ESTIMATE OF THE MAXIMUM PROBABLE PRECIPITATION FOR ALBERTA RIVER BASINS

by

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ABSTRACT

Point measurements of maximum depth showed that over 50% of the rainstorms occur in June and July, with only a small percentage in April (5.6) and September (10.1). The greatest frequency of occurrence is observed in the Waterton Lakes Park area (just about 1 per year), with relatively high frequencies along the continental divide and decreasing eastward along the foothills and plains of Alberta.

Point measurements of maximum depth also showed that the greatest frequencies of occurrences are those in the Waterton Lakes Park area with probability of 2.0 (twice a year) for depths 50 mm and more; 0.38 (1:3 year event) for depths 100 mm and more; and 0.09 (1:10 year event) for depths 150 mm and more. Seasonally the greatest frequencies are observed in June for southern Alberta and in July for central Alberta. Severe storms (150 mm and greater in depth) are observed to occur in four main regions of the province.

Estimates of "Probable Maximum Precipitation" (PMP) using the meteorological approach were made for six river basins for 6-, 12-, 24-, 48-, 72-, 96-hour rainfalls. The maximum estimates of the PMP seem to occur in June for the basins in the southern portion of the province, while in central and northern Alberta the maximum estimates were found to occur in July. Spatial variability of the PMP is also observed in each of the river basins. The largest decrease of the maximum PMP is recorded in the South Saskatchewan River basin. Here at the eastern edges of the basin, the PMP estimates are about 80% lower than those calculated at the western edges.

A second method of estimating the PMP, using the statistical technique developed by Hershfield, was also applied to 27 first-order stations. These estimates were about 50 mm higher (for areas of about 250 km^2) in the six river basins. The largest estimates by this technique were also obtained in the South Saskatchewan River basin.

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1. INTRODUCTION

1.1 BACKGROUND

For many years, scientists have recognized the importance of meteorological and climatological phenomena in their relationship to hydrological problems, particularly flooding which results from major rainstorms. Heavy rainfalls may result in extreme flooding which can cause extensive damage. In situations where the risk of a structure's failure must be minimized, the "Probable Maximum Precipitation" (PMP) is used in the design of a structure. Thus, by incorporating meteorological parameters, an attempt is made to fix physical upper limits to the rainfall that could occur over certain basins during specified time intervals. To understand the spatial and temporal distribution of PMP, it is desirable to identify those rainstorms (their location, time of occurrence, and severity) which may contribute to extreme flooding.

It is these aspects of the PMP in Alberta which are addressed in this study. To obtain a better understanding of the spatial and temporal distribution of rainstorms in Alberta, rainstorms which produced a depth 50 mm or more for the period 1921 to 1978 were first identified from all readily available data sources. The rainstorms were classified according to maximum severity and examined for spatial and temporal variations. For all severe rainstorms where a depth-area-duration (DAD) analysis was available, a PMP was estimated based on meteorological consideration of available moisture in the six river basins examined. A second method of estimating the PMP, using a statistical technique developed by Hershfield (1961,1965), was employed to the precipitation data from all first-order weather stations in Alberta. Results calculated using the statistical technique are compared to those calculated by the traditional approach (where méterological considerations are applied) for six river basins in Alberta. A review of the available literature on PMP and data sources used precedes the results of this study.

1.2 LITERATURE REVIEW

1.2.1 United States Studies

A large number of studies of PMP have been conducted over the past 40 years. The disastrous floods in the United States during the late 1930's initiated investigations by a number of authors (Craeger 1939; Bailey and Schneider 1939; Hathaway 1939) into the subject of the "maximum probable flood" and its relationship to spillway capacity in considering the design of dams. With these studies, the concept of PMP gained favour and a number of comprehensive research programs were initiated. Prior to that time, the design of spillways was based on historical records and spillways were constructed to allow a flood 50 to 100% greater than the largest which had occurred for the recorded period (mostly less than 25 years). The theory of probability was first applied to flood studies about 1914; that is, curves were derived from past records on a stream and the frequency with which a given flood could be expected to occur. From periods with a few years of records (seldom exceeding 20 years and very seldom exceeding 30 or 40 years), probability curves were extrapolated to estimate average expected flooding during longer durations of time - once in 1 000, 5 000, or 10 000 years. The return flood period curves were then selected for the design capacity of the spillway. Some of the floods which occurred in the 1930's, based on probability studies, would have a return period, not of the usually assumed 1 000 to 10 000 years, but of once in millions or even billions of years. One such example is the flood in 1935 on the Republican River in Nebraska which was over 10 times as large as had ever occurred on that river during the 40 years recorded. The probability method would not have made provision for an adequate spillway for that storm. By 1939, the probability method was proven by advanced studies and a greater accumulation of data to be entirely inadequate. Because of these circumstances, the importance of meteorological studies in the design of flood control structures was realized and initiated (Creager 1939). During this period, the idea of mass rainfall curves was developed and used for storm analysis (Hathaway 1939; Bailey and Schneider 1939). The next important development was the use of dew points as a measure of the precipitable water in the moist air. Showalter and Solot (1942) concluded that the maximum amount of rain which can occur over a given basin can be determined from the amount of moist air that can flow over the basin and the maximum amount of moisture which can be precipitated from that moist air. Using the two examples given in their study, the authors determined these functions from combined synoptic statistical studies of major storms.

It was not until 1953 (Paulhus and Gilman 1953) that PMP was defined and a distinction drawn between it and probable maximum storm. To this time, the terms were used liberally and interchangeably in the literature, the distinction being that the probable maximum precipitation for a specific area is usually determined by several types of storms. Paulhus and Gilman further outlined a maximizing procedure used in the derivation of PMP, which consists chiefly of moisture adjustment and, when justifiable, transposition of the observed storms. This procedure serves today as the basis for calculating estimates of the PMP and is found in the literature under various names: "traditional", "meteorological" or "physical" approach. Moisture adjustment of a storm involves the estimation of the increased precipitation that could be expected if maximum atmospheric moisture were available. The surface dew point is used as an index of the moisture in the storm and of the maximum moisture in the basin. Paulhus and Gilman (Ibid.) further mention that the tests they conducted indicated that the lowest dew point in the 12-hour period corresponding most nearly to the 12-hour period of greatest rainfall was most representative of the average moisture in the storm centre. This dew point was labelled as the "representative 12-hour persisting dew point". The maximum 12-hour persisting dew point to which the storm values are adjusted is the highest value below which the dew point did not drop during any 12-hour period of record. All dew points were reduced pseudoadiabatically to the 1 000 mb level to make the dew points for stations at different elevations comparable and to permit the use of tables and charts of moisture in atmospheric columns with base at 1 000 mb. Maps of maximum dew points and tables of moisture content, expressed in terms of precipitable water, have been published by the U.S. Department of Commerce, Weather Bureau (1948, 1951).

For many years this "traditional" approach continued to be popular and was generally accepted. A different variation for calculating the PMP was introduced by Hershfield (1961), who proposed a statistical method for the systematic analysis of precipitation data in estimating the PMP. He proposed that the 24-hour PMP at a precipitation observing point be estimated from the generalized frequency equation (Chow 1951) in the form:

$$X_m = \overline{X}_n + K_m S_n \qquad (1)$$

The data required for this evaluation include the maximum observed daily precipitation during each recorded year. $\overline{X}_n$ and S_n are the mean and the standard deviation of the series. X_m is the desired PMP while K_m is a constant to be determined empirically by an enveloping process. Hershfield evaluated K_m individually from 2 645 station records in the United States and elsewhere and found this quantity to vary from about 1.2 to 15. In his study, Hershfield did not assume a distribution in evaluating K_m. The transposed factor in this method is the maximum observed value of K_m; namely, the number of standard deviations that must be added to the mean of the annual series to produce an extreme. Concern over sampling errors led the author to derive empirical adjustment factors for such data deficiencies as small sample size and calendar-day rainfall rather than the 1 440-minute maximum rainfall. Hershfield (1965) expanded on the statistical procedure introduced in 1961 by analyzing a series of annual maximum rainfalls for seven durations ranging from 5 minutes to 24 hours for 200 50-year U.S. Weather Bureau stations. In addition, 2 500 24-hour stations used previously in the 1961 paper were also analyzed to determine the statistic, K_m. This method is now known as the "Statistical Method of Estimating the PMP". Like other schemes depending on empirical coefficients, the equation proposed by Hershfield is a convenient way of approximating an answer when little is known about the estimated quantity. It fails to yield a precise answer because of lack of universal transposibility of any one value of K_m.

Severe rainstorms also occur in various parts of Canada. During the late 1950's and throughout the 1960's, a number of studies were begun to estimate the PMP for various Canadian river basins.

1.2.2 Canadian Studies

In Canada, one of the preliminary estimates of PMP for severe storms was researched by Bruce (1957a) who performed an analysis of the rainfall for the most severe storm on record in Ontario, i.e., storm "Hazel" (14 to 15 October 1954). At that time, the only depth-area-duration analysis available for Canadian storms were analysis for those storms which crossed the border from United States to Canada and which were documented in the various, storm rainfall in the U.S. series published by the U.S. Dept. of Commerce, Weather Bureau. Employing storm maximization and transposition as given by Paulhus and Gilman (1953), Bruce was able to use available DAD analysis to obtain preliminary estimates for southern Ontario. Bruce realized the importance of this work and outlined a number of studies which must be undertaken before the PMP could be examined for individual basins in southern Ontario, the main needs of analysis and research being: (1) DAD analyses of major storms of record; (2) determination of maximum snow melt in conjunction with maximum spring rainfall for individual basins; and (3) augmentation of the existing meteorological observation network with more precipitation stations, snow measuring locations, and temperature-humidity stations. Bruce's plea was answered in part with the Canadian Department of Transport, Meteorological Branch initiating a study which resulted in the "Storm Rainfall in Canada" series[1] which contains DAD analyses for major storms in Canada. This is a continuing series with a number of rainstorm analyses added each year.

Canadian research advanced in the 1960's when a number of studies were conducted to examine the critical meteorological conditions for maximum floods for specific river basins. One such study was that done by Bruce and Sporns (1963) for the St. John River Basin, New Brunswick. The main purpose of the study was to provide the design engineers with the basic information needed to estimate maximum flood flows. This included data on physical upper limits to storm rainfall, water snow accumulation, snowmelt rates, and optimum combinations of snowmelt and rain. In the study, a DAD of 63 storms was carried out and the PMP was estimated using the "physical approach". Comparison of the 24-hour-10 mi^2 (25 km^2)

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[1] Published by the Climatology Division of Atmosphere Environment Service in Toronto, Ontario.

values obtained by the storm maximization method showed very good agreement with results obtained using the Hershfield method. Bruce and Sporns did not evaluate K_m for the storms examined in the study, instead they assumed a value of K_m equal to 15 in the frequency equation[1]. The snowmelt computations were calculated using the generalized snowmelt equations based on energy balance considerations, developed by the cooperative snow hydrology studies carried out in western U.S. (U.S. Corps of Engineers 1956). These computations were compared with those obtained using the degree-day method. Bruce and Sporas concluded that the maximum melting rates accompanying major spring storms could be divided into two categories: short period (2-day) high melt rates[2]; and long period (6-day) lower melt rates[3].

A second study was that done by Bruce et al. (1965) for the Portage Mountain Reservoir, Peace River, British Columbia. The purpose of this study was to provide meteorological data and analyses to make an assessment of maximum inflow into the reservoir, of snowmelt, and storm rainfall. As in the previous report, maximization of the major recorded rainstorms was carried out using the physical approach. Even though the statistical method of Hershfield was used to corroborate the estimates of the PMP, it was found that the statistical method gave only slightly lower values than those obtained by the physical analysis. Maximum snow accumulation was calculated using two different

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[1] Hershfield found the maximum value of K_m for rainstorms from studies of data to be 15: this includes data from severe storms in India. The value of K_m equal to 15 is, of course, an upper limit, and not necessarily obtainable for Canadian storms.

[2] Bruce and Sporns denote this as the melt rate associated with air temperatures between 45 and 50°F accompanied by strong winds over 30 mph in a 24-36 hour duration.

[3] This is the melt rate resulting from air temperatures between 33 and 45°F, with moderate winds of 15 to 30 mph persisting for about 7 days.

approaches: the snowstorm maximization technique, and the partial season method. This accumulation was found to be 194% of the mean annual value 3302 mm depth or approximately 330 mm water equivalent.

Another study was performed for the St. Francois and Chaudiere River Basins, Quebec by Gagnon et al (1970). Like the previous two studies, this work considered only the meteorological aspects of rainstorms, snow accumulations, and snowmelt. The physical approach was also used in examining the PMP for the two basins. Given in the report are the maximum possible rainfalls for areas from 135 to 13450 km^2 and for durations from 6 to 108 hours. Gagnon et al. conclude that, for the above two river basins, the maximum possible flood for a small watershed results from a summer rainstorm but, for a large watershed, results from a combined spring rainstorm and snowmelt event.

