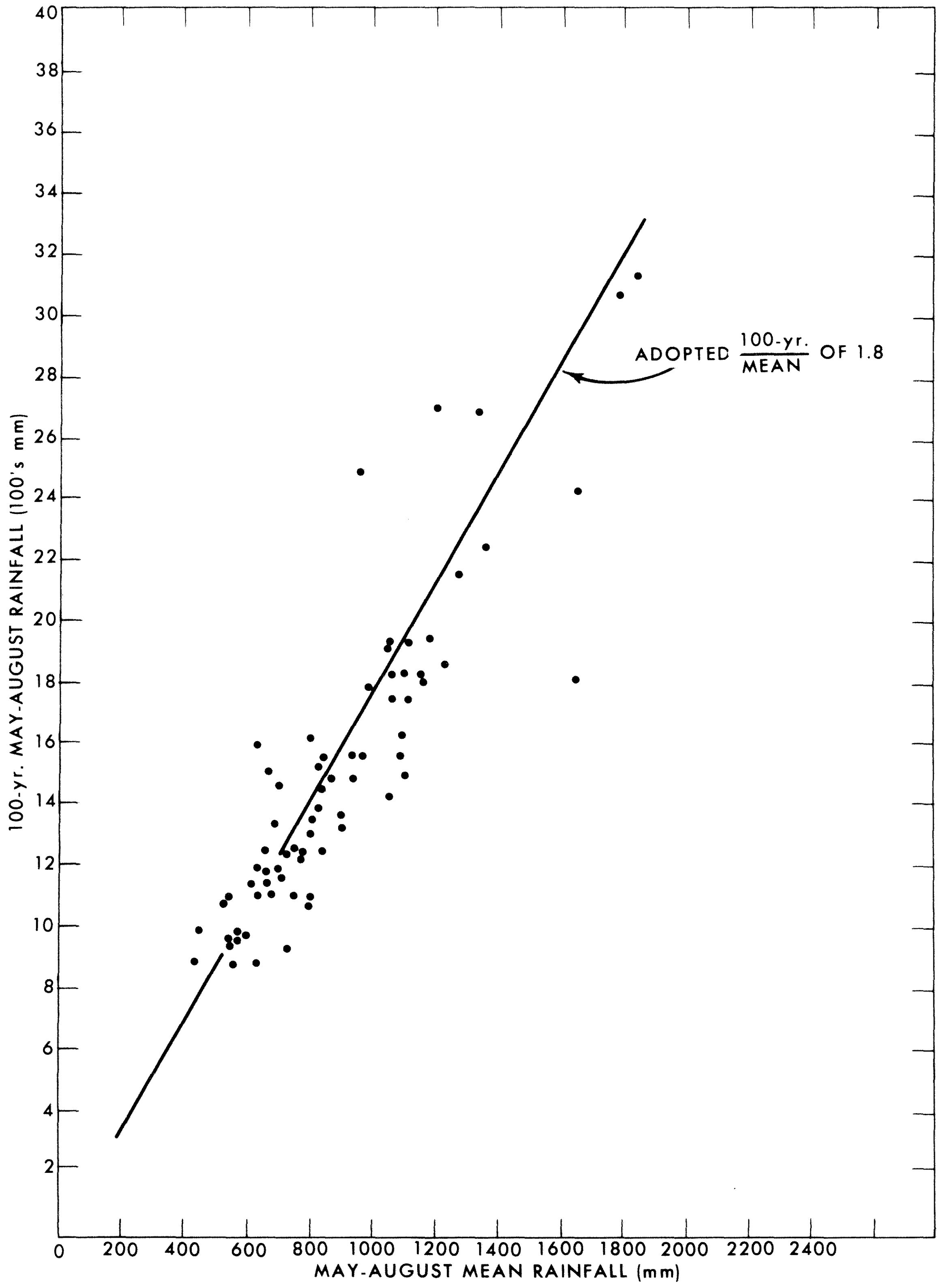


Figure 5-3. May through August, mean vs. 100-yr station rainfall

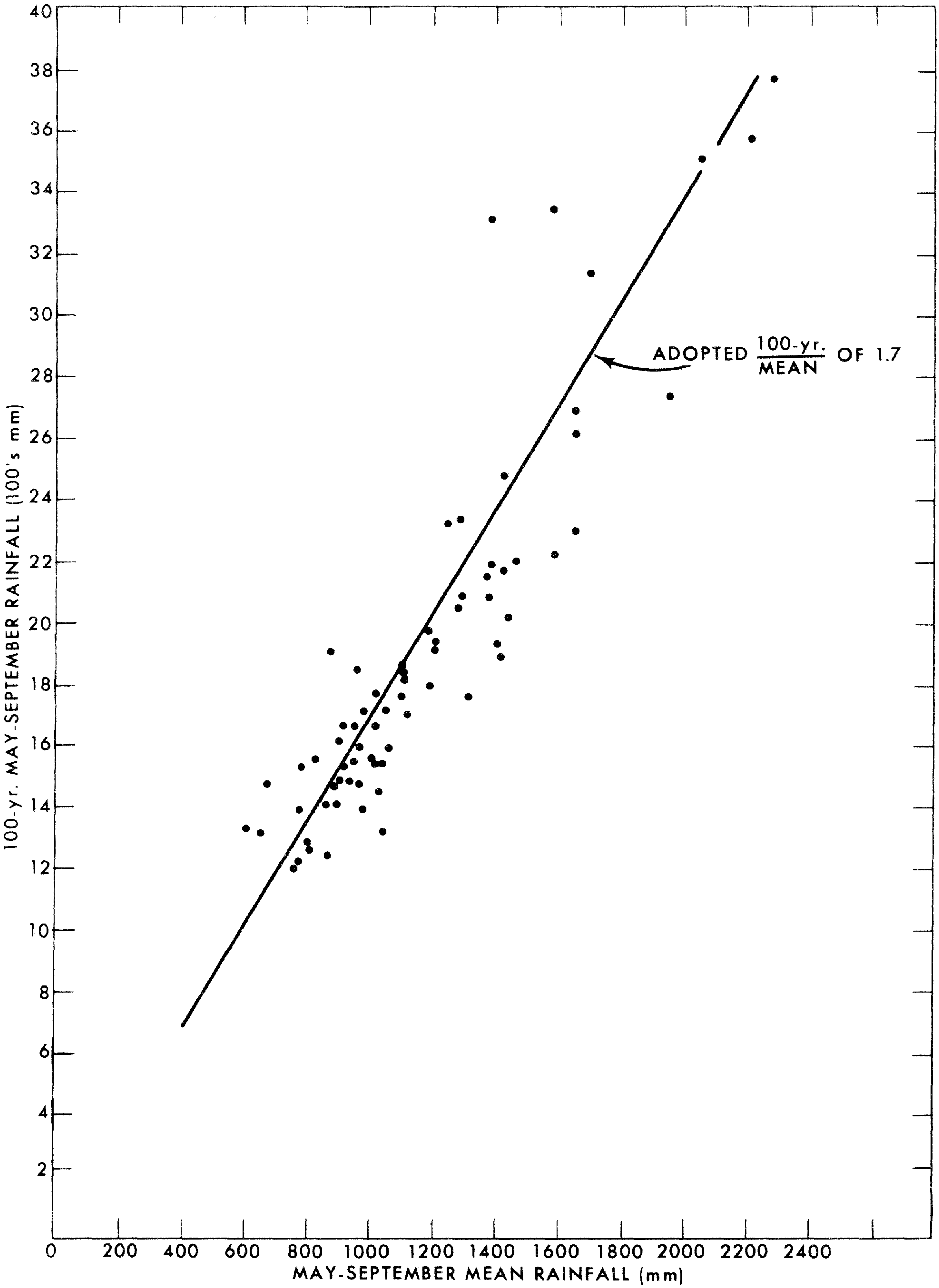


Figure 5-4. May through September, mean vs. 100-yr station rainfall

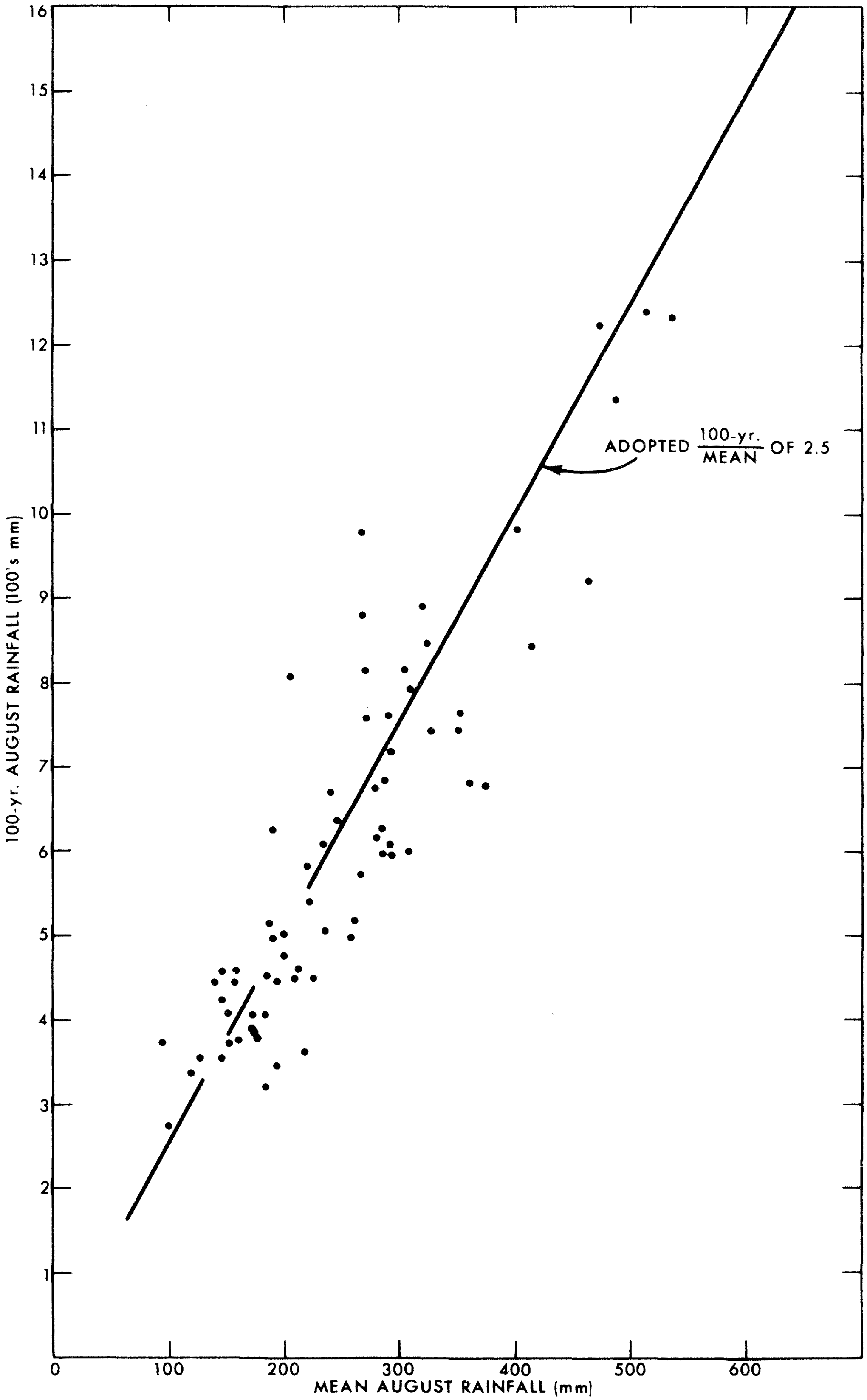


Figure 5-5. August, mean vs. 100-yr station rainfall

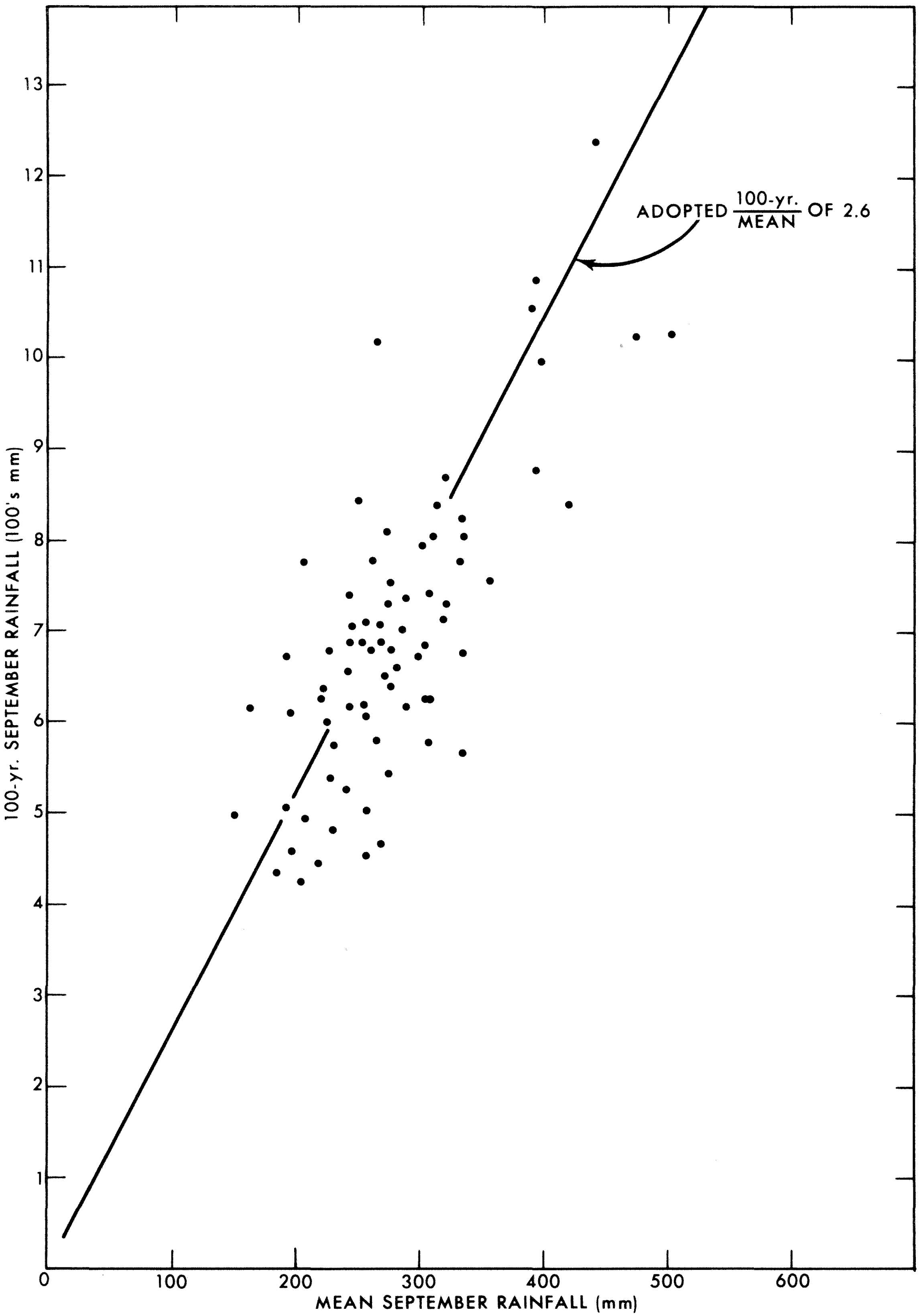


Figure 5-6. September, mean vs. 100-yr station rainfall

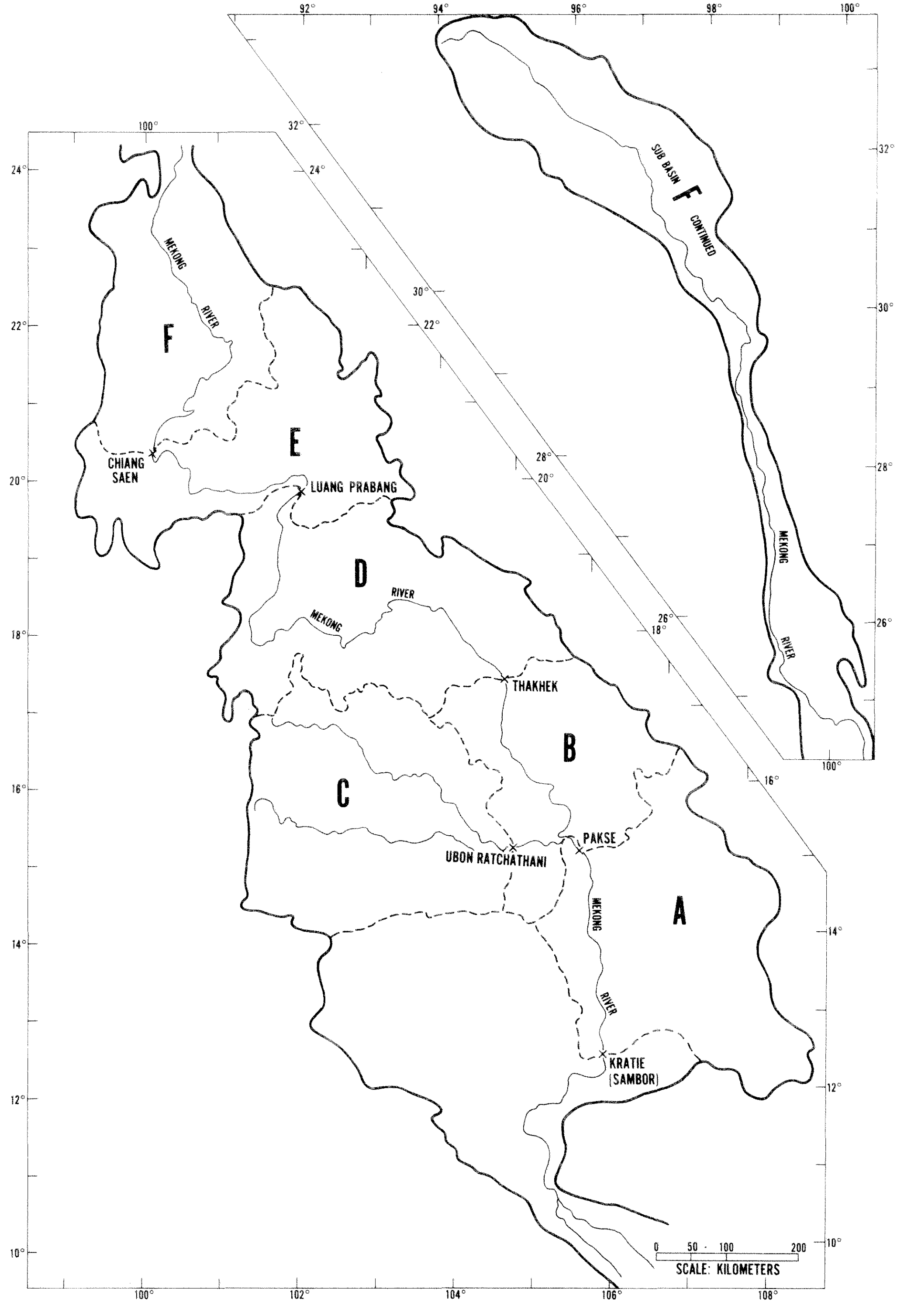


Figure 5-7. Subdrainages of the Mekong Basin