1.2.3 Alberta Studies

Much of the work found in the literature for Alberta has been conducted by McKay and involves using the statistical approach for estimating the PMP. In one of the first of these studies, McKay (1965) obtained estimates of PMP for the prairie provinces by examining series of 24-hour extreme precipitation values for 191 long-term weather stations during the period from 1916 to 1960. The characteristics of the frequency factor K_m were presented, along with maps of the coefficient of variation and the mean. Average relationships for translating point rainfall information into areal rainfall were also computed for large prairie storms from available DAD analyses. McKay supplied graphs showing the conversion from a point with 24-hour rainfall extremes to durations of 1, 6, and 12 hours. McKay concluded that, during the late spring and throughout the summer, the foothills of southwestern Alberta have the greatest storm potential within the prairie provinces.

In another study, McKay (1968) examined the meteorological conditions leading to the project design and probable maximum flood on the Paddle River. Again the statistical approach was used to examine available severe storms analyses. In addition, McKay computed snowmelt rates, using the U.S. Corps of Engineers melt rate equations and coefficients, and combined these estimates with the snowmelt associated with a major spring storm. Estimates of the water yield from the combined rain and snowmelt were computed, as shown in Figure 1, for various combinations of snow and forest cover. The solid lines in the figure indicate the total water released from: (a) the storm, (b) the storm plus one day melt, (c) the storm plus two day melt, and so on. The broken line shown indicates how much snow can be expected to be on the ground under average ablation rate conditions.

Buckler (1969) has examined the probable maximum rainfall for the Bighorn Power Development in Alberta. Maximization of the precipitation using the meteorological approach was carried out for seven Alberta rainstorms from 1900 to 1969 with the largest rainfalls for 1 000 mi^2 (2560 km^2) areas and durations of 1 to 3 days. In this study, Buckler analyzed 16-year period of dew point records (1953-1968) for three stations (Calgary, Rocky Mountain House and Lethbridge Airport) by frequency analysis and obtained 100-year return period values of computed dew point temperatures for durations of 1, 3, 6, 12, 24, 48, and 72 hours, for each station. It should be pointed out that no tests were made to determine if the persisting dew point temperatures were representative of the moisture content of the storm. Paulhus and Gilman (1953) concluded that the 12-hour persisting dew point temperature was most representative of the average moisture in the storm centre, and this has been for years the internationally accepted value used in estimating the PMP. In this report, the 12-hour persisting dew point temperature is used, following the procedure outlined in the World Meteorological Organization

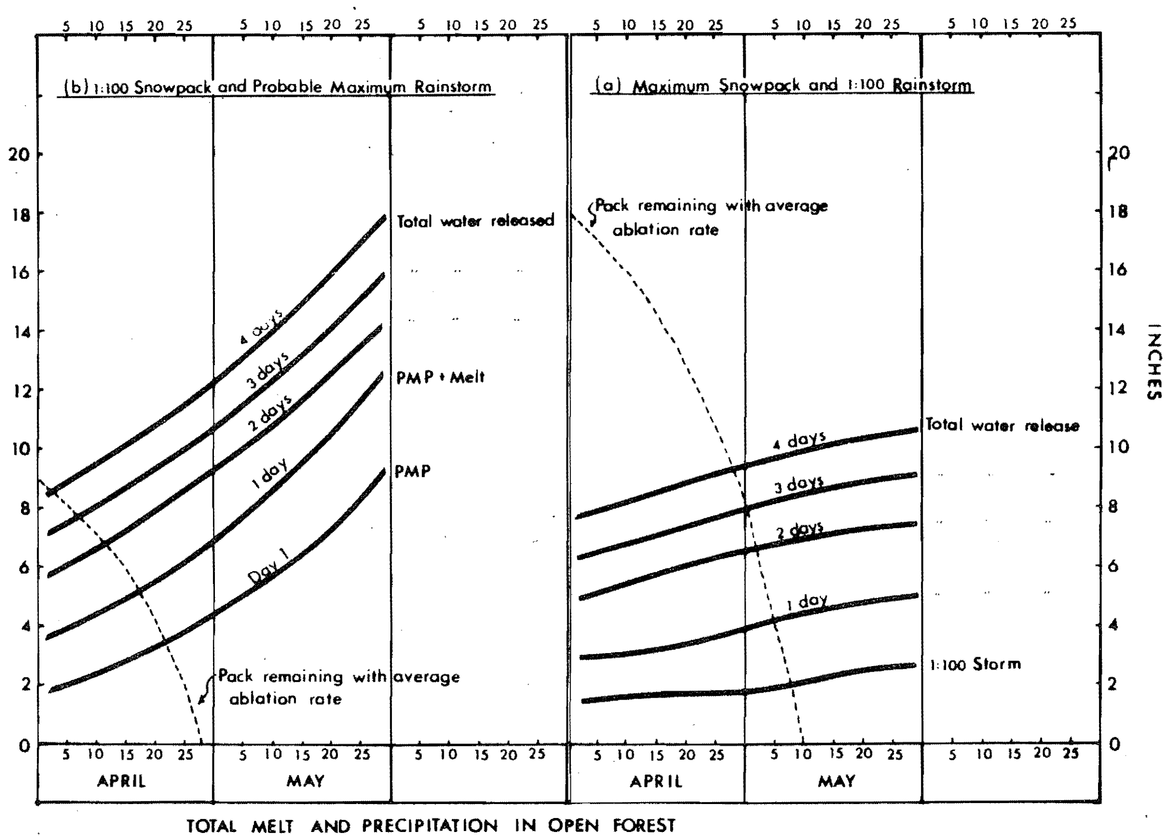

Figure 1 Snowmelt and precipitation computed for various combinations of snow and forest cover (McKay, 1968).

(W.M.O.) (1973) and advocated by many hydrologists. The use of dew point temperatures for durations other than 12-hour was introduced first by McKay (1963b) for a few stations with a short record length in the prairie provinces. The physical interpretation and the method of using these values is not well understood and requires further research. Buckler (1969) concluded in his work that, for the watershed of the Bighorn Power Development, snowmelt floods can occur in June and that the maximum possible flood would be the result of a combined snowmelt and rainfall event.

Another study which examined critical meteorological conditions for maximum flow was that presented by Buckler and Quine (1971) for the Pembina Valley north of Entwistle. They estimated the probable maximum snow accumulation in the winter season and calculated the melt due to the highest possible warm spell followed by a 3-day rainstorm (Figure 2). The melt rates were calculated using the energy balance equations and coefficients developed by the U.S. Corps of Engineers (1956). The results were compared with the PMP likely to be encountered in that climatic zone. The PMP was estimated by the physical approach and gave average amounts of 14.2 inches (360 mm) of rainfall in the Pembina basin.

The first extensive research effort to examine snowmelt and the rain-on-snow event was conducted by the U.S. for the western part of the United States at the Central Sierra Snow Laboratory (CSSL), Soda Springs, California. Using the experimentally evaluated coefficients of snowmelt, in terms of appropriate meteorological parameters, and applying thermal-budget indices of snowmelt to drainage basins, the Corps of Engineers derived general snowmelt equations applicable to drainage basins according to their physical characteristics. These equations are referred in the literature as the "generalized snowmelt equations" or "energy balance equations" developed by the U.S. Corps of

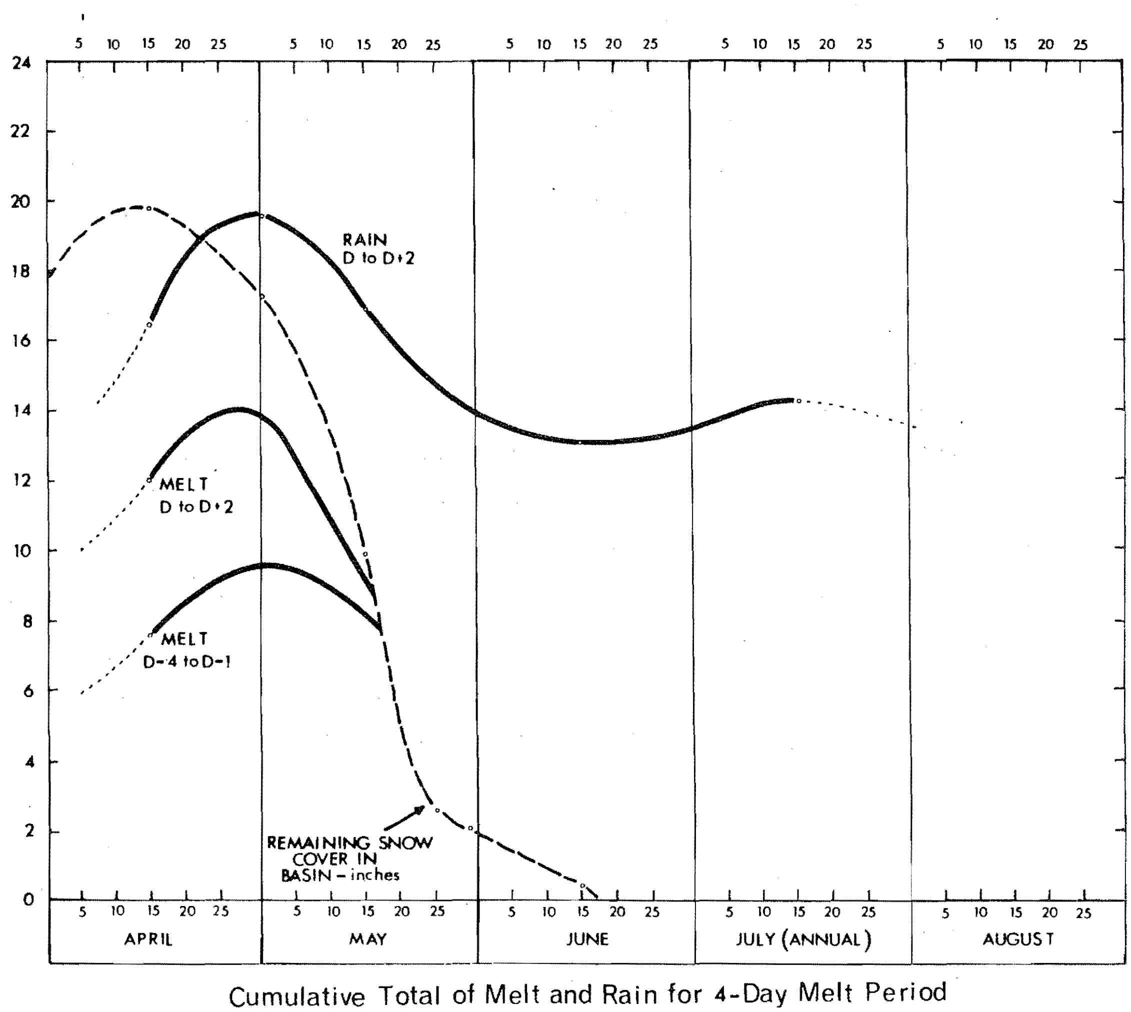

Figure 2 Cumulative total of melt and rain for 4-day melt period (Buckler and Quine 1971).

Engineers, and have been employed to data in Alberta by various authors (McKay 1965, 1968; Buckler and Quine 1971; Storr 1978) in computing snowmelt.

McKay (1968) conducted a study to examine the questions of floods due to possible snowmelt and rainfall for the Paddle River, Alberta. In his analysis, McKay employed the equations and coefficients of the "generalized snowmelt equation" for an open forest cover, together with postulated weather conditions likely to be associated with a major spring storm. The size of the concurrent storm was estimated statistically using a modified version of the frequency equation given by Chow (1951). The total melt and precipitation for April and May were computed for the maximum snowpack assuming the occurrence of a one in 100-year rainstorm and the results presented in graphical form. Verification of these results against actual runoff events was not tested because of insufficient data.

In another study, Storr (1978) found close agreement in daily snowmelt calculated by the "generalized snowmelt equation" with that measured by snowpillows at Marmot Creek, Alberta. For days uncomplicated by snowfall, priming of the snowpack, or a partially bare pillow, the slope of the best fit line is close to unity. Large differences between the model and the pillow were observed at the beginning and the end of the melt season. The data from the five melt seasons (1973 to 1977) in the mountainous environment of Marmot Creek showed that the average contributions to the calculated melt were as follows: shortwave radiation, 78.6%; longwave radiation, 20.9%; convection-condensation, 0.4%; and rain on the snowpack, 0.05%. Storr stressed that, if the snowpacks were subject to higher temperatures, humidities, wind speeds, or more rainfall, the melting responses would be different and the contributions would change. The importance of these results is that, for snowmelt without rainfall, nearly all of the total melt is due to radiation. This concludes the work done to date regarding the assessment of the PMP for river basins in Alberta.

1.2.4 Other Precipitation Studies Conducted for Alberta

Several other precipitation studies have been published for Alberta, however in most of these the authors examined individual storms that resulted in extensive flooding of the areas affected. One such study was the work by Thompson (1976), who reconstructed from archive records three storms (June 1897, July 1902, and June 1915) on the Bow and North Saskatchewan Rivers. From the records available, Thompson concluded that the storm type which produced heavy rainfall in all three cases was a "cold low"[1]. The rainfall which resulted in record floods from the 1897 and 1915 storms was of extraordinary intensity[2] whereas with the third storm (1902) was not as intense[3]. The latter event, however, was preceded by an exceptionally wet period during which the soil very likely became saturated and thereby enhanced storm runoff.