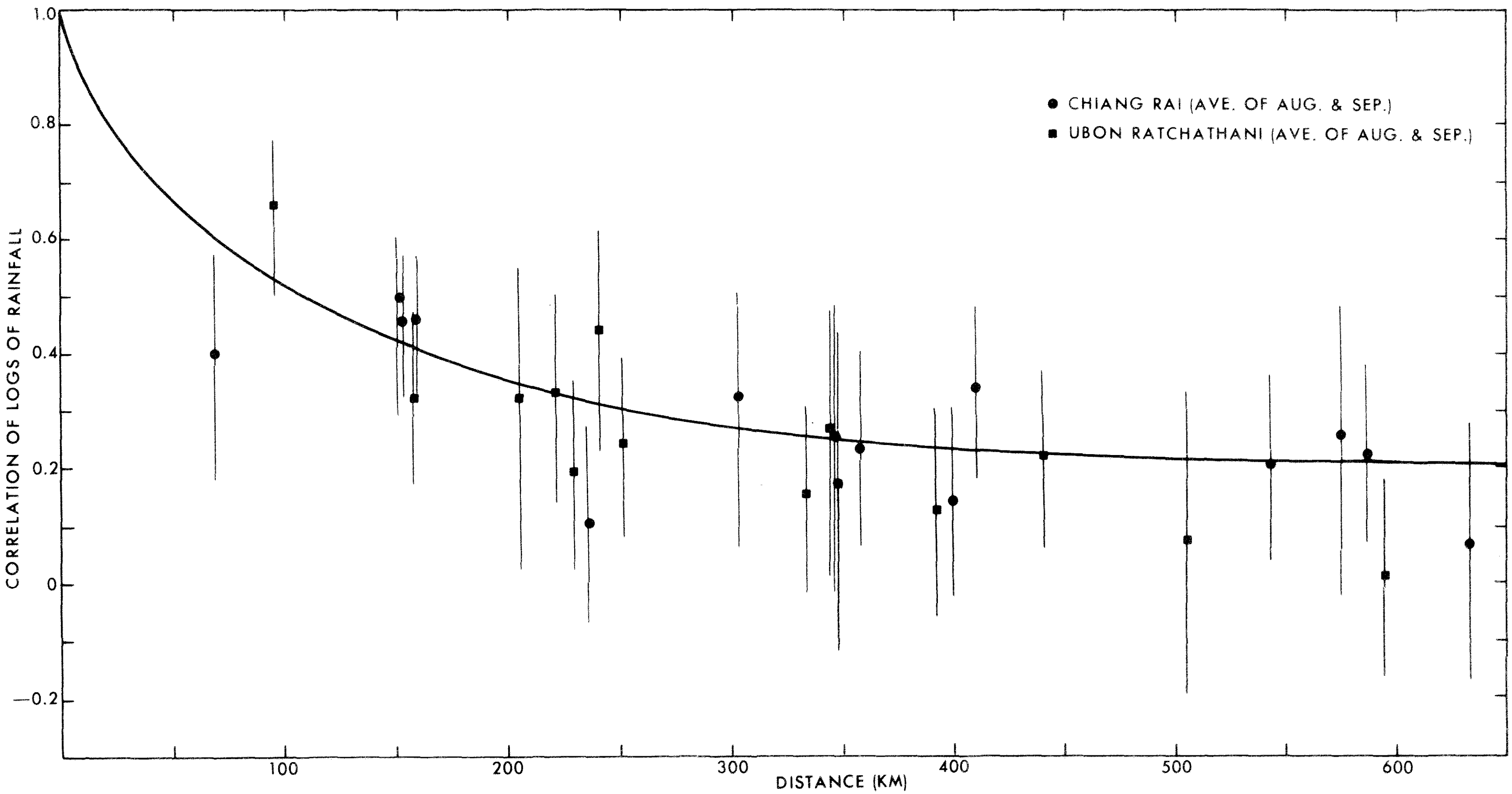


Figure 5-8. Monthly rainfall correlations vs. distance, Mekong Basin. Based on correlations of rainfall at Chiang Rai and Ubon Ratchathani, Thailand, with other stations to north and east during August and September.

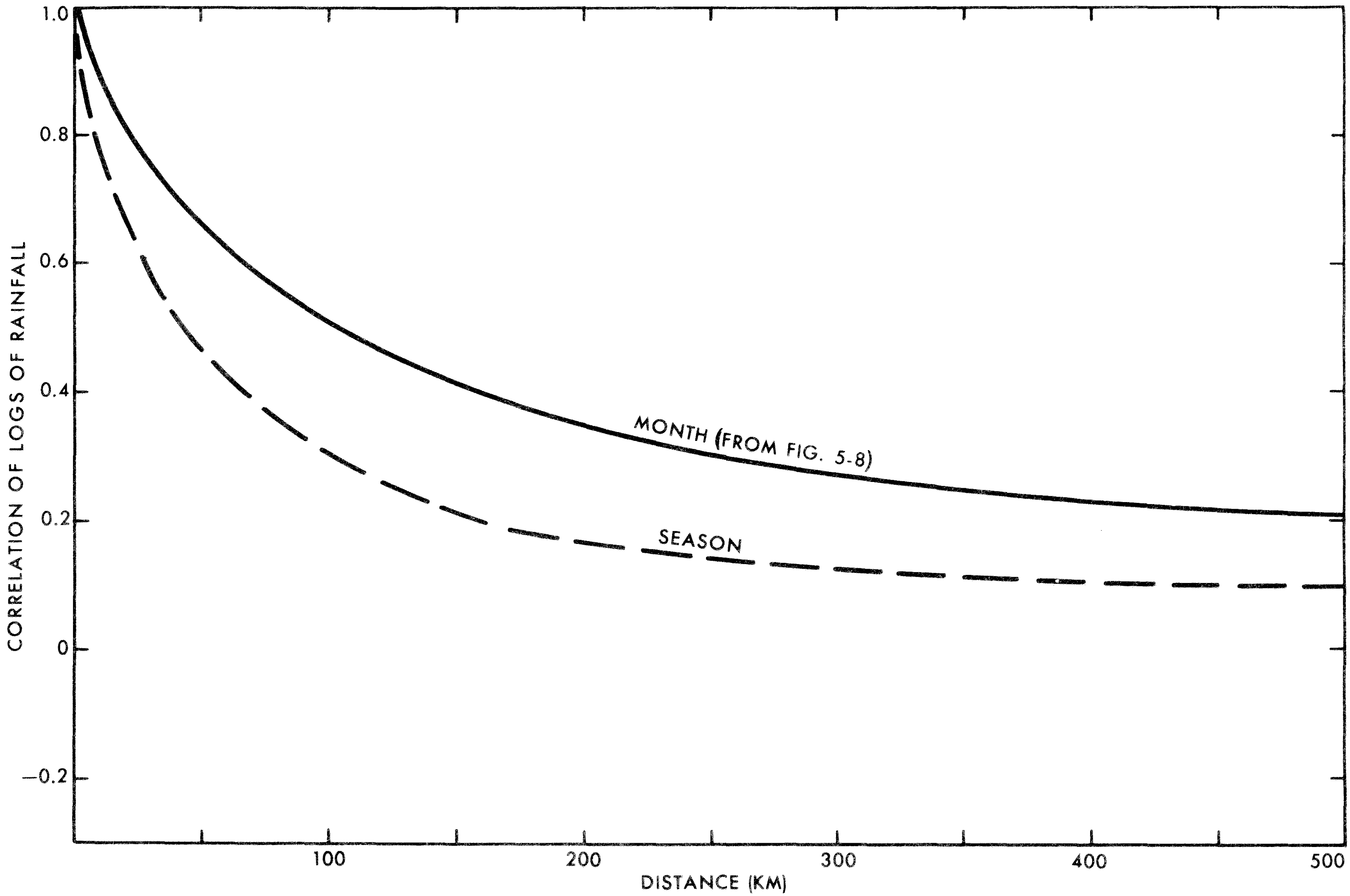


Figure 5-9. Monthly and seasonal rainfall correlations vs. distance, Mekong Basin. Monthly curve from figure 5-8. Seasonal curve is for May through August or May through September. Derived by reduction of monthly curve. See text.

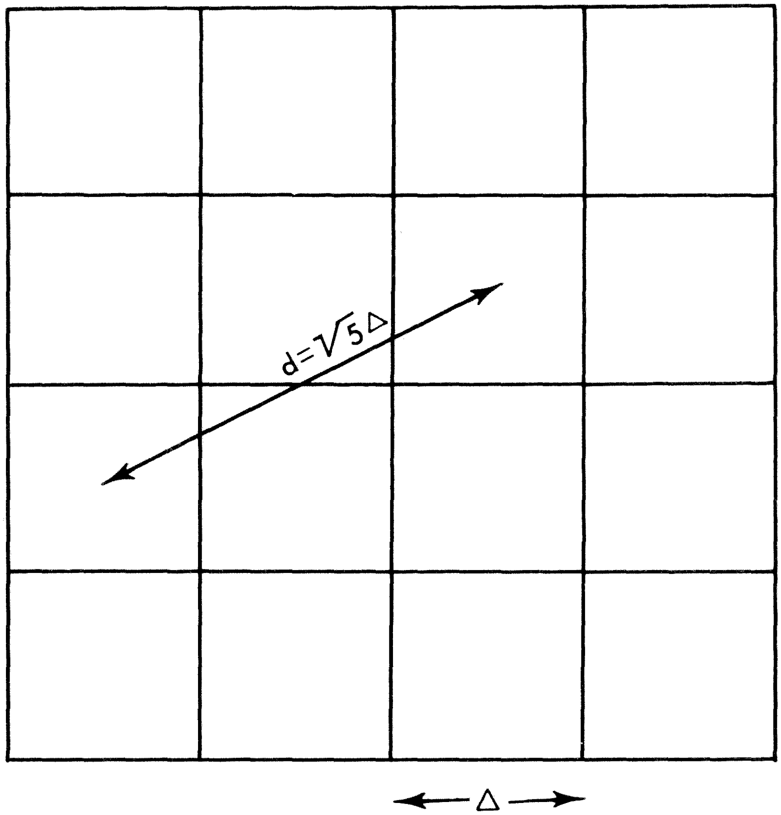


Figure 5-10. Schematic division of basin into squares N=16. Q=4.

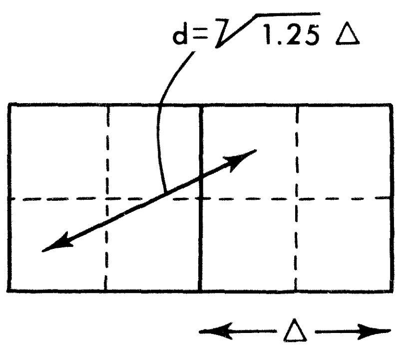


Figure 5-11. Division of adjacent squares into quarter-squares for refinement of correlation coefficient