A more recent example of a rainstorm which produced severe flooding was that of the 7 to 8 June 1964 (Warner 1973), which occurred in the headwaters of many streams in Montana and southwestern Alberta. The main flood-producing area affecting Alberta was Waterton Lake National Park. Flooding was attributed

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[1] A "Cold Low" is defined by Huschke (1970) as: "At a given level in the atmosphere, any 'low' that is generally characterized by colder air near its center than around its periphery. A 'low' is defined as 'area of low pressure', referring to a minimum of atmospheric pressure in two dimensions (closed isobars) on a constant-height chart or a minimum of height (closed contours) on a constant-pressure chart".

[2] The four-day rainfall amount in the 1897 storm exceeded a 1:100 year event, while in the 1915 storm the two-day rainfall amount exceeded a 1:50 year value at Nordegg and Lovett.

[3] The heaviest one- and three-day amounts recorded during the storm are less than one in ten year return period amounts.

primarily to extreme rainfall influenced by pre-existing conditions: below normal temperatures which delayed the usual snowmelt-runoff pattern (from March to May); and above normal precipitation in May which resulted in large-scale melting of the snowpack in the latter part of May and continuing into June at a sustained high rate. The onslaught of the rain from the storm, totalling up to 16 inches (405 mm) at higher elevations along the Continental Divide in Montana and over 10 inches (255 mm) (an unofficial estimate) in the Waterton Park area of Alberta, followed a belt approximately 70 miles (110 km) wide that ran parallel to the eastern slope of the Rocky Mountains and along the foothills for some 200 miles (320 km) north of Helena, Montana.

Flood-producing rainstorms are not restricted to the southern part of the province, as mentioned in a study by Warner and Thompson (1974), who presented a report on the 11 to 12 June 1972 rainstorm in which more than 6 inches (150 mm) of rain fell over parts of the Peace River basin southwest of Grande Prairie, resulting in record flows in nearly all streams in that area. The heavy rain occurred because a cold low passed over central Alberta, which resulted in moist air to prevail over the southern Peace River basin for about 36 hours.

Other documented examples of rainstorms causing flooding conditions include studies in northern Alberta by McKay (1965) of the 30 July to 1 August 1953 storm on the Paddle River; by Froelich (1967) of the June 1965 storm in the southern Peace, Athabasca and North Saskatchewan basins; and by Mustapha (1970b) of the 27 June to 1 July 1970 storms in the Lesser Slave Lake and Lac La Biche forestry regions.

Regionalized estimates of probable maximum floods have been carried out for 72 sites in the prairie provinces by the Saskatchewan Nelson Basin Board (Godwin 1975). The estimates were made for floods covering areas with mountain-fed and prairie streams. The results show a linear decrease in the maximum mean daily peak flow per unit area (Figure 3) with an increase in drainage area for both types of streams, with the mountain-fed streams having a higher magnitude. The total volume per unit area (Figure 4) for a given drainage area was also observed to follow a similar pattern.

Studies of the synoptic conditions of severe rainstorms have also been published (Thompson 1976; Warner and Thompson 1974; McKay 1965). Chisholm (1962) analyzed the storm of 30 June to 1 July 1961 which produced most of its precipitation in the Grande Prairie to Lac La Biche area. This rainstorm, although the most intense storm occurring in Alberta in 1961, was by no means a "record-breaker". However this storm served as an example of a typical cold low which sometimes occurs in Alberta during the summer. In western Canada, it has been recognized by forecasters for some time that the 500 mb cold lows are responsible for many of the larger summer storms and that these are the source of more than half of the total summer precipitation in central and northern Alberta. The recognition of the cold low as a synoptic feature responsible for extensive precipitation on the surface was first documented by Thompson (1950), elaborated on by Mokosch (1961), and classified by Burrows (1966). Burrows examined daily precipitation data for 16 years (1950 to 1965) in the Edmonton region and classified the data into two basic types of storms; "cold low" and "cold trough" (see Section 2.7, Table 2 for classification). Under these two basic types, several sub-classes were also assigned. Of the 60 storms analyzed [with rainfall 0.75 inches (19 mm) or greater], 42 storms were identified as cold lows, while 18 were as a cold trough[1] type. Of the 42 in the cold low category, the largest number of storms (29) was found to fall into the Type IA category[2] with the heaviest

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[1] In meteorology an elongated area of relatively low atmospheric pressure; the opposite of a ridge.

[2] Cold Low Storm with rapid cyclogeneses east of the Rocky Mountains due to a cold low originating in the gulf of Alaska.

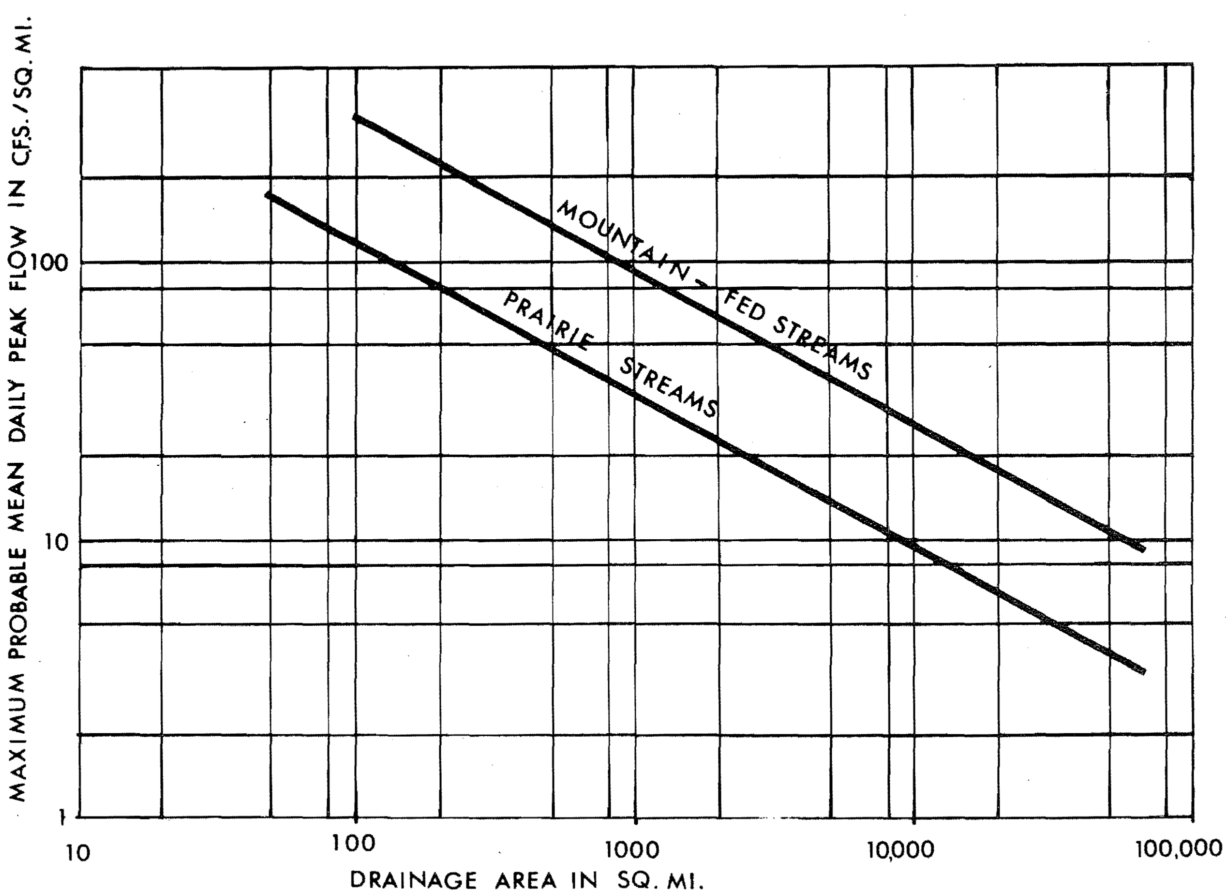

Figure 3 Mean daily peak flow vs drainage area for probable maximum floods (Godwin 1975).

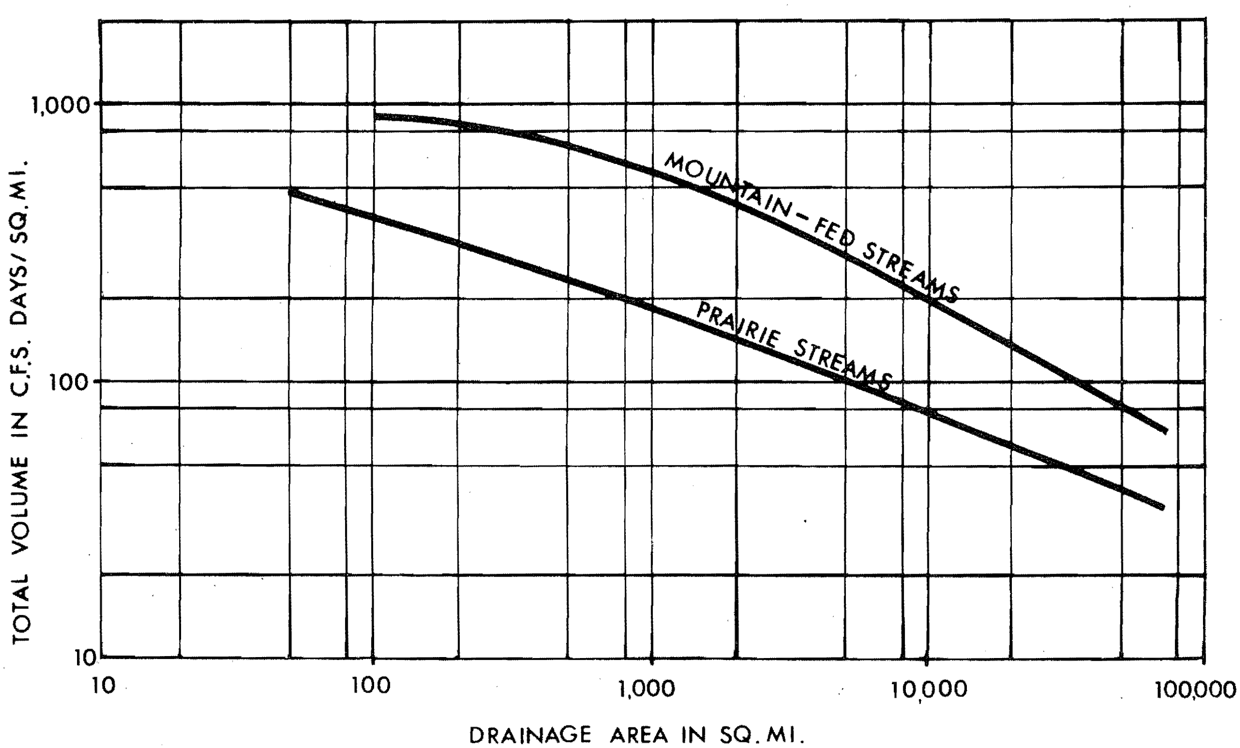

Figure 4 Total volume vs drainage area for probable maximum floods (Godwin 1975).

rainfalls occurring at Edmonton when cyclogenesis was observed in southeastern Alberta or northern Montana. For the cold trough storms, 15 out of 18 storms were recorded in the Type IIA category[1]. Burrows further observed that the heavy rainfalls associated with cold fronts from the north are infrequent (3 out of 42). Storms that develop south of the Canadian prairies as a cold low approaches from the southwestern United States are also infrequent (3 out of 42), but these are perhaps the heaviest rain producers over a large area.

The above summary concludes the efforts of rainstorm analyses in Alberta; however, it should be mentioned that a number of further studies using precipitation data have been carried out. These studies examined precipitation on a yearly, monthly and daily basis as well as investigated regional and temporal variations of rainfall in Alberta. For example, Walker (1964) analyzed the normal monthly precipitation amounts for weather stations in western Canada using a Fourier analysis approach. The technique was shown to be a sensitive method of classifying climatic regions. Muttitt (1961) documented spring and summer rainfall patterns in Alberta from analysis of five years of monthly precipitation data (1955 to 1960). To investigate regional and monthly variations in the frequency of high intensity rainfall in Alberta, Storr (1963) examined the monthly records of precipitation data for the heaviest one day rainfall for each month (May, June, July and August) for 73 stations for the period 1916 to 1960. For each month, a one-day rainfall map for the 5-, 10-, and 25-year return period were produced. Storr noted that a marked axis of high intensity rainfall[2] exists from the general area of Pincher Creek to Nordegg to about 100 mi (160 km) south of Grande Prairie [which coincides with the pattern observed by

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[1] Cold troughs moving in from the west coast or the north.

[2] Maximum one-day rainfall of 4.1 inches (104 mm) at High River for 25-year return period in June.