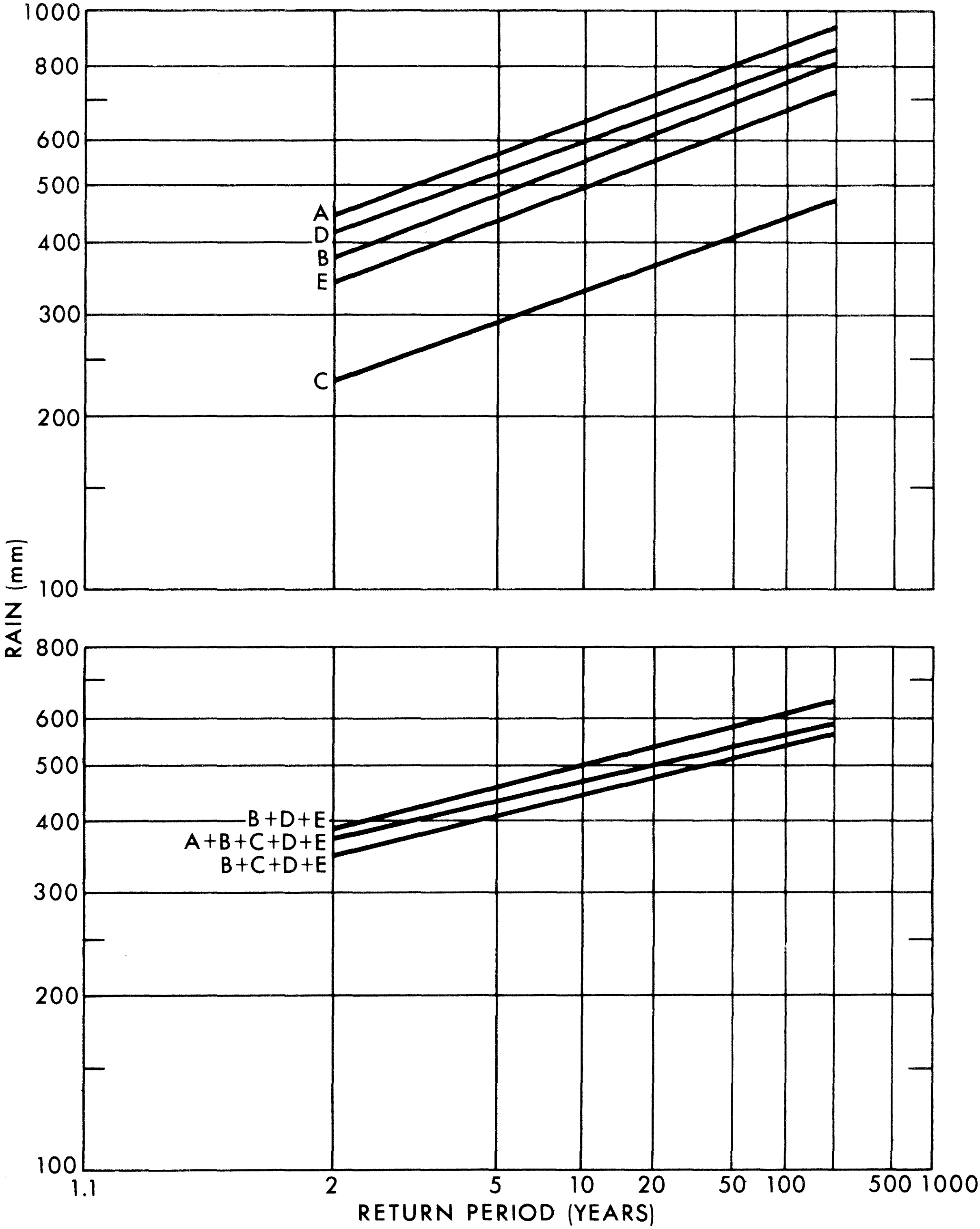


Figure 5-12. Rainfall frequencies, August

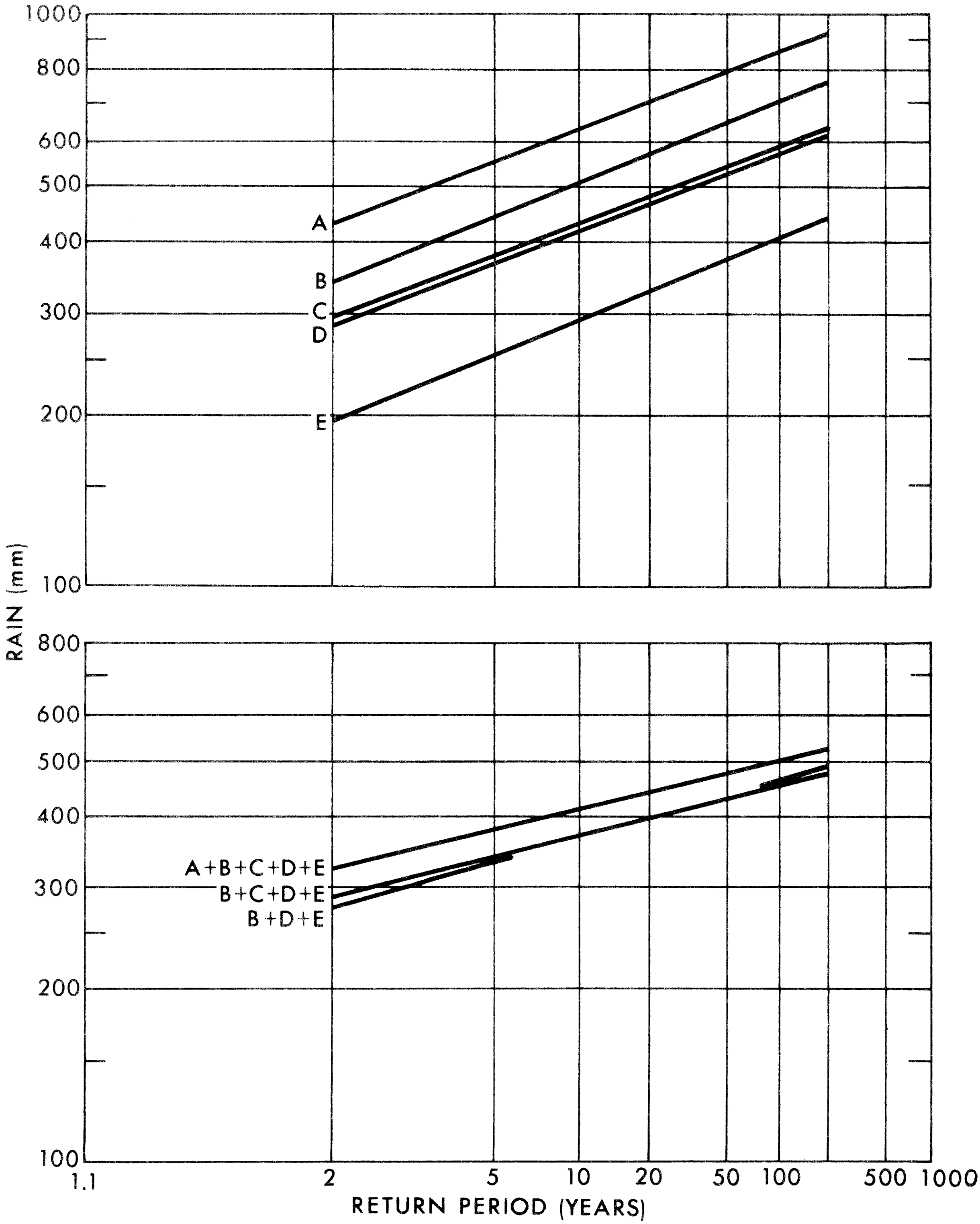


Figure 5-13. Rainfall frequencies, September

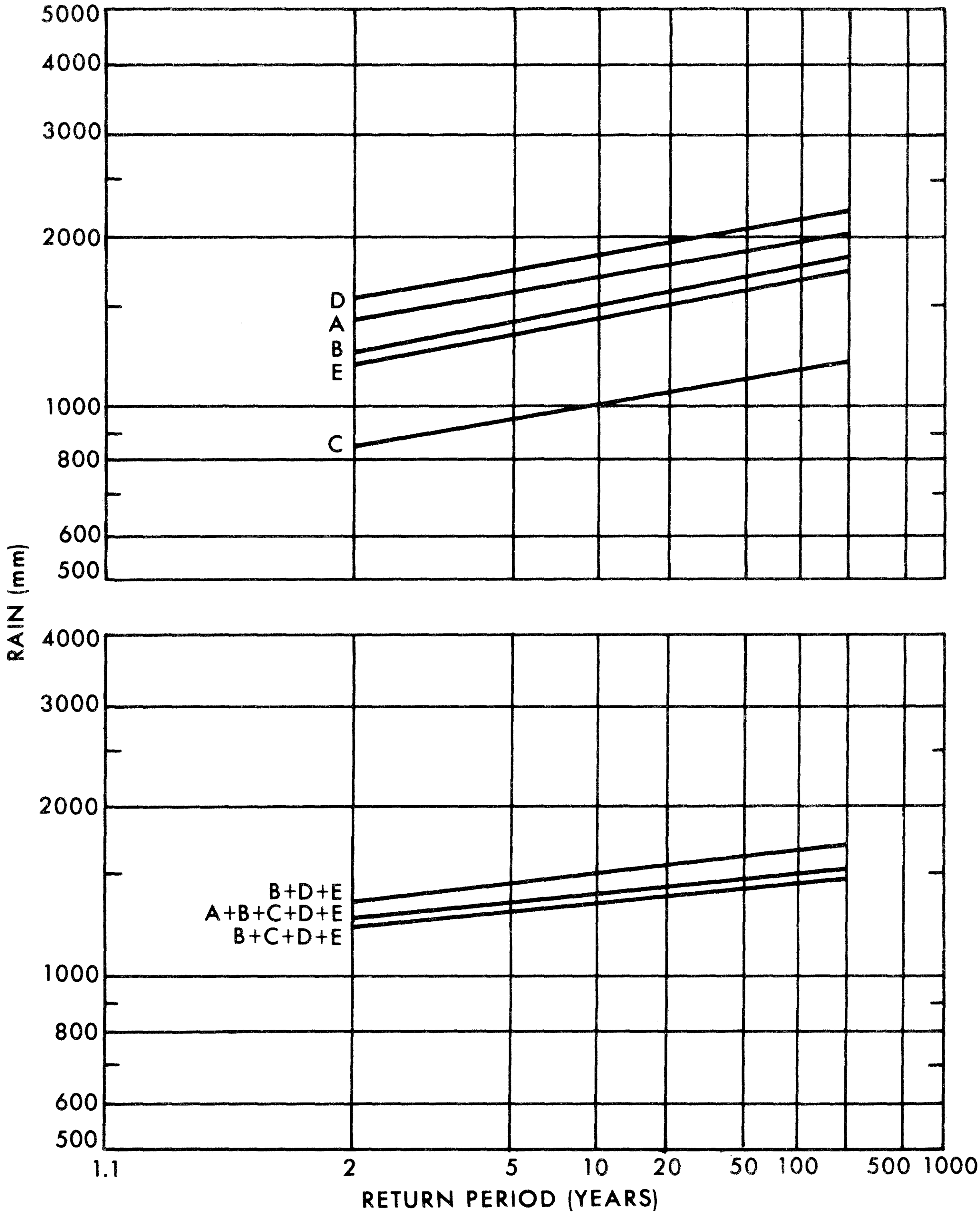


Figure 5-14. Rainfall frequencies, May-August

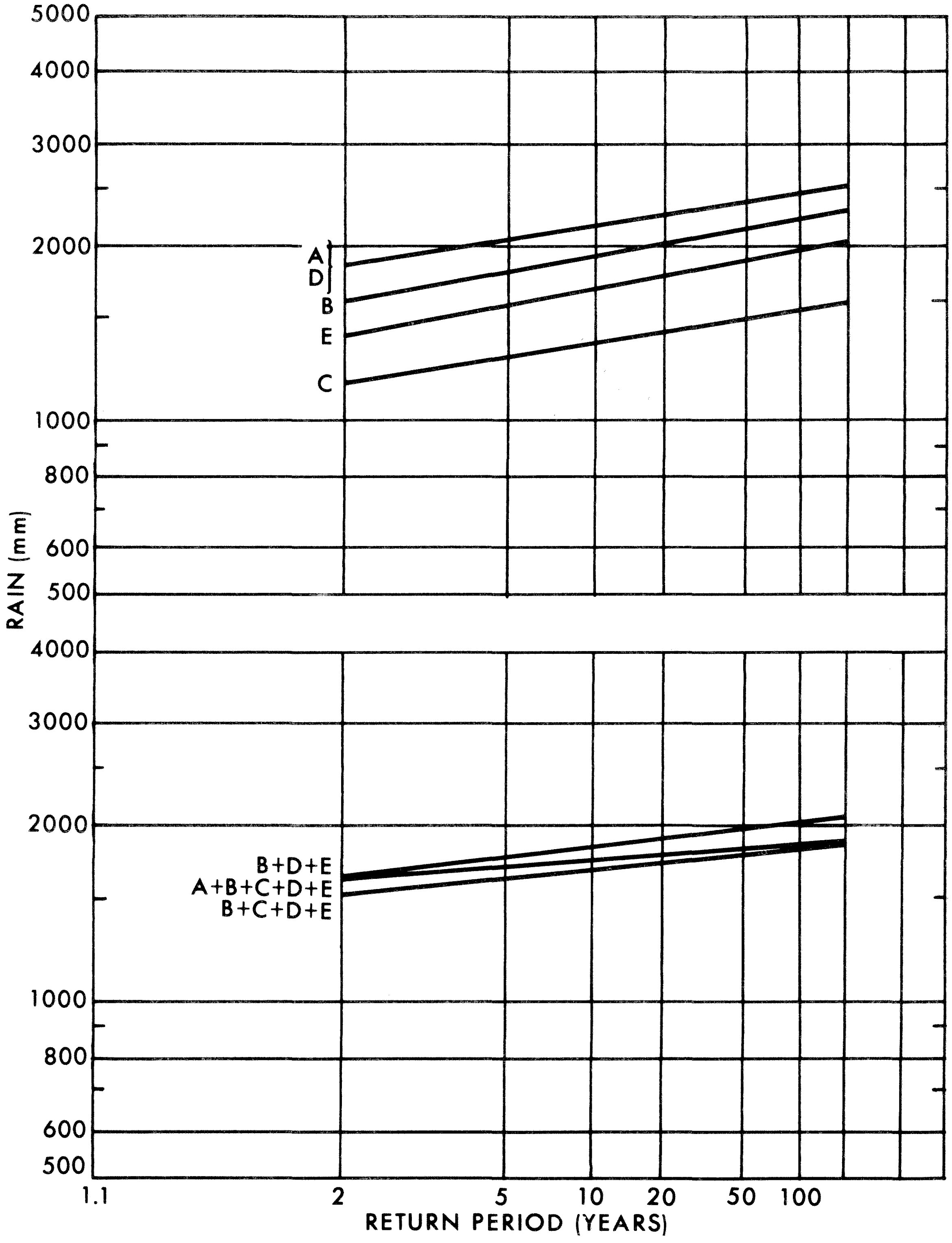


Figure 5-15. Rainfall frequencies, May-September

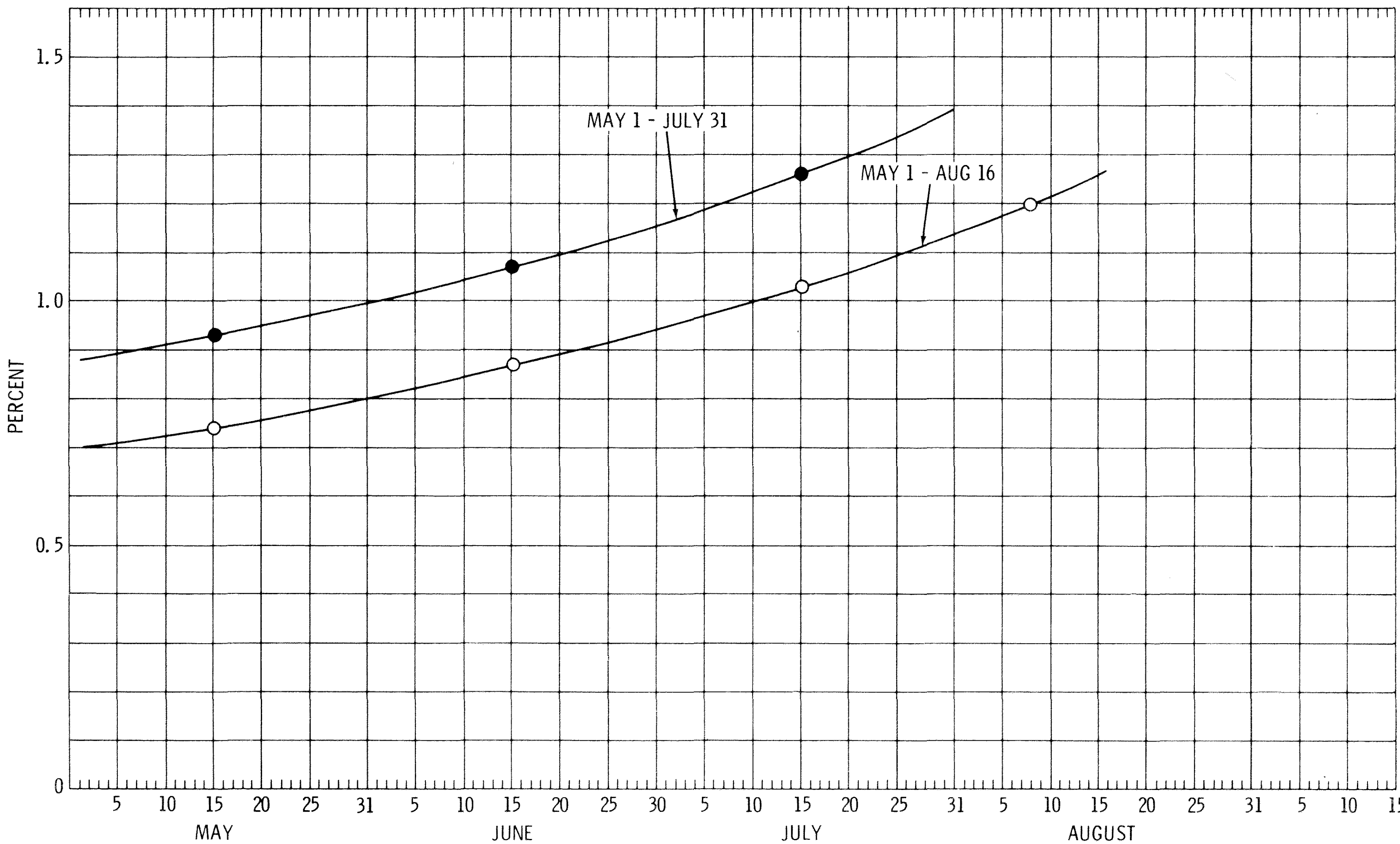


Figure 5-16. Smoothed percents of May 1-July 31 and May 1-August 16 rainfall for each day

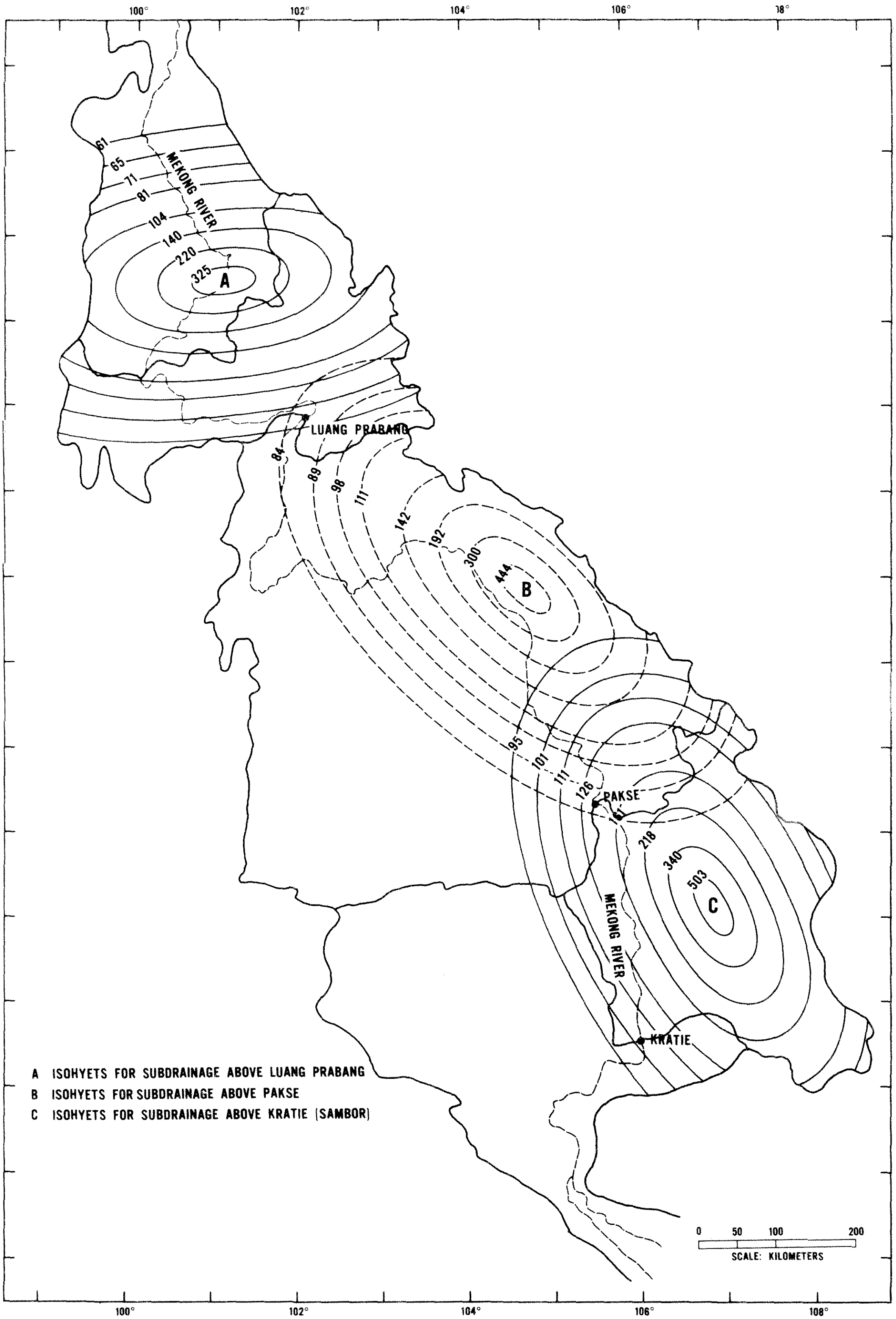


Figure 5-17. 1-day typhoon PMP isohyets in subdrainage upstream from dam sites

APPENDIX

ANALYSIS OF IMPORTANT TROPICAL STORMS AFFECTING THE LOWER MEKONG BASIN

Introduction

A survey of the record of typhoons and other tropical disturbances (2-3, 2-7, A-1) highlights a few typhoons which produced large rainfall amounts in the Lower Mekong. Two of these important storms were Tilda of September 21-25, 1964, and Vae of October 20-22, 1952. A third storm, typhoon Violet of September 14-17, 1964, was important for providing large rainfall amounts antecedent to Tilda.

Vae was particularly noteworthy as a severe storm at an unusually low latitude. Tilda, on the other hand, was a more prodigious rain-producer over large areas. This fact, combined with the greater abundance of precipitation data in this more recent storm, resulted in a more detailed analysis of the rainfall for Tilda.

The tracks of the October 1952 storm and the two storms of September 1964 are shown in figure A-1. Surface and upper-air weather maps, along with other sources of data (e.g., (2-3)), were used to define the smoothed storm paths.

Discussion of October 20-22, 1952 storm

Four typhoons affected Thailand in October 1952 but Vae was by far the most important. The discussion by the Thailand Meteorological Department emphasizes the unusual character of typhoon Vae. Vae moved westward in the China Sea on October 18 and later southwest at about 10 knots. Figures A-2 through A-4 show the surface and upper-air (approximately 6 kilometers) weather features of the storm.

The storm on the 20th had winds of about 40 knots. On the 21st it passed approximately 100 kilometers north of Saigon on a westerly track. On the 22d it passed close to Bangkok where a minimum pressure of 998.2 millibars was observed. Wind reached 49 knots at Bangkok and 53 knots at Sattahip on the east coast.

One-day rains amounted to 111 mm at Bangkok, 303 mm at Sattahip and 337 mm at Chantaburi.

It is instructive to make a comparison of the observed daily rains with what has been observed in an area affected by the passage of many hurricanes. Only 12 of 119 stations in the State of Florida, U.S.A. have experienced more than 337 mm of rainfall in a day (A-2) in spite of the large number of hurricanes that have affected the area. This points up the unusual nature of typhoon Vae for its latitude of occurrence.

Storm rainfall analyses

A primary purpose of a storm rainfall analysis is to obtain the maximum areal rain depths that occurred for selected durations. This is often termed a storm depth-duration-area (DDA) analysis. The procedure for carrying out such analyses is described in (A-3) and (A-4). In summary, it consists of drawing a total storm isohyetal map, and determining the largest areal average depths for selected time periods during the storm.

The usual procedure followed for the latter purpose is to construct mass rainfall curves (accumulated rainfall vs. time) for all reported rainfall totals within some selected minimum isohyet on the isohyetal map. An average mass curve is then constructed for all the stations within each isohyet, from the one with the greatest magnitude (inclosing the smallest area) to the one with the selected minimum magnitude (inclosing largest area). Each average mass curve is then adjusted by multiplying by the ratio of the total-storm average depth within its isohyet, determined from the isohyetal chart, to the total-storm depth of the mass curve before adjustment. From these adjusted mean mass curves, 6-hr incremental values are read and used to obtain maximum depths for 6, 12, 24, etc. hours.

After this is accomplished, largest areal depths for durations such as 6, 12, 24, etc., hours for areas within various storm isohyets can be selected and plotted on a graph and the maximum depths for the different area sizes smoothly enveloped for each duration (for example, see figure 3-3). Reading off values from such a chart at standard area sizes results in a table such as table A-1. A catalog of these data for all major storms in a region is basic to many hydrologic problems. For the present study it was only possible to select and analyze a few storms that appeared to be the most critical.

September 21-25, 1964 storm (Tilda). The total-storm isohyetal map is shown in figure A-5. Figure A-6 gives the rainfall stations. The isohyetal analysis was terminated at the major mountain ridge between Laos and Vietnam. Rains at coastal Vietnam stations appear deficient relative to rains in Thailand and no rain amounts are available for the coastal slopes. A similar cutoff of lesser importance was used on the western boundary.

Hourly rainfall values were available for 10 stations in Thailand. These stations are underlined on figure A-5. Almost all of the rain at these stations fell in approximately 36 hours, on the 22d and 23d, with little rain for several days before and after. The shape of the mass curve at all of these recorders is similar, but with an evident progression toward the west in the timing of the main rainfall burst. Therefore, the central and western portions of the total-storm isohyetal map were broken down into shorter time units of rainfall, in the manner described in reference (A-4) by use of a single standardized mass curve derived by averaging the recorders, but with a smooth progression in starting time of rainfall from east to west along the storm track.

Farther east, the rains were more uniform and spread over about six days between the 19th and the 25th. The timing of individual bursts was more chaotic. The time breakdown of rainfall here was based on mass curves obtained by direct average of groups of stations and some smoothing but no specific progression along the storm track.

Table A-1 gives the maximum depths for standard durations and areas derived by this analysis.

October 20-22, 1952 storm (Vae). An isohyetal map for typhoon Vae for the storm period of October 21-22, 1952, is shown in figure A-7. Although admittedly uncertain, an estimate was made of the overwater precipitation (not shown) from this storm in order to complete a reasonable isohyetal pattern.

Because of the limited amount of rainfall data in this storm, a detailed DDA analysis was not carried out. Instead, one- and two-day isohyetal maps were constructed independently by five meteorologists, and one- and two-day depth-area curves computed. Averages of the five resulting fairly consistent sets were used as representative of what occurred. Depths for standard areas of this storm are shown in table A-2.

September 14-17, 1964 (Violet). The total-storm isohyetal map for this storm is shown in figure A-8. Timing of rain was determined in a manner similar to that for Tilda. Hourly data were available for the same stations. Table A-3 gives maximum DDA values for the storm.

Table A-1

MAXIMUM RAIN DEPTHS FOR TILDA, SEPTEMBER 21-25, 1964

(Thailand and Laos)

Area Km^2	Duration (hr) 6	12	24	36	48	72
	Depth (mm)					
1000	165	282	385	412	427	470
2000	130	240	352	380	395	438
3000	112	219	336	364	378	420
5000	100	200	315	345	356	396
10,000	90	179	283	315	326	362
20,000	75	155	245	278	290	329
30,000	70	140	222	252	266	305
50,000	62	119	186	216	230	273
100,000	50	83	123	150	180	225
200,000	35	59	82	104	130	170
300,000	28	45	65	81	100	130

Table A-2

MAXIMUM RAIN DEPTHS FOR VAE, OCTOBER 21-22, 1952

Area Km^2	Duration 1-day (24 hr)	2 days (48 hr)
	Depth (mm)	
2000	305*	382*
3000	292	378
5000	275	370
10,000	245	355
20,000	207	332
30,000	180	315
50,000	147	287
100,000	98	225

* = estimated

Table A-3

MAXIMUM RAIN DEPTHS FOR VIOLET, SEPTEMBER 14-17, 1964

(Thailand and Laos)

Area Km^2	Duration (hr) 6	12	24	36	48
	Depth (mm)				
1000	95	120	170	205	215
2000	90	114	163	196	208
3000	88	110	160	190	200
5000	82	105	153	184	193
10,000	76	98	143	172	182
20,000	68	89	130	159	169
30,000	61	81	121	150	160
50,000	53	73	110	135	145
100,000	40	56	88	110	125
200,000	20	35	58	80	96

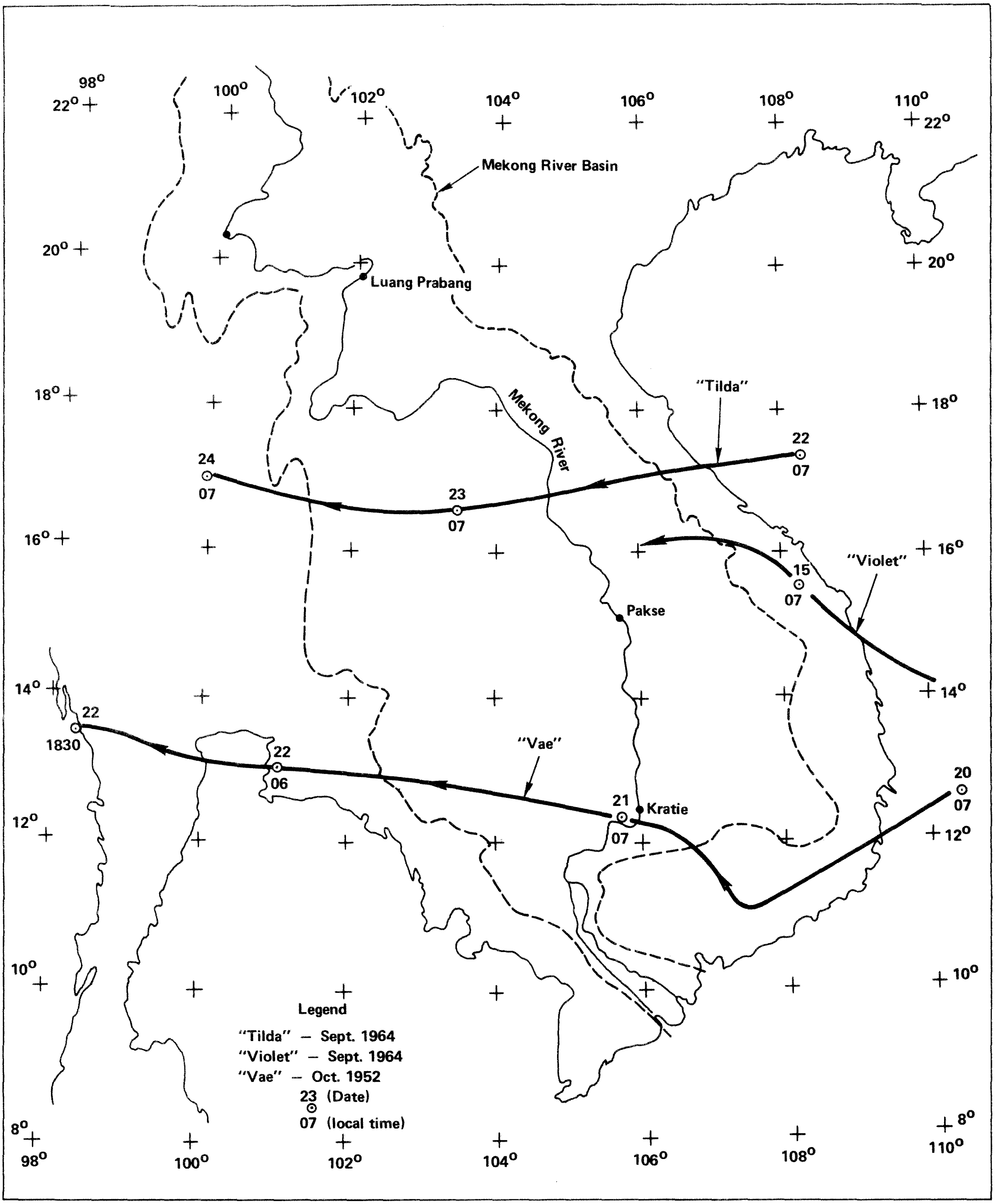
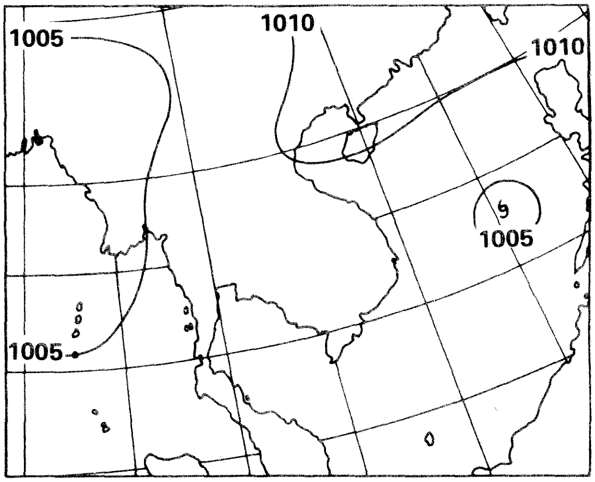
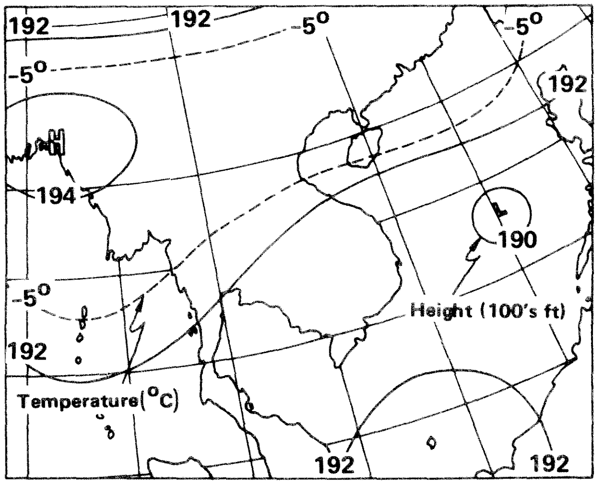