Muttitt (1961)]. A low intensity area[1] is observed on all the maps in southeastern Alberta with a trough which can be traced through Drumheller to Alix and Wetaskiwin. Storr also observed a definite relationship between storm intensity and elevation; however it should be kept in mind that other topographical features such as slope have a marked effect on rainfall intensity which may augment or diminish the effect of elevation. In 1967, Storr presented charts of the maximum two- and three-day rainfall to be expected once in 5, 10, and 25 years from frequency analysis of rainfall data of 81 climatological stations in Saskatchewan, Alberta, and northeastern British Columbia (using available precipitation records from 1921 to 1960). He also attempted to relate the variations in the rainfall patterns to topographic features and to areal variations in the distribution of cyclonic and convective rainstorms. He found that there exists a marked overall similarity between the one-day and the two-day patterns and the three-day pattern, and that the pattern over Alberta was well defined.

1.3 SOURCES OF DATA

A number of different sources of data were examined in the analysis of the results of this report. The daily precipitation records received the greatest usage, serving as the basis for the climatological analysis and the estimation of the PMP using the statistical approach. The available DAD analyses and dew point temperatures were used in the estimation of the PMP employing the physical approach, while daily precipitation records were employed in the statistical approach of estimating the PMP.

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[1] Minimum one-day rainfall of 1.6 inches (41 mm) at Camrose for 25-year return period in June.

First, the questions on the climatology of rainstorms in Alberta were researched because the review of the available literature revealed that very few rainstorm analyses had been published. The largest single source of analyzed rainstorm data are the "Storm Rainfall in Canada" series published by the Climatology Division of Atmospheric Environment Service (AES) in Toronto, Ontario. Unfortunately these (for Alberta) are incomplete, with the full set consisting of 62 analyses in the period 1902 to 1975 inclusive. The complete set of 62 analyses were acquired from various sources (AES, Edmonton office; Hydrology Branch, Alberta Environment; and Department of Civil Engineering, University of Alberta). In addition to an isohyetal map, each analysis provides (in most cases) the surface weather map, the mass curves of rainfall, and the maximum DAD curves. The two-inch (50 mm) isohyet contour is the minimum precipitation depth given on the isohyetal map, and also is used as the minimum depth criterion for other storm analyses. Another source of isohyetal maps was the unpublished precipitation surface maps produced for internal use by the Edmonton office of AES (beginning about 1960) from available AES and Dept. of Forestry data. These contributed data for a further 58 rainstorms. It became obvious that to answer the questions of climatology of rainstorms in Alberta, especially before 1960, further data reduction and plotting of isohyetal maps were required. The most logical choice was the monthly records published by AES, which contain the most complete and extensive data set of daily precipitations records for Alberta. Examining these publications on a daily rainfall basis, month by month from April to October, 488 additional rainstorms with a minimum depth of 50 mm were identified for the period 1921 to 1978, making a total of 604 rainstorms[1]. Even though the monthly

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[1] Four of the rainstorms in the "Storm Rainfall in Canada" series occurred before 1921 and are not included in this total since dew point temperatures are not available for a PMP estimate. However, even if dew point temperatures were available, the envelopes of the DAD curves given later in this report would not have been effected.

records date to the 1880's for several Alberta stations, it was not until 1921 that the daily precipitation values for all operating stations were included in the publication. Prior to 1921, monthly records gave the daily precipitation for the five main stations (Banff, Calgary, Edmonton, Fort McMurray, and Medicine Hat) and monthly summaries for other stations. In addition, seven other rainstorms were identified from other sources. Longley and Janz (1979) contributed data for one storm, the Alberta Research Council's Atmospheric Sciences Division (ASD) precipitation program near Red Deer contributed records for two storms, while the Alberta Wheat Pool records[1] not only added data for four more storms, missed by the AES network, but also helped in many cases to define more closely the isohyet contours for rainstorms in eastern and central Alberta (especially before the 1950's). Thus a total of 611 rainstorms were identified for the period 1921 to 1978. A listing of these storms with the location and greatest depth reported (in inches and millimetres) is given in Appendix 8.1. Rainstorms marked with a star preceding the date come from the "Storm Rainfall in Canada" series.

Daily precipitation records collected by AES were used to obtain the maximum annual series of 24-, 48-, 72- and 96-hour rainfall amounts for all first-order weather stations. This series was used in the estimation of the PMP employing the statistical approach. Furthermore, annual series for the four durations were computed for each month from April to September.

The main source of DAD analyses was the "Storm Rainfall in Canada" series with a supplementary analysis obtained from Warner (1973) for the storm of 7 to 8 June 1964 in the Waterton Lake National Park area. All DAD curves were digitized to allow rapid analysis of various combinations of duration for the different basins in the estimates of the PMP. A second source of data used in the estimate of the PMP applying the physical

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[1] Records in the library of the Meteorology Division, Department of Geography, University of Alberta, Edmonton.

approach was the dew point temperatures. These were obtained from AES for 16 first-order stations in digitized form on an hourly basis[1] with most stations having records from 1953 to 1977. The 1978 dew point data were tabulated from summary sheets produced by AES. Dew point data before 1953 are available on microfilm at AES headquarters (Toronto, Ontario) for a few first-order Alberta stations. Dew point data were also obtained for those storms before 1953 with a DAD analysis.

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[1] Most of the first-order stations were on an hourly basis; those that were not gave dew point temperatures on a 3-hour basis.

2. CLIMATOLOGY OF RAINSTORMS IN ALBERTA

2.1 INTRODUCTION

The importance of understanding rainstorms, their location, time of occurrence and severity cannot be overemphasized. For example, an agriculturist is concerned with the availability and occurrence of precipitation for water supply management. Lack of low availability of moisture from rainstorms for several years in areas capable of producing crops could create drought conditions in these areas. The lack of precipitation has stimulated the interests of meteorologists dealing with weather modification, especially in rain enhancement programs. Excessive precipitation in a given region may be just as devastating as insufficient precipitation, for the crops maybe completely lost due to flooding. Extreme flooding is mainly the result of major rainstorms, rapid snowmelt of significant duration, or a combination of these two factors, and hence of interest to hydrologists. Heavy rainfalls may result in flooding which causes extensive damage to property and topography as well as hydraulic structures. Thus it is important to understand the spatial and temporal distribution of rainstorms in Alberta (their location, time of occurrence, and severity) which may contribute to extreme flooding. In this study, to address this aspect, rainstorms in Alberta which produced a minimum depth of 50 mm for the period 1921 to 1978 were identified from all readily available data sources. The precipitation data comes from a network in which the density has varied from year to year; due to the fact that stations were either relocated, discontinued, or added to the network since its incorporation. Beginning with a handful of stations in the 1880's, the number of stations in Alberta has increased to the extent that at present most of the province is represented to some degree.

2.2 SPATIAL AND TEMPORAL DISTRIBUTION OF PRECIPITATION STATIONS IN ALBERTA

The spatial and temporal distribution of the number of stations was examined to give an insight to the validity of data and the conclusions that can be drawn from the analysis. The precipitation data collected and preserved by AES is documented for each station and record length. Using this information, a number of analyses were performed. In one such analysis, the number of stations operating during a given year were plotted for a spatial block[1] for each year from 1921 to 1978. Figure 5 is an example of the maps produced. It depicts the number of stations that collected precipitation data in 1901 in Alberta. As is obvious from the figure, rainstorms covering large areas could have occurred in numerous parts of the province in that year without being detected by the operating stations. A sequence of six maps every ten years beginning with 1921 is given in Appendix 8.2. An examination of these maps shows that not only did the number of stations increase within the spatial blocks (in most cases) but that there is also an increase in the number of spatial blocks (or total area) with at least one station. As the northern parts of the province became developed, more stations in that area were established. This is shown more clearly in Figure 6 where the percentage of the number of spatial blocks (equivalent to the area) with at least one station is plotted for each year from 1921 to 1978[2]. Four curves are shown in Figure 6: (1) the first curve is for the entire province; (2) the second curve is for the Peace River-Fort McMurray area[3]; (3) the third

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[1] A spatial block was chosen to be 1° in the latitude by 0.5° in longitude.

[2] The percentage is determined by multiplying by 100 the ratio of the number of spatial blocks with at least one station out of the total potential number of blocks.

[3] All spatial blocks north of 56° Latitude.

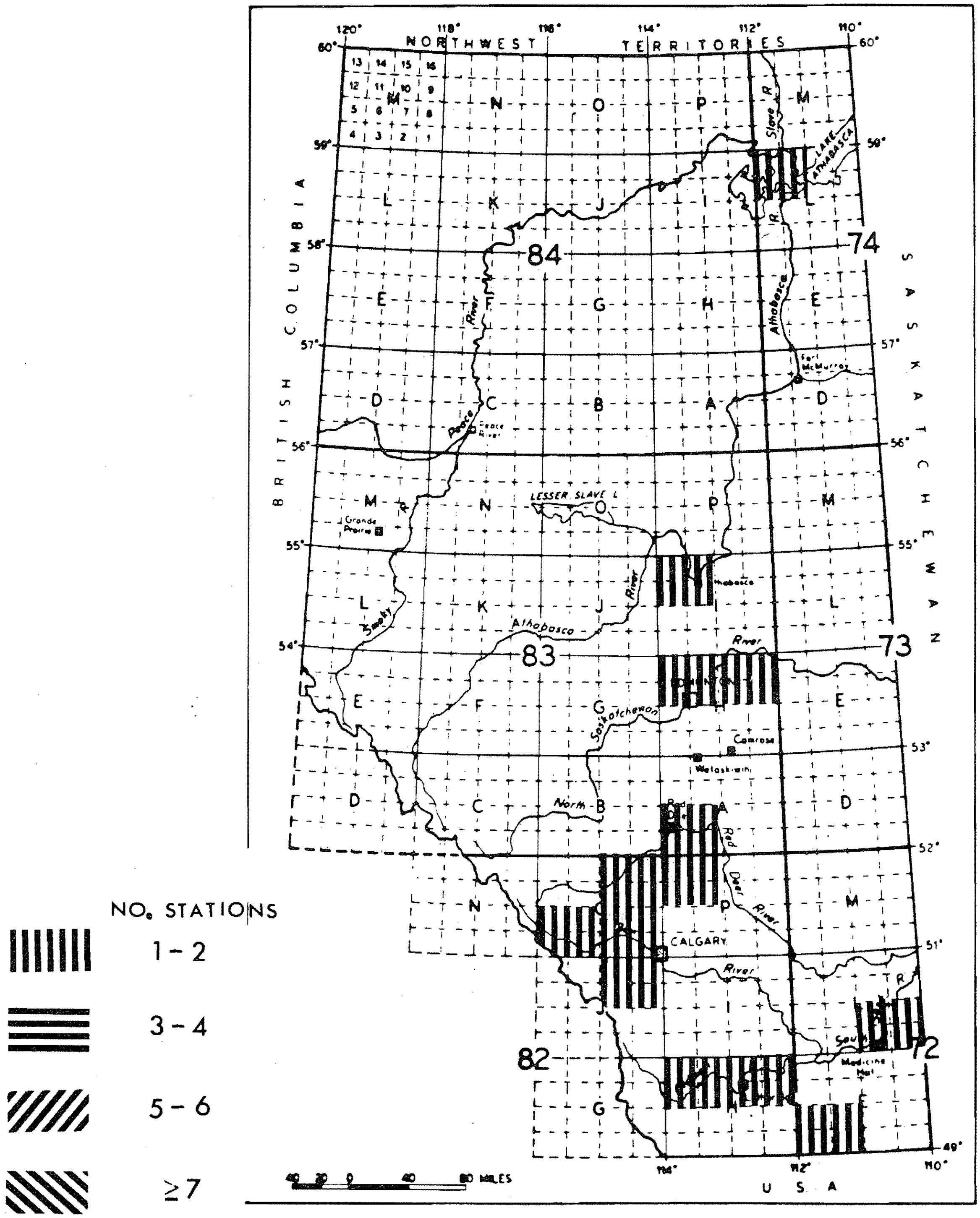

Figure 5 Spatial distribution of stations collecting precipitation data in 1901 in Alberta.