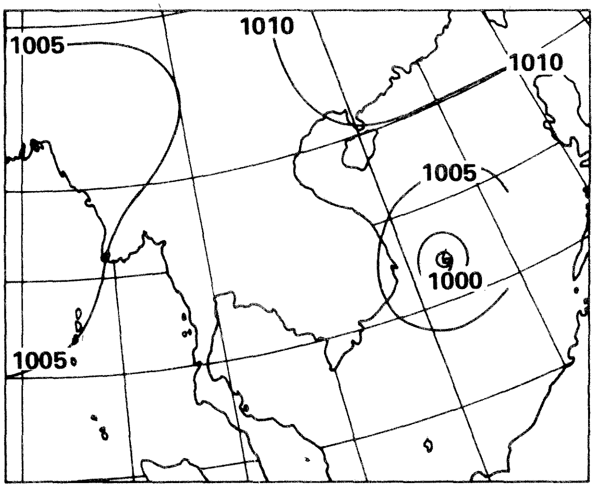
Figure A-1. Tracks of three Lower Mekong typhoons



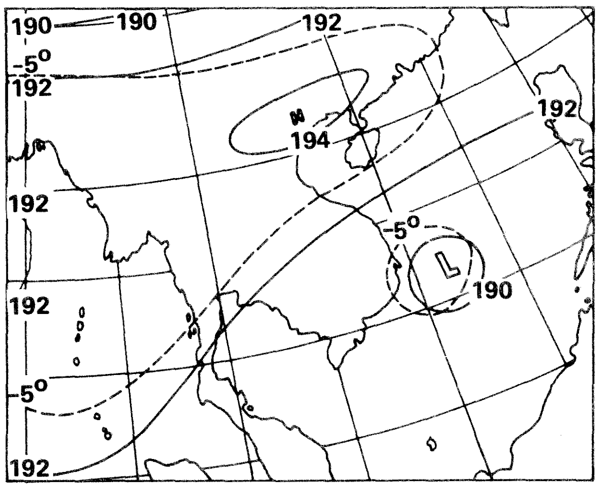
(Surface)
October 18, 1952 (1230 GMT)



(500 mb.)
October 18, 1952 (1500 GMT)

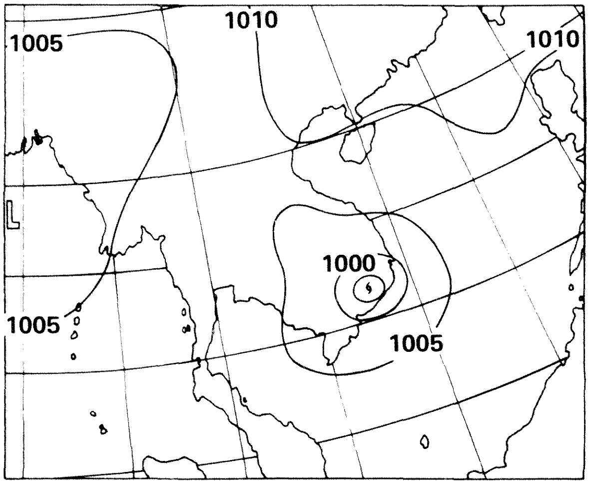


(Surface)
October 19, 1952 (1230 GMT)

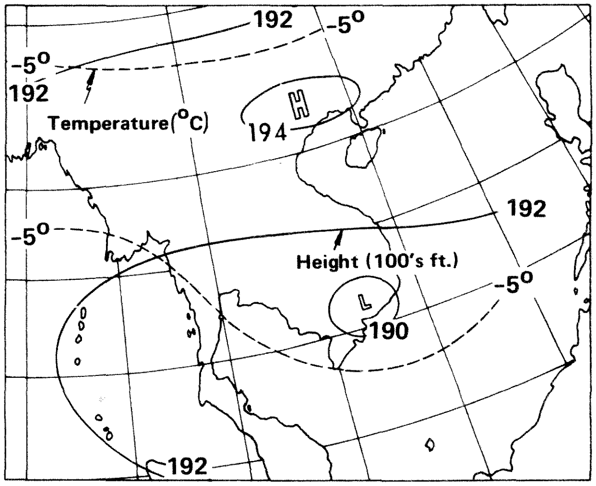


(500 mb.)
October 19, 1952 (1500 GMT)

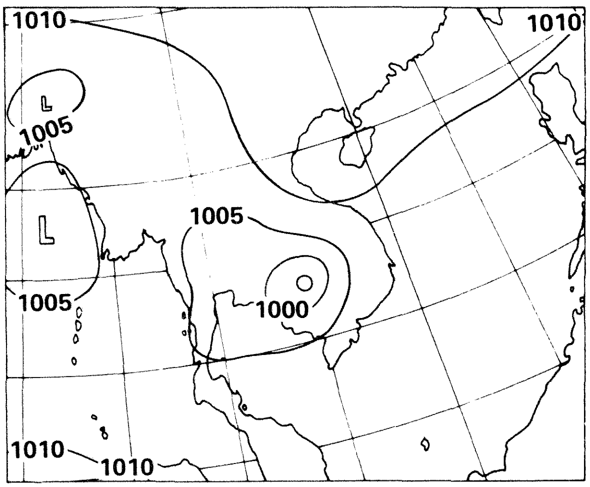
Figure A-2. Surface and upper-air charts for Typhoon Vae, October 18-19, 1952



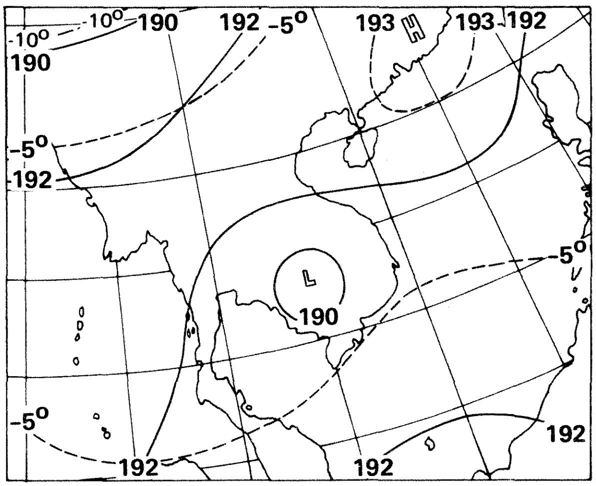
(Surface)
October 20, 1952 (1230 GMT)



(500 mb.)
October 20, 1952 (1500 GMT)

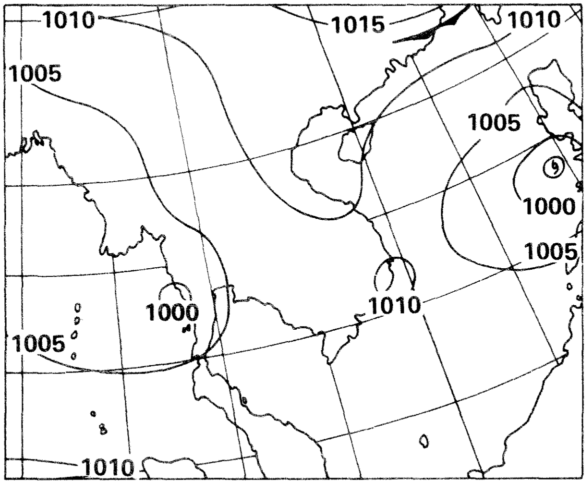


(Surface)
October 21, 1952 (1230 GMT)

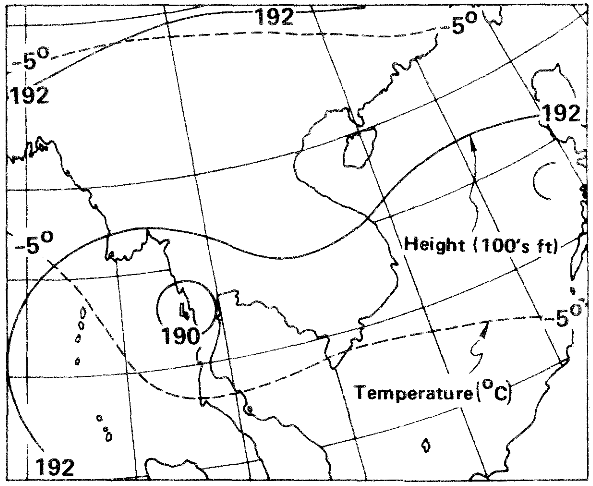


(500 mb.)
October 21, 1952 (1500 GMT)

Figure A-3. Surface and upper-air charts for Typhoon Vae, October 20-21, 1952



(Surface)
October 22, 1952 (1230 GMT)



(500 mb.)
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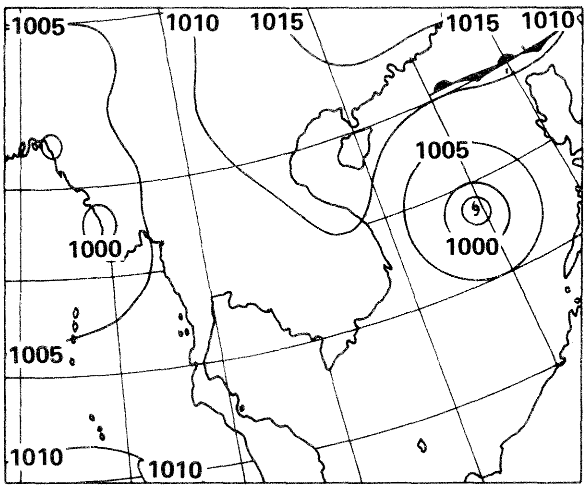
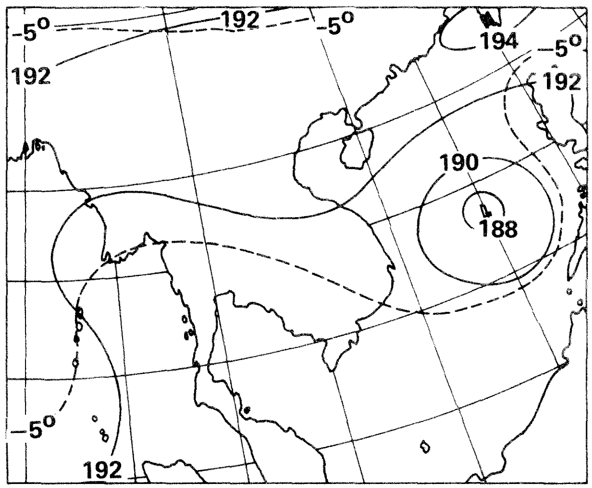


(Surface)
October 23, 1952 (1230 GMT)



(500 mb.)
October 23, 1952 (1500 GMT)

Figure A-4. Surface and upper-air charts for Typhoon Vae, October 22-23, 1952

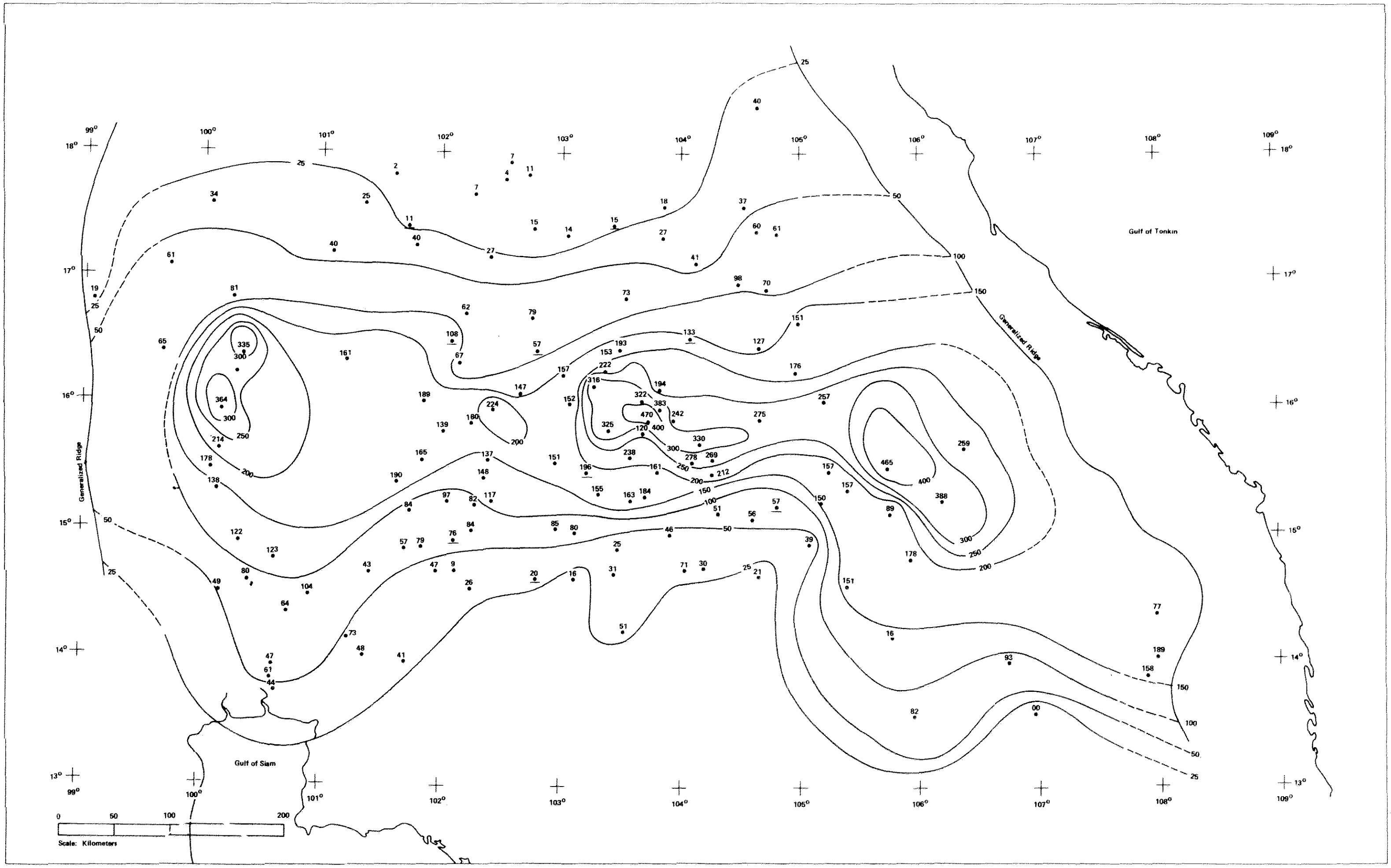


Figure A-5. Rainfall (mm) for storm of September 21-25, 1964 (Tilda)

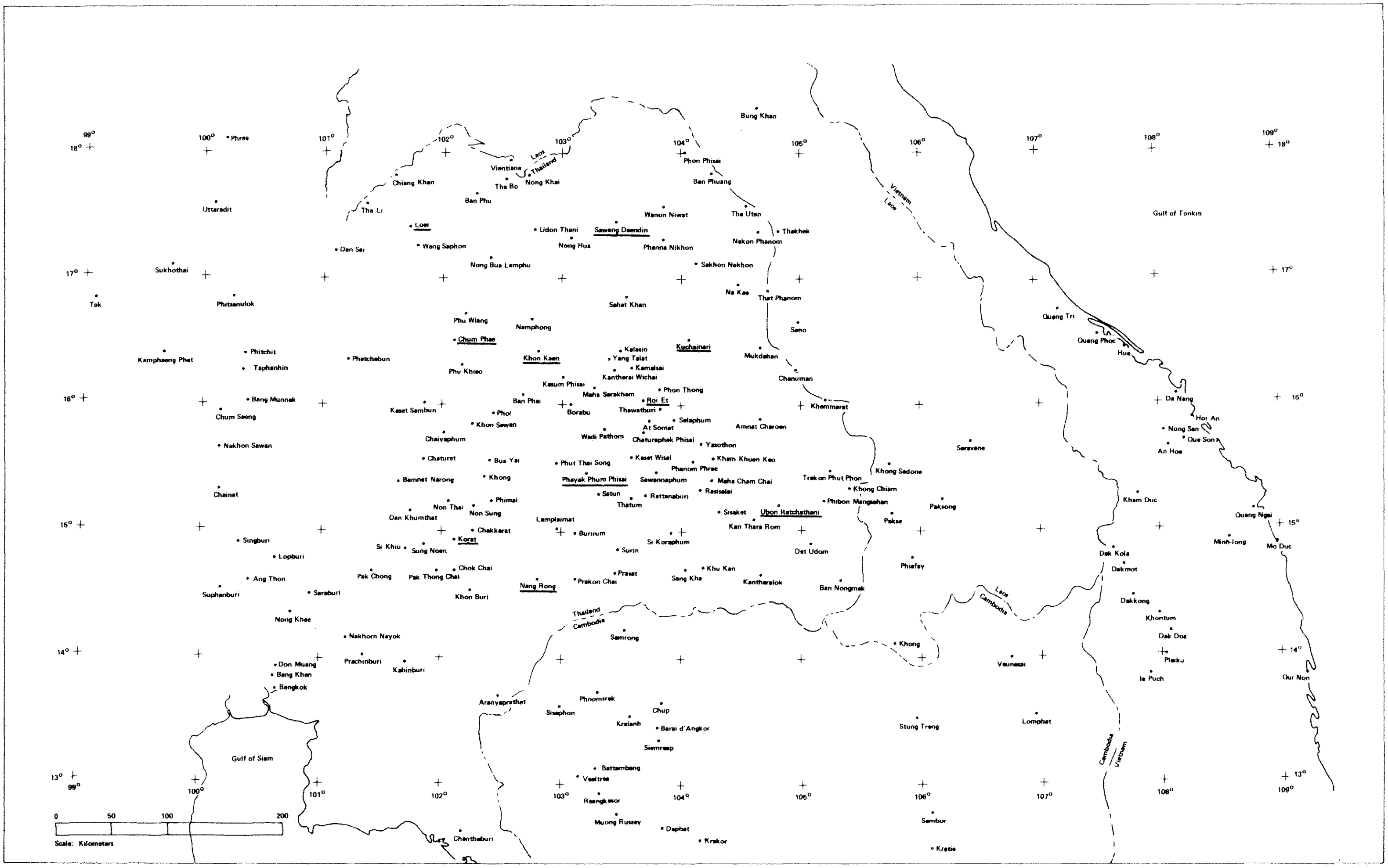


Figure A-6. Station locations for September 21-25, 1964 rainfall

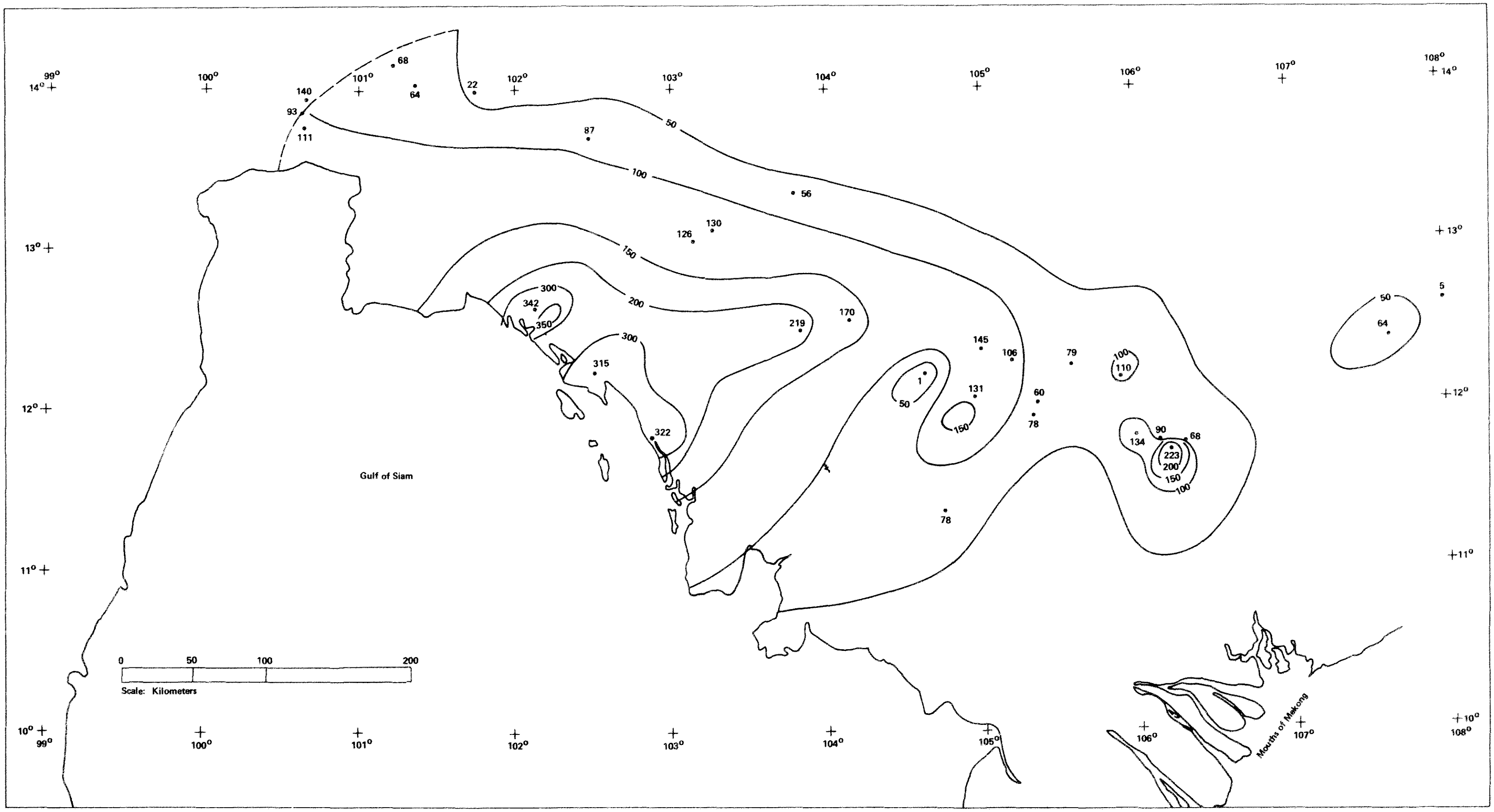


Figure A-7. Rainfall (mm) for storm of October 21-22, 1952 (Vae)