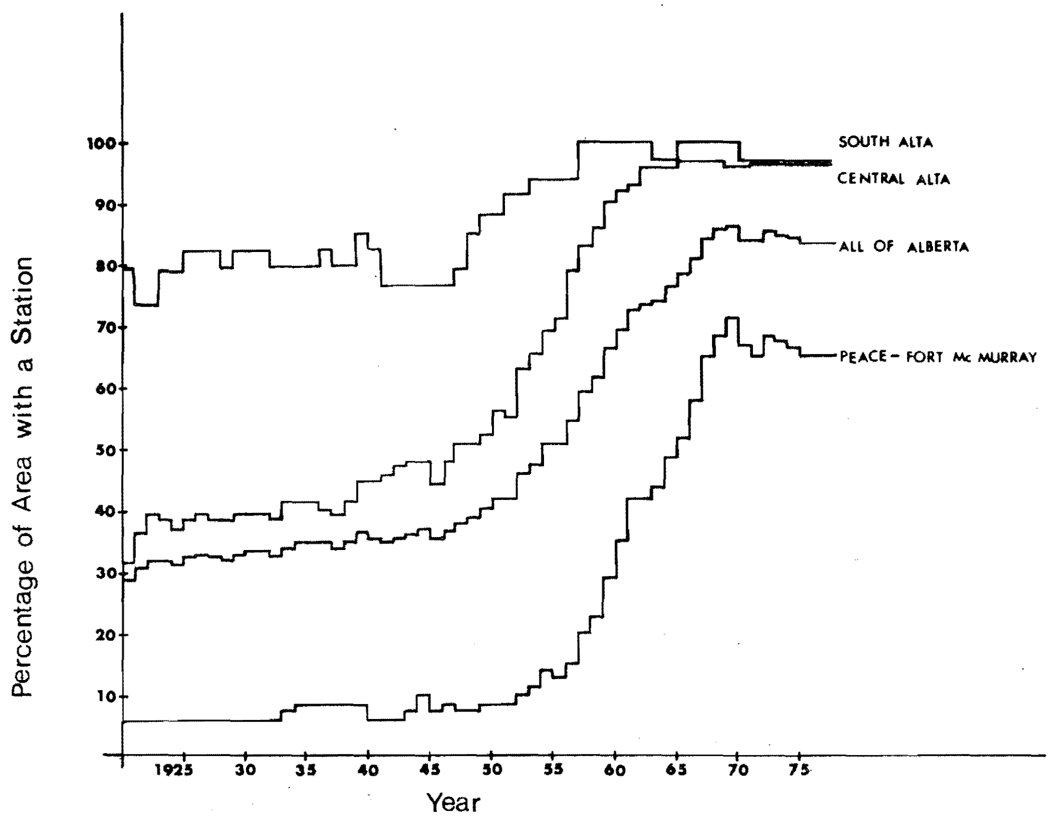

Figure 6 The temporal variation of the percentage of the number of spatial blocks with at least one station.

curve is for central Alberta[1]; and (4) the fourth curve is for southern Alberta[2]. The province was divided into three areas to examine any north-south variation in the spatial block representation.

The percentage of blocks with at least one station was about 30% for the entire province in the 1920's and remained about constant until the 1950's. In the 1950's, a network of forestry stations[3] was established to supplement the AES network, with many of the stations in uninhabited regions of the province. These new stations provided meteorological data previously lacking and helped in defining more closely the precipitation patterns of rainstorms. Up to 1950, approximately 8% of the spatial blocks had at least one precipitation station in the northern area. The station expansion of the 1950's and 1960's is observed in all three regions of the province, with the greatest increase in the Peace River-Fort McMurray area. The smallest percentage increase occurs in the southern part of Alberta (south of 52° Latitude) since this area already had a high representation. Because of the high percentage coverage of the southern area through the 58 years, it is doubtful whether any storms with a depth of 100 mm or more would have been missed by the AES network in this area. Some isolated thunderstorms producing a maximum depth of 50 mm or so with an area of less than 3 000 km^2 may have been missed. But even now the number of stations in the area is of insufficient density to record some localized thunderstorms of 50 mm depth with a isohyetal area less than 1 000 km^2.

In central Alberta, the percentage of coverage is less than in the southern part of the province, thus storms with a greater isohyetal depth area could occur without being recorded by the network. A conservative upper limit of the isohytal depth

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[1] All spatial blocks located between 52° and 55° Latitude.
[2] All spatial blocks in Alberta south of the 52° Latitude.
[3] Stations located in the mountainous and forestry areas of the province.

area would be 5 000 km^2 before the 1960's. Regions where storms were missed before this date would be the area southwest of Edmonton (near Drayton Valley), the Edson-Hinton, and the Swan Hills areas.

In the northern area, there is no doubt that storms were missed, however the number would be small since this area is not conducive to rainstorms with depths greater than 50 mm. In this area care should be taken in applying the available results due to the short data period and the large linear spacing between many of the observing weather stations. However, even though there are gaps in the density of the data collecting network, the insufficient density would result only in small rainstorms (less than 50 mm), from the point of view of hydrologists, being missed. Analysis of rainstorms with a minimum depth of 150 mm or more showed that the area under the 50 mm isohyetal lines in these storms was more than 20 000 km^2. Hence only in the northern areas before the 1950's would a storm of such magnitude not be documented.

Using the available precipitation data, Section 2.3 examines the point measurements of the maximum depth reported; in Section 2.4, the rainstorms as a whole are treated; in Section 2.5 the stormstation density ratios are examined; in Section 2.6, the direction of motion of the storm precipitation pattern for severe storms[1] is presented; while in Section 2.7, severe storms are classified by storm systems.

2.3 MAXIMUM DEPTH

For those storms not already analyzed by other sources, the precipitation produced during the storm was first plotted and then objectively hand contoured, with the isohyetal lines expressed

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[1] Storms classified as those which produced reported depths 150 mm or more during their lifetime.

in approximately 25 mm intervals. The procedure used was similar to that used by AES in drawing of the ishyetal maps in the "Storm Rainfall in Canada" series. Next, the maximum depth reported and its location were identified for each rainstorm (see Appendix 8.1 for list of storms), and the information digitized for computer processing. One obvious stratification of the data is to group the information into depth intervals and monthly categories. The resulting frequency of occurrence of the monthly distribution of the maximum depth reported for the 611 rainstorms is given in Table 1.

The majority of the rainstorms (46%) occurred in the smallest category chosen (i.e., 50 to 74.9 mm), not an unexpected result. The number of rainstorms decreases logarithmically with increased depth category (see Figure 7). Extrapolating back to the 24 to 50 mm category in this figure, it is estimated that about 550 rainstorms would have occurred in this category for Alberta during the 58-year period between 1921 and 1978. Extrapolating to the other extreme, Figure 7 suggests the occurrence of one rainstorm greater than 250 mm in depth during the 58 years. This agrees with the reported records, since the storm of 7 to 8 June 1964 in the Waterton Lakes area was observed with this magnitude.

The yearly frequency of occurrence of rainstorms for depths 50 mm and greater is shown in Figure 8, while that for depths 100 mm and greater is given in Figure 9. The greatest number of 50 mm or greater rainstorms in one year was 18 (in 1964 and 1973), while the least number occurred was 4 (in 1921). In both Figures 8 and 9, the 5- and the 20-year running means are shown. Although at first glance the two running means would suggest an increase in the number of storms after the 1950's, this in part would be an incorrect conclusion since the number of stations also increased in the same time period (as was shown in Figure 6). The number of rainstorms with depths 100 mm and more

Table 1 Frequency of occurrence of the monthly distribution of the maximum depth of precipitation reported for depths 50 mm (1921-1978)

Month	Depth of Precipitation (in mm) 50.0 74.9	75.0 99.9	100. 124.	125. 149.	150. 174.	175. 199.	200. GRT	TOT	% TOT (611)
April	20	4	5	3	0	2	0	34	5.6
May	54	20	9	5	1	3	0	92	15.1
June	47	40	27	14	7	4	5	144	23.6
July	78	48	22	11	3	1	0	163	26.7
Aug.	48	35	21	4	6	1	1	116	19.0
Sept.	35	15	8	4	0	0	0	62	10.1
Total	282	162	92	41	17	11	11	611	100.1
%	46.2	26.5	15.1	6.7	2.8	1.8	1.0	100.1	

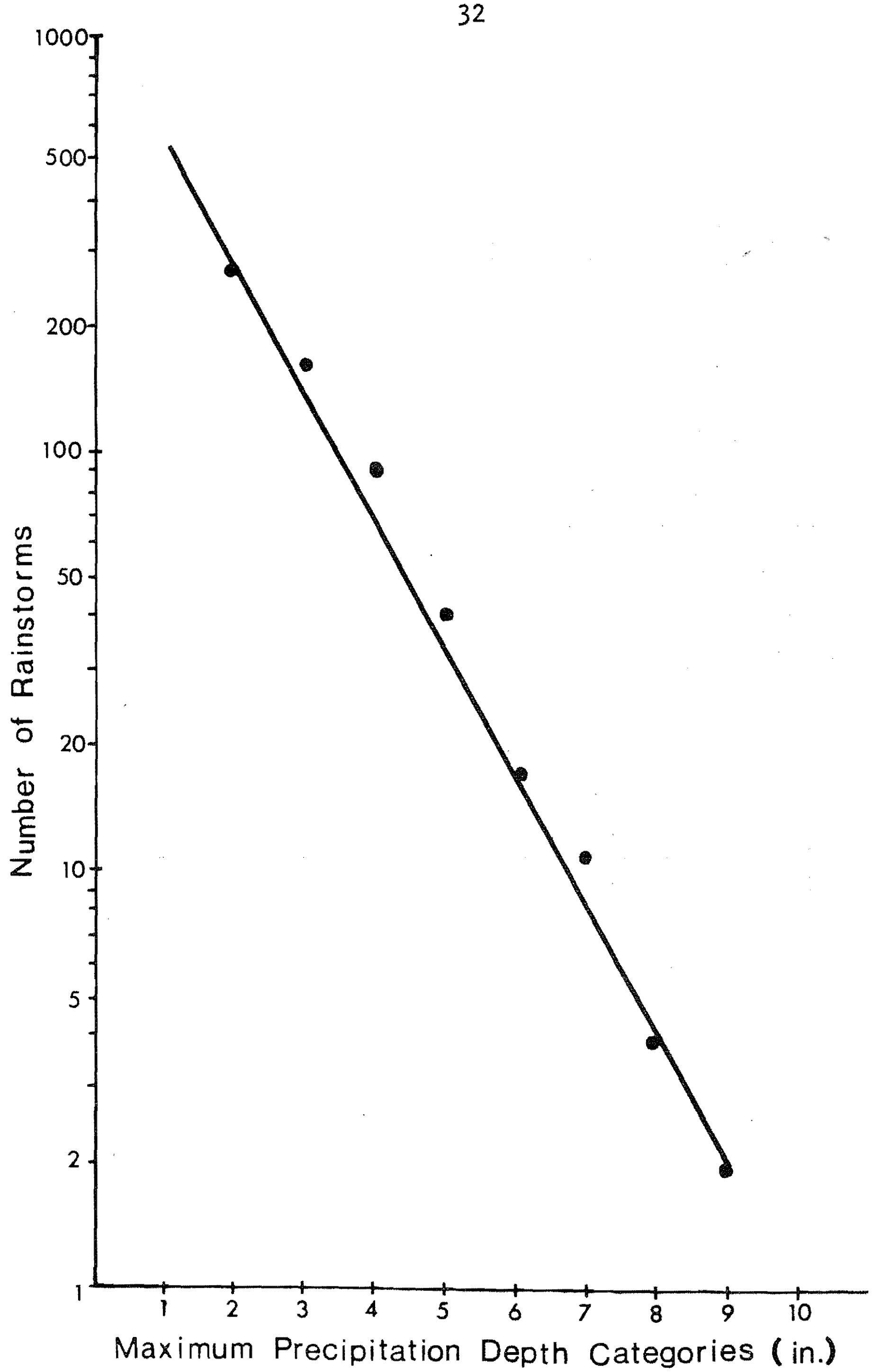
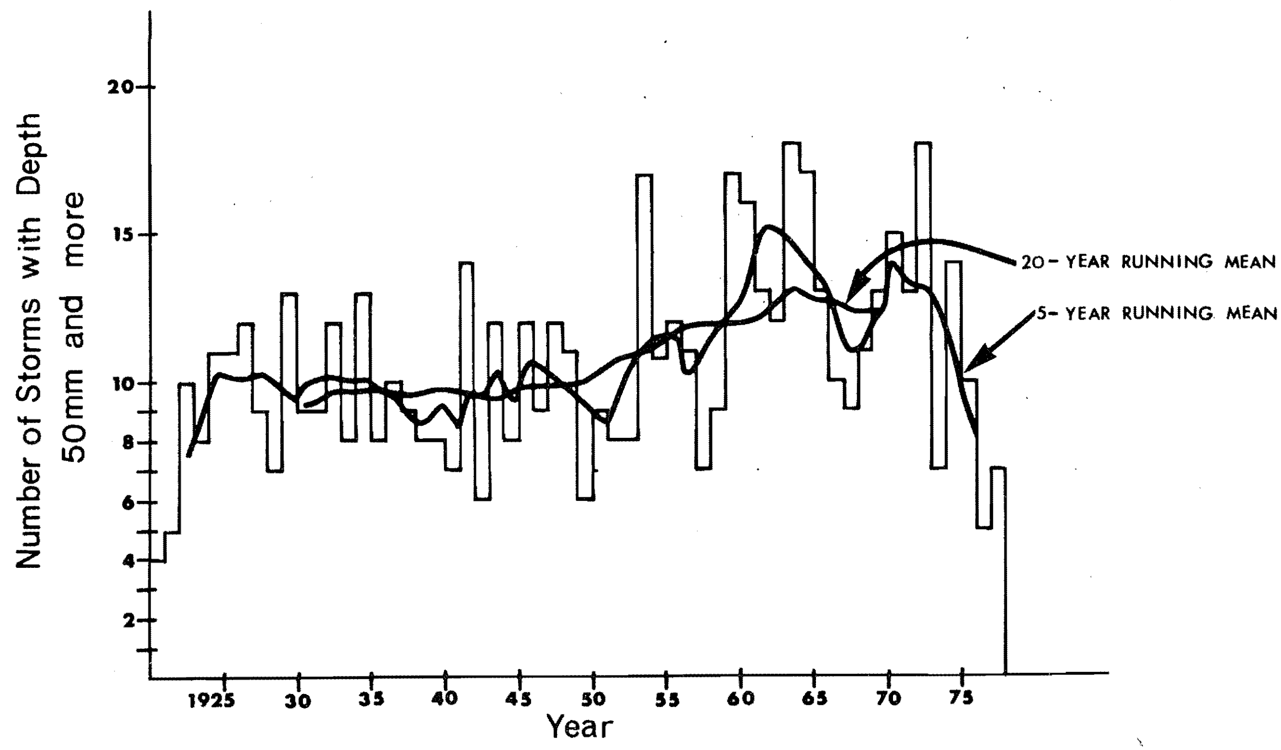
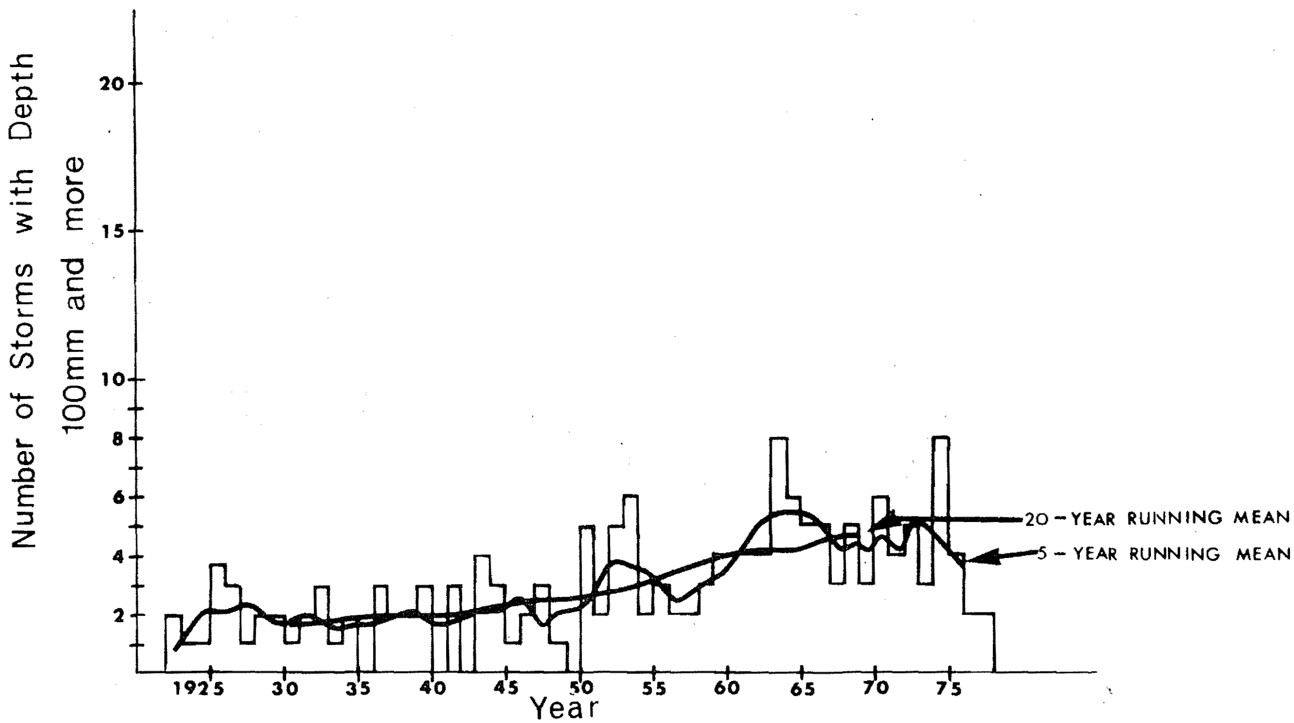


Figure 7 Graph of the number of rainstorms for maximum precipitation depth category.



Yearly Frequency of Occurrence of Rainstorms In Alberta

Figure 8 Yearly frequency of occurrence of rainstorms with maximum depth 50 mm and more in Alberta.



Yearly Frequency of Occurrence of Rainstorms in Alberta

Figure 9 Yearly frequency of occurrence of rainstorms with maximum depth 100 mm and more in Alberta.

is less than for depths 50 mm and more, as is observed in Figure 9. The greatest number that has occurred in any year was 8 (in 1964 and 1975), while none was observed to occur in the following six years: 1921, 1922, 1936, 1941, 1943, and 1950.

Rainstorms with depths of about 50 mm are of little interest to a hydrologist (even though they may be important to an agriculturist), since these in most cases rarely produce flooding conditions. However, severe storms (i.e., rainstorms with a depth 150 mm or more) have a greater probability of causing flooding, and thus become important to the hydrologist. If a depth of 150 mm or more is used as a criterion of flooding conditions, then the results of Table 1 show that only a very small percentage (i.e., about 5.6%) of rainstorms with depth 150 mm and more fall in this category. That is, 1 out of 18 rainstorms can be called severe by the above criterion, and on the average such a storm occurs about once every two years somewhere in the province. The monthly distribution of the maximum precipitation depth is also given in Table 1. Rainstorms begin to occur in April, and the frequency of occurrence increases, reaching a maximum in July, after which a gradual decrease in the number of occurrences occurs until the middle of September. Rainstorms with maximum depths 50 mm and more are extremely rare (1:100 year event) in the first two weeks of April, as well as in the last two weeks of September. Severe rainstorms (depths 150 mm or greater), on the other hand, exhibit two maxima, one in June and one in August. No occurrences of these storms have been observed in September or October.

To examine the spatial distribution of the occurrence of the maximum depth reported, the Province of Alberta was divided into spatial blocks 0.5° in latitude and 1.0° in longitude. The point frequency of occurrence of maximum depth (for depths 50 mm and more) reported in each spatial block was determined and the results for the 58 years of data are shown in Figure 10. The

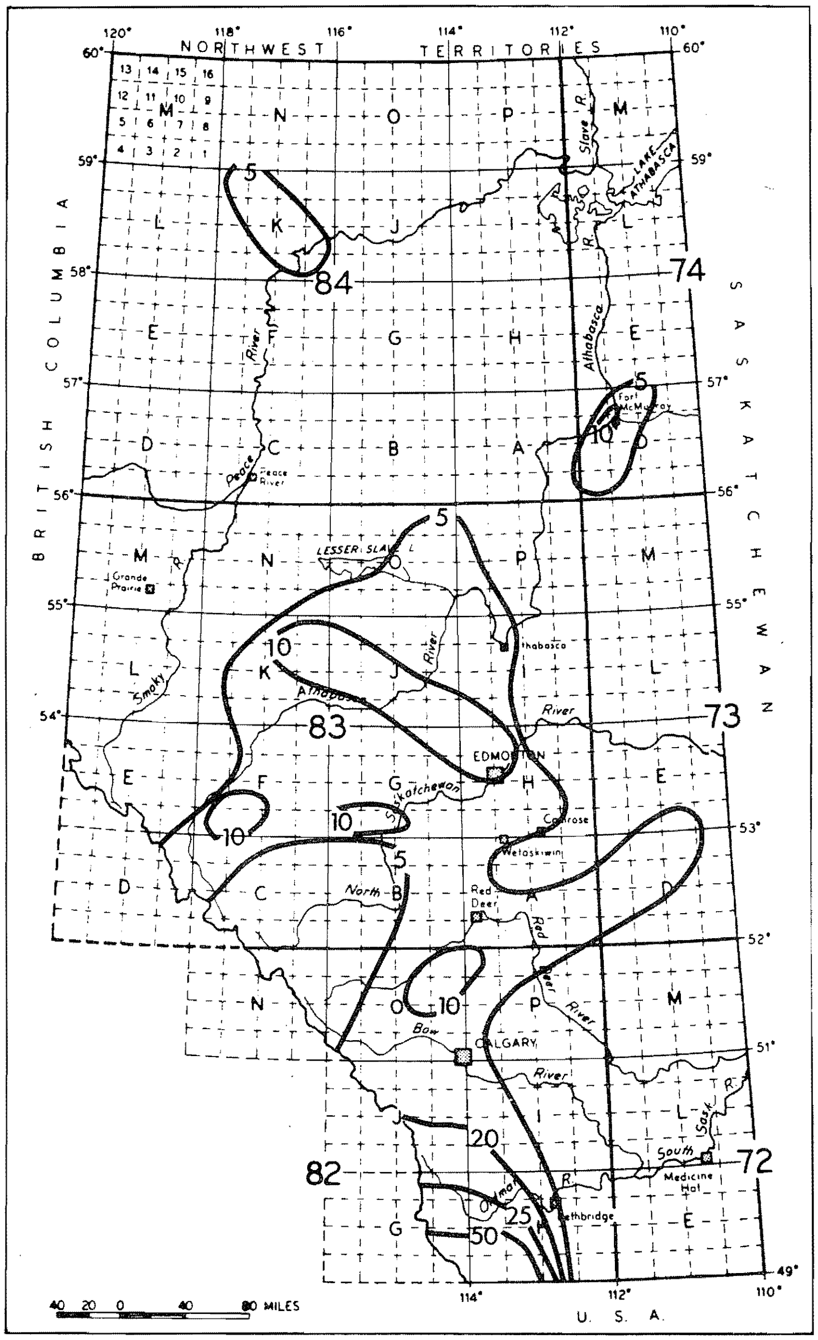


Figure 10 Number of occurrences of the point measurements of the maximum depth reported for rainfalls 50 mm and more in the period 1921 to 1978.

greatest number of occurrences of the maximum depth are observed in the mountainous area between Banff and Waterton Lakes Park, in the headwaters of the Bow and South Saskatchewan River basins. The area of the Waterton Lakes Park is observed to have the greatest frequency of occurrence (57), or just about one per year. A number of isolated pockets of moderate occurrence (once in six years) are observed through central Alberta: the largest of these is through the Whitecourt-Edmonton area, with smaller ones in the Drayton Valley and Sundre areas. In northern Alberta where the number of observing stations is few, the Fort McMurray area seems to record a pronounced isolated pocket of moderate occurrence.

2.4 SPATIAL AND TEMPORAL DISTRIBUTION OF RAINSTORMS

The analysis of the maximum depth reported gives the frequency of occurrence and location of a point value within the storm structure. To obtain a better understanding of the climatology of rainstorms, the areal distribution should be considered. This was accomplished by digitizing the 611 contoured isohyetal maps in terms of area coverage and the average intensity of the rainfall occurring in the spatial block. The map of Alberta was classified for convenience of analysis into spatial blocks of 0.5° in latitude and 0.25° longitude (approximately equivalent to 400 mi^2 or 1 060 km^2 in the southern portion, and about 285 mi^2 or 760 km^2 in the northern portion of the province). For each storm, the average intensity in each spatial block through which the storm occurred was digitized, thus allowing a number of analyses to be conducted. For simplicity, the results are expressed in the number of occurrence out of a 100 years and can be interpreted as a probability of occurence[1]. Figure 11 shows

[1] To help in the interpretation of the results, even though only 58 years of data were used.

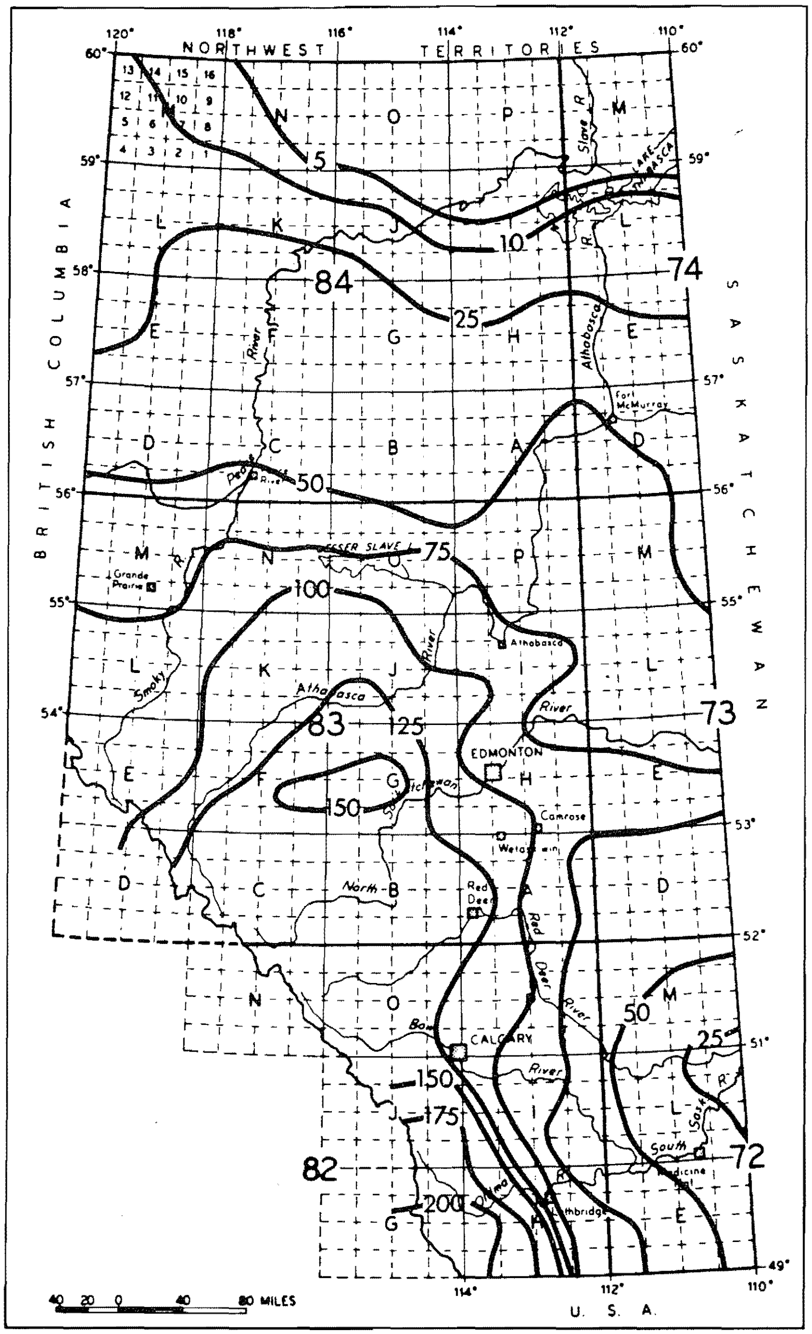


Figure 11 Number of occurrences of storms with depths 50 mm and more in 100 years.

the number of occurrences of rainstorms with depths greater than 50 mm in 100 years. In central and southern Alberta, a general decrease in the occurrence is observed extending east from the continental divide, with the maximum observed in the Waterton Lakes Park area (twice a year on the average) and the minimum at the Alberta-Saskatchewan border (once every four years). The gradient of the constant frequency lines is not as sharp in central Alberta as in southern Alberta. A general decrease in the number of occurrences is also observed from south to north with storms occurring in much of the northern area from once in two years to once in 20 years (probability of 0.50 to 0.05).

Depths of 100 mm and more occur less frequently, as is seen in Figure 12. Again the Waterton Parks Lakes area is observed to have the greatest frequency of occurrence of these storms, with a probability of occurrence of 0.36 or one storm in every three years. Moderate probabilities of occurrence (0.10 or once in 10 years) are observed in the foothills along the continental divide extending north from the U.S. border to the Edson area. Figure 12 also shows an eastward and northward decrease in probability. Probabilities between 0.05 and 0.15 dominate much of central Alberta. The northern part of Alberta has the lowest probabilities of occurrence; this in part is due to an insufficient number of stations for much of the record length. It is believed that, even with greater record lengths, this area would still have low probabilities of occurrence of rainstorms of this magnitude.

The number of occurrences of storms with depths 150 mm or more in 100 years is shown in Figure 13. The maximum values again are observed along the continental divide in southern Alberta with minimum values in the eastern and northern parts of the province. The largest probability observed is 0.05 (1:20 year event). Of note are the large pockets of 0.02 (1:50 year occurrence) in central Alberta and one from Lesser Slave Lake to just south of Fort McMurray.

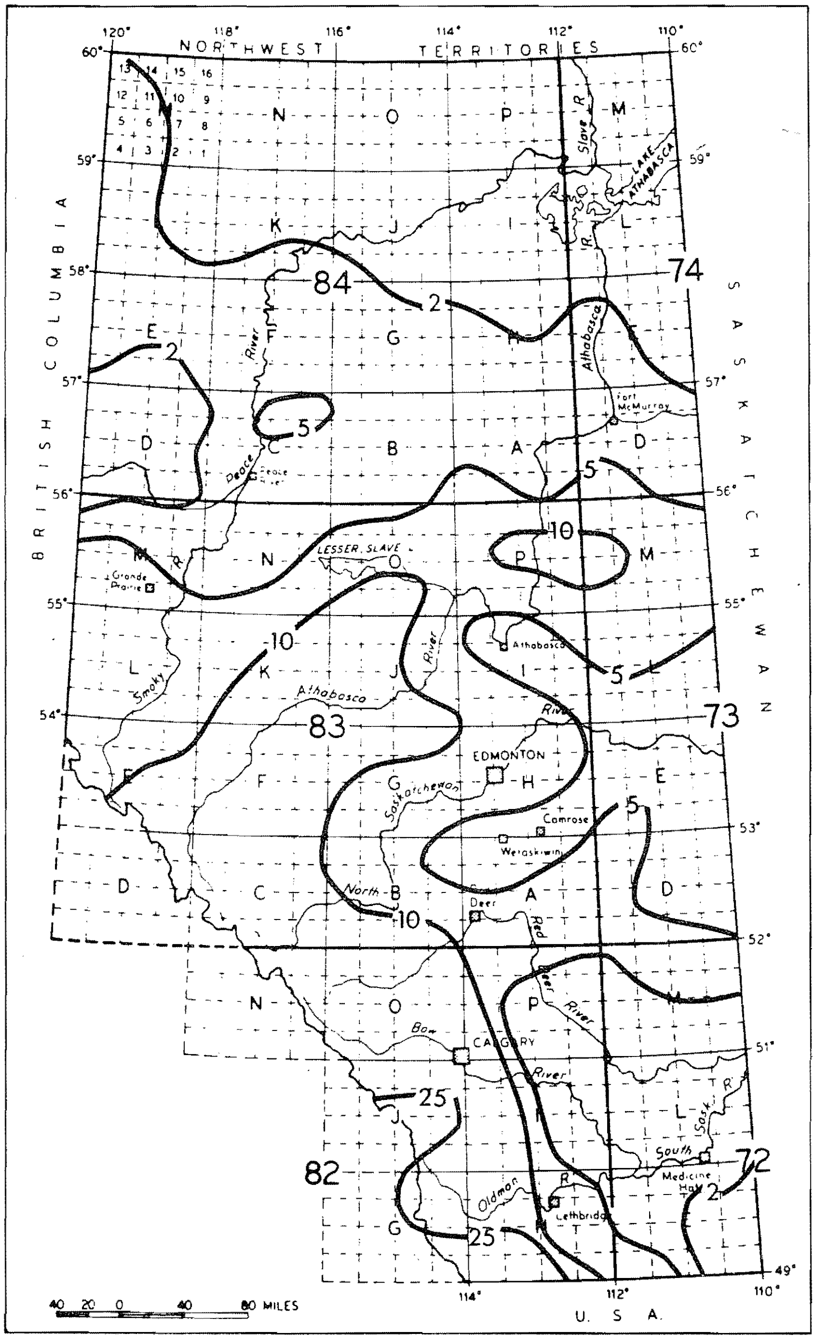


Figure 12 Number of occurrences of storms with depths 100 mm and more in 100 years.

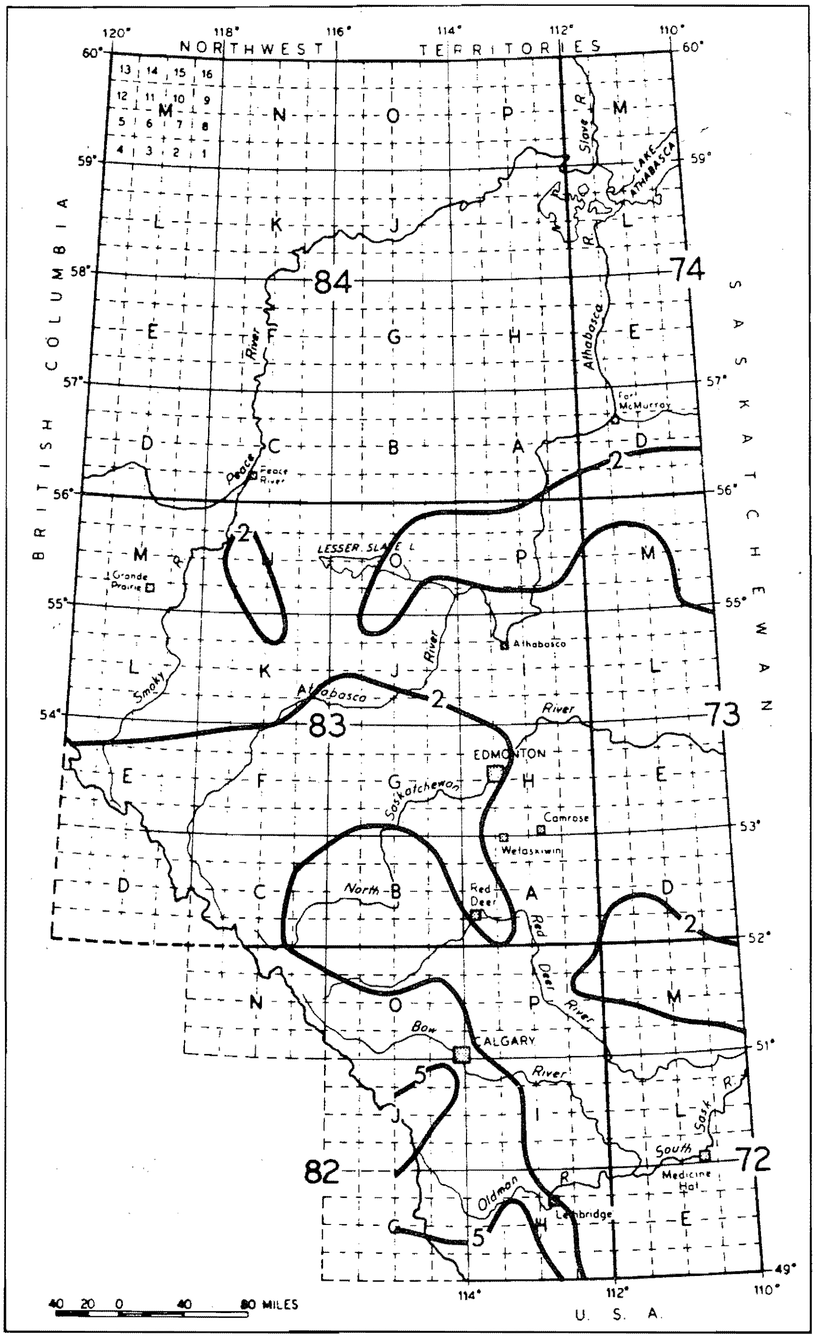


Figure 13 Number of occurrences of storms with depths 150 mm and more in 100 years.

The spatial variations of the frequency of occurrence of depths 50 mm and more, 100 mm and more, and 150 mm and more for each month from April to September are given in Appendix 8.2. For southern Alberta, the probability of occurrence of precipitation with 50 mm and more reaches a maximum in June and a minimum in April and September. May and June are the months with the greatest probability of observing precipitation of this magnitude. In central and northern Alberta, June and July are the months with the greatest probability of occurrence mainly due to the occurrence of thunderstorms in these regions. Depths 150 mm and more are infrequent in most of Alberta, the exception being June in southern Alberta. In April and May the occurrence of storms producing these depths is confined mainly to southern Alberta. In June, a northward trend of the probability of occurrence is observed with isolated pockets observed in parts of central Alberta. In July, storms of this magnitude occur in central and parts of northern Alberta, with none recorded in southern Alberta. In August (as in July), numerous isolated pockets of 0.02 (1:50 year event) probabilities are observed. By September, the occurrence of these storms is comparatively rare with only isolated occurrences of probability of 0.02 in the province.

2.5 STORM-STATION DENSITY

The number of stations in an area greatly influences the chances of a storm being recorded. This aspect was examined by comparing the ratio of the number of storms (point maximum depths) to the number of stations in each of the 220 spatial blocks in Alberta for the 58 years of data. The sum and the cumulative average of the ratio were investigated for each of the spatial blocks in order to determine spatial variability of the storm occurrences.

For storms with depths greater than 50 mm, the sum of the ratio of the number of storms (point maximum depths) to the number of stations is shown in Figure 14. High values of the ratio indicate regions of consistently greater occurrences of the maximum depth, while low values suggest regions of low occurrences. Three pronounced regions of high occurrences are observed in Figure 14: 1) in southern Alberta near the Waterton Lakes Park; 2) southwest of Lesser Slave Lake to Edmonton; and 3) around Fort McMurray. This confirms the high occurrences observed in Figure 10.

For storms with depths 100 mm and more (Figure 15), the high values of the ratio occur in the Waterton Lakes Park area and the region southwest of Lesser Slave Lake to Edmonton. A number of isolated pockets of lower values occur through parts of central and northern Alberta. Low and zero values of the ratio occur on the eastern border of the province and in the northern most parts of Alberta.

For severe storms (depths 150 mm and more), the sum of the ratio is given in Figure 16. As in Figures 14 and 15, a number of regions exhibit a pronounced high value of the ratio. Five distinct regions are observed in this figure: (1) Fort Chipeywan area; (2) area just northwest of Edmonton; (3) area southwest of Calgary; (4) area north of Nordegg; and (5) area northeast of Coronation. Severe storms seem to occur in three belts in Alberta: the first extends through southern Alberta, just south of Calgary; the second in central Alberta from south of Edson to the Edmonton region; and the third from Lesser Slave Lake to the Fort McMurray area. A fourth belt is believed to exist around the Fort Chipeywan area, but Figure 16 does not confirm this belief.

To examine the temporal variation of storm occurrence, ten-year time periods were chosen and the ratio plotted for each period (see Appendix 8.2, Figures 80-84). The results confirm

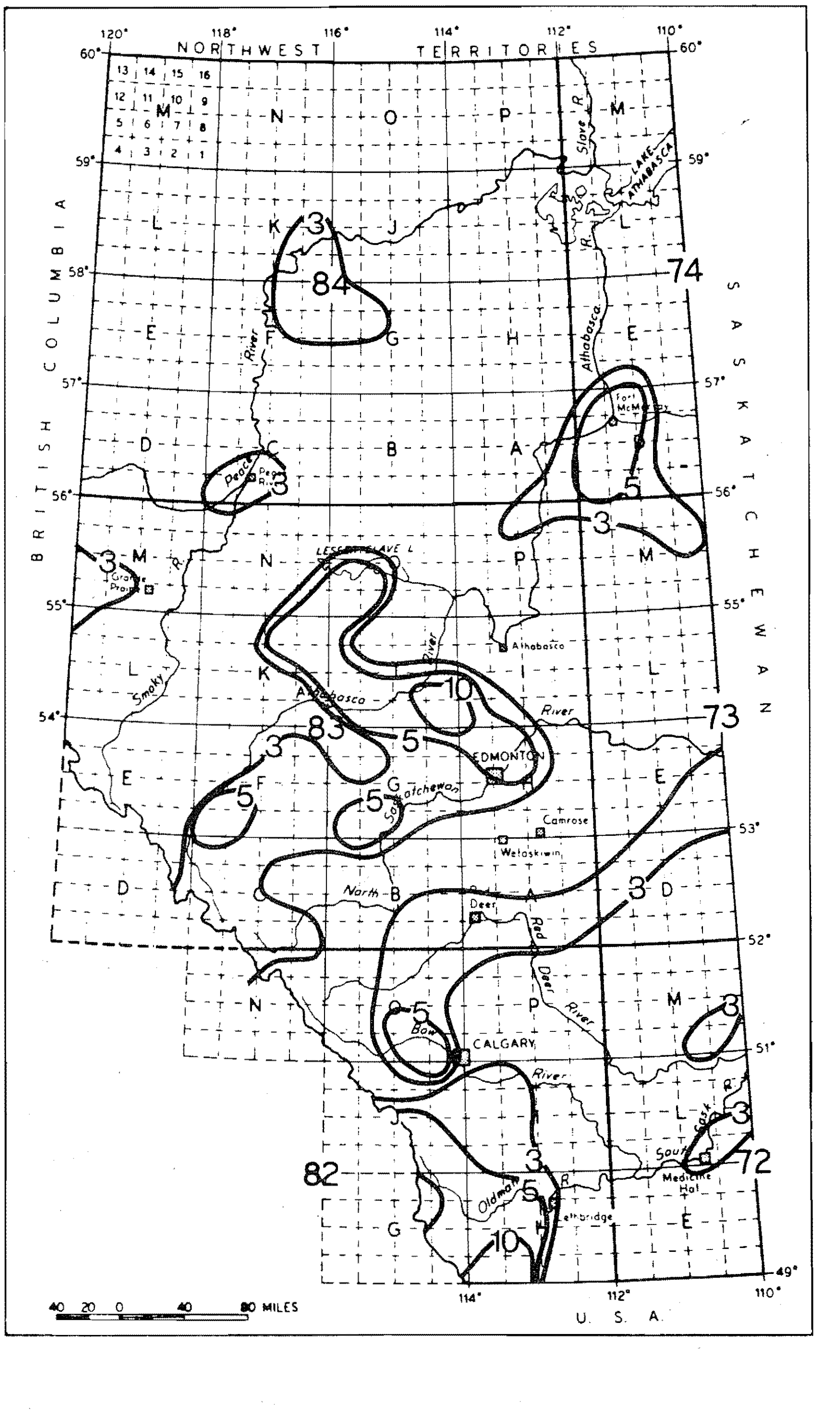


Figure 14 Sum of storm-station density for depths 50 mm and more.

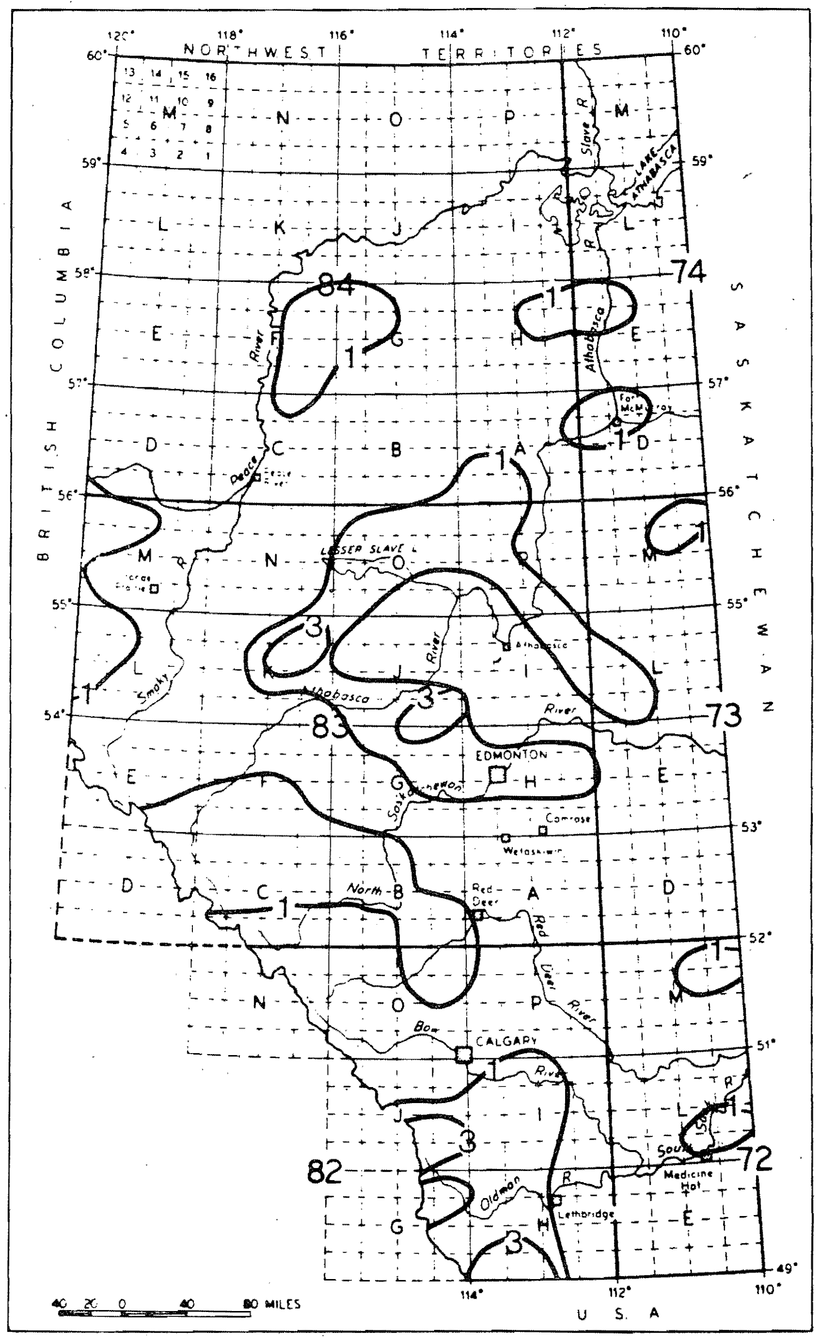


Figure 15 Sum of storm-station density for depths 100 mm and more.

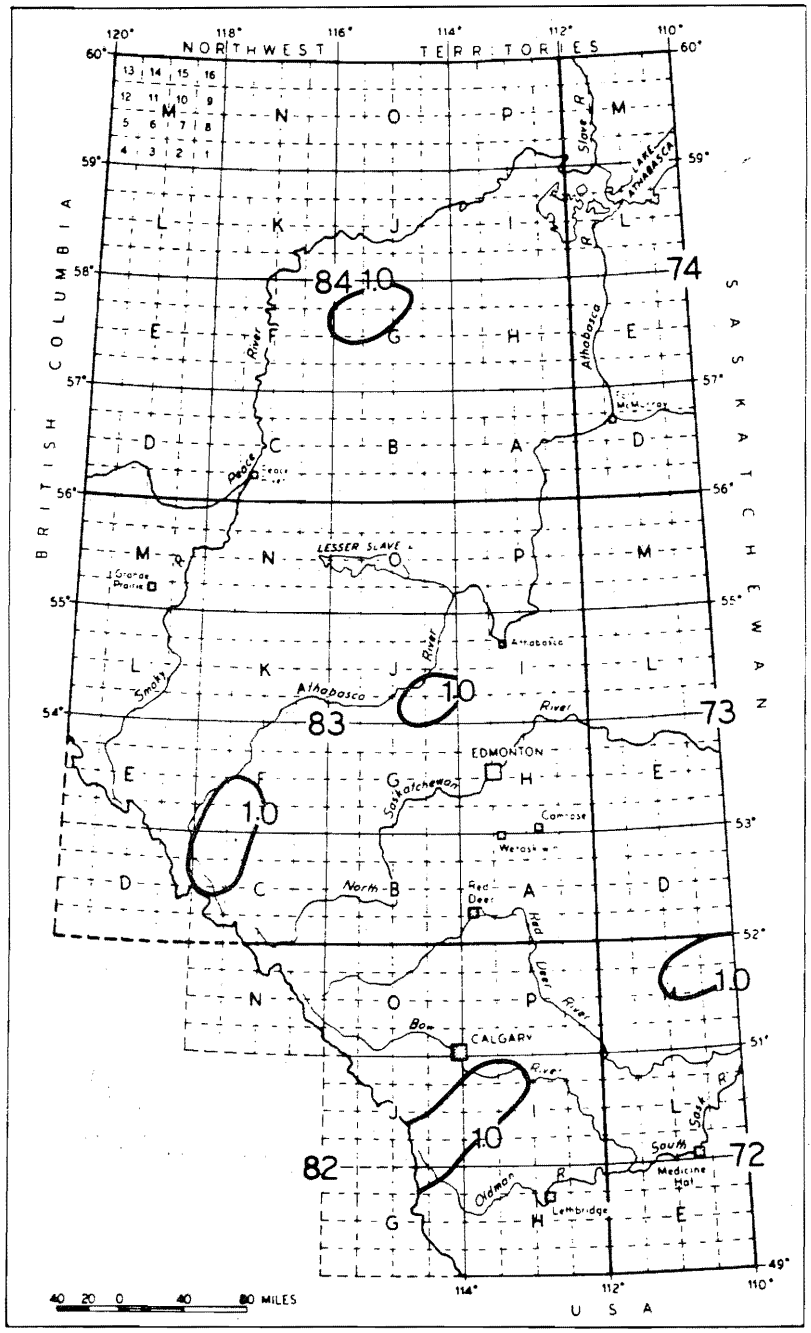


Figure 16 Sum of storm-station density for depths 150 mm and more.

the existence of the three belts described above. The conjecture regarding the fourth belt in the Fort Chipeywan area (Figure 16) is also confirmed.

The temporal variation of the spatial blocks was also examined by plotting an annual series of the cumulative average of the ratio. This average gives the variability of the ratio for the spatial blocks. A spatial block can be called "stable" if, for the period of record, the ratio fluctuates very little and forms a straight line. An "unstable" spatial block, on the other hand, would exhibit fluctuations throughout the period of record. Figures 17 and 18 show examples of spatial blocks exhibiting a "stable" and an "unstable" effect in the cumulative average of the ratio.

The spatial distribution of regions in Alberta with high variability in storm occurrence are shown in Figure 19. Four major areas seem to stand out: (1) the area south and west of Calgary; (2) the area extending from the southwest to the northwest of Edmonton; (3) the area around Fort McMurray; and (4) the area around Fort Chipeywan.

2.6 SURFACE PRECIPITATION TRACKS OF SEVERE STORMS

For the rainstorms which produced a depth 150 mm or more during their lifetime, mean precipitation pattern tracks were produced and these are depicted in Figure 20. The