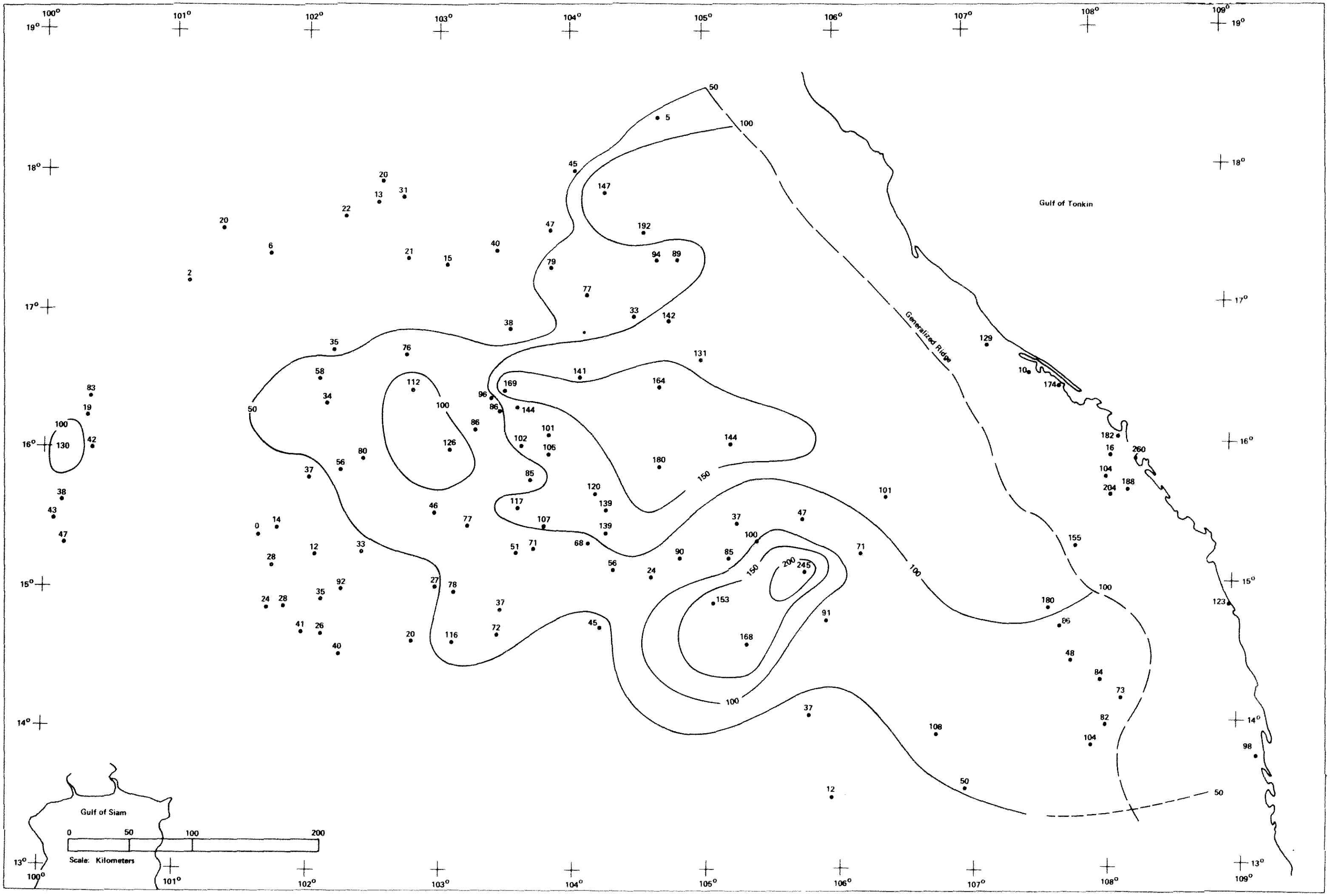


Figure A-8. Rainfall (mm) for storm of September 14-17, 1964 (Violet)

ACKNOWLEDGMENTS

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REFERENCES

1-1. United Nations, "A Compendium of Major International Rivers in the ECAFE Region," Water Resources Series No. 29, 1966.

1-2. Thailand Meteorological Department, "Monthly and Annual Rainfall of Thailand with Departure from Normal," (1911-1960), Bangkok.

1-3. Royal Thai Navy, "Monthly and Annual Rainfall of Thailand," (annuals), Bangkok.

1-4. Khiou-Bonthonn, "The Climat du Cambodge," (The Climate of Cambodia), Phnom-Penh, Cambodia, 1965.

1-5. Service Meteorologique, "Resume Mensuel du Temps en Indochine."***

1-6. Bruzon, E., and P. Carton, "Le Climat de L'Indochine et les Typhons de la Mer de Chine," Hanoi, 1930.

1-7. Service Meteorologique, "Bulletin Pluviometrique de Indochine,"* Phu-Lien, Hanoi.

1-8. Service Meteorologique, "Annales de L'Indochine," Phu-Lien, Tonkin**

1-9. Meteorological Department, Thailand, "Annual Meteorological Bulletin," Bangkok, various years.

1-10. World Meteorological Organization, "Climatic Normals (Clino) for Climat and Climat Ship Stations for the Period 1931-1960," Technical Paper No. 52.

1-11. Harza Engineering Company, "Hydrologic Data Mekong River Basin, Vietnam," various years.

1-12. Harza Engineering Company, "Hydrologic Data Mekong River Basin, Thailand," various years.

1-13. Harza Engineering Company, "Hydrologic Data Mekong River Basin, Laos," various years.

1-14. Harza Engineering Company, "Hydrologic Data Mekong River Basin, Cambodia," various years.

* Authors vary
** Issuing office varies
*** Title and issuing office vary

REFERENCES (Cont'd.)

1-15. Harza Engineering Company, "Lower Mekong River Basin Discharge Data Prior to 1960."

1-16. Technical Services 20th Weather Squadron, U. S. Air Weather Service, "Climate of North Vietnam," Special Study No. 105-4.

1-17. Technical Services 20th Weather Squadron, U. S. Air Weather Service, "Climate of Republic of Vietnam," Special Study No. 105-9.

1-18. Technical Services 20th Weather Squadron, U. S. Air Weather Service, "Climate of Thailand," Special Study No. 105-10.

1-19. U. S. Naval Weather Service, "U. S. Naval Weather Service Worldwide Airfield Summaries," Vol. I, Southeast Asia, June 1967.

1-20. Sternstein, Lawrence, "The Rainfall of Thailand." A study supported by the U. S. Army Quartermaster Corps, 1962.

1-21. U. S. Quartermaster Research and Development Center, Natick, Mass., "Environment of Southeast Asia," August 1953.

1-22. Environmental Data Service, "World Weather Records 1951-1960," ESSA, U. S. Department of Commerce, 1967.

1-23. Hydrographic Department, Admiralty, London, "China Sea Pilot," Vol. I, 2nd edition, 1955.

1-24. Weather Bureau, "An Annotated Bibliography on the Climate of the Republic of Vietnam," ESSA, U. S. Department of Commerce, 1966.

1-25. Weather Bureau, "An Annotated Bibliography on the Climate of North Vietnam," ESSA, U. S. Department of Commerce, 1965.

1-26. Environmental Data Service, "An Annotated Bibliography on the Climate of Laos," ESSA, U. S. Department of Commerce, 1967.

1-27. Environmental Data Service, "An Annotated Bibliography on the Climate of Cambodia," ESSA, U. S. Department of Commerce, 1967.

1-28. Technical Services 20th Weather Squadron, U. S. Air Weather Service, "Climatic Atlas of Indochina," Special Study 105-6.

1-29. Technical Services 20th Weather Squadron, U. S. Air Weather Service, "Far Eastern Climatic Atlas," Special Study 105-7.

REFERENCES (Cont'd.)

1-30. Schutz, C., "Monsoonal Influences on Wind, Rain, and Cloud Throughout Southeast Asia: A study covering the peninsula and Archipelago." The Rand Corporation, California, 1967.

1-31. United Nations Committee for the Coordination of Investigations of the Lower Mekong Basin, Lower Mekong Hydrologic Yearbook, various years.

1-32. United Nations, Economic Commission for Asia and the Far East (ECAFE), Water Resources Journal, various months.

1-33. Great Britian Meteorological Office, Air Ministry, Tables of Temperature, Relative Humidity and Precipitation for the World, Part 5, Asia. London, 1960.

1-34. Yao, A. Y. M., "Precipitation for Chinese Stations." Selected sheets with stations in vicinity of Mekong Basin.

1-35. Gherzi, S. J., "Etude Sur La Pluie en Chine 1873-1925."

1-36. Central Meteorological Bureau "Chung-Kuo Ch'i-hou T'u." (An Atlas of Chinese Climatology), Peiping, 1960. (Translated by the U. S. Joint Publications Research Service).

1-37. U. S. Corps of Engineers, unpublished rainfall data.

1-38. National Geographic Society, National Geographic, Vol. 134, No. 6, December 1968, map insert of Southeast Asia.

1-39. Meteorological Department, "Climatological Data of Selected Meteorological Stations in Burma," (1950-1960), Vol. I, Revolutionary Government of the Union of Burma, 1962.

2-1. Rainbird, A. F., "Weather Disturbances over Tropical Continents and Their Effect on Ground Conditions," Department of Atmospheric Science, Colorado State University, 1968.

2-2. Riehl, H., "Cumulus Convection and Orographic Convection Cells," Department of Atmospheric Science, Colorado State University, 1965.

2-3. Chin, P., "Tropical Cyclones in the Western Pacific and China Sea Area from 1884 to 1953," Hong Kong, 1958.

2-4. Fujita, T., H. Neustein, and M. Tepper, "Mesoanalysis - An Important Scale in the Analysis of Weather Data," U. S. Weather Bureau Research Paper No. 39, 1956.

REFERENCES (Cont'd.)

2-5. Griffiths, J. F., and W. K. Henry, "Research on Tropical Rainfall Patterns and Associated Mesoscale Systems," Texas A&M University, Department of Oceanography and Meteorology, Report No. 4.

2-6. Henry, W. K., "The Mesoscale Rainstorm in Cambodia," Part F of Research on Tropical Rainfall Patterns and Associated Mesoscale Systems, 1968.

2-7. Fleet Weather Control, "Annual Typhoon Report," various years.

3-1. Remenieras, G., "Statistical Methods of Flood Frequency Analysis," in "Assessment of Magnitude and Frequency of Flood Flows," Water Resources Series No. 30, ECAFE, United Nations, 1967.

3-2. Myers, Vance A., "The Estimation of Extreme Precipitation as the Basis for Design Floods - Resume of Practice in the United States," International Symposium on Floods and Their Computation, Leningrad, August 15-22, 1967. Also distributed in slightly modified form as "Meteorological Estimation of Extreme Precipitation for Spillway Design Floods," U. S. Weather Bureau Technical Memorandum WBTM HYDRO-5, 1967.

3-3. Cry, George W., "Tropical Cyclones of the North Atlantic Ocean," U. S. Weather Bureau Technical Paper No. 55, 1965.

3-4. U. S. Weather Bureau, "Probable Maximum and TVA Precipitation Over the Tennessee River Basin above Chattanooga," Hydrometeorological Report No. 41, 1965.

3-5. Watts, I. E. M., "Equatorial Weather, with Particular Reference to Southeast Asia," Pitman Publishing Co., New York City, N. Y. 1955.

3-6. U. S. Hydrographic Office, "Sailing Directions for Soenda Strait and the Western Gulf of Borneo and Off-lying Islands," 1951.

3-7. Gray, William M., "Global View of the Origin of Tropical Disturbances and Storms," Monthly Weather Review, October 1968.

3-8. Arakawa, H., "Typhoon Climatology as Revealed by Data of the Japanese Weather Service," from Technical Report of the Japanese Meteorological Agency No. 21, March 1963.

3-9. Koteswaram, P., "Movement of Tropical Storms Over the Indian Ocean," Indian Meteorological Department, New Delhi, 1963.

REFERENCES (Cont'd.)

3-10. Pacific Science Board, National Academy of Sciences - National Research Council, "A Report on Typhoon Effects Upon Jaluit Atoll," Atoll Research Bulletin No. 75, Washington, 1961.

3-11. Riehl, H., "Southeast Asia Monsoon Study," Department of Atmospheric Science, Colorado State University, 1967, p. 12.

3-12. U. S. Weather Bureau, "Interim Report - Probable Maximum Precipitation in California," Hydrometeorological Report No. 36, Washington, 1961.

3-13. Weather Bureau, "Probable Maximum Precipitation, Northwest States," Hydrometeorological Report No. 43, ESSA, U. S. Department of Commerce, 1966.

4-1. Corps of Engineers, U. S. Army, "Storm Rainfall in the United States," Washington, 1945-.

5-1. Thom, H. C. S., "Some Methods of Climatological Analysis," World Meteorological Organization Technical Note No. 81, Geneva, 1966.

5-2. Chow, V. T., "Frequency Analysis," Handbook of Applied Hydrology Chapter 8, McGraw-Hill Book Company, New York, N. Y. 1964.

5-3. Benson, M. A., "Uniform Flood-Frequency Estimating Methods for Federal Agencies," Water Resources Research, Vol. 4, No. 5, October 1968, pp. 891-908.

5-4. Water Resources Council, Hydrology Committee, "A Uniform Technique for Determining Flood Flow Frequencies," Bulletin No. 15, Washington, 1967.

5-5. Beard, L. R., "Statistical Methods in Hydrology," U. S. Army Engineer District, Corps of Engineers, Sacramento, California, 1962.

5-6. David, F. N., "Tables of the Correlation Coefficient in Small Samples," Biometrika Office, University College, London, Cambridge University Press, 1954.

5-7. U. S. Weather Bureau, "Probable Maximum Precipitation Susquehanna River Drainage above Harrisburg, Pa.," Hydrometeorological Report No. 40, 1965.

A-1. Thailand Meteorological Department, Weekly Weather Report, various years.

REFERENCES (Cont'd.)

A-2. U. S. Weather Bureau, "Maximum 24-Hour Precipitation in the United States," Technical Paper No. 16, 1952.

A-3. World Meteorological Organization, "Guide to Hydrometeorological Practices," Publication No. 168T, Switzerland, 1965.

A-4. World Meteorological Organization, "Manual for Depth-Area-Duration Analysis of Storm Precipitation," WMO - No. 237, TP. 129, 1969.

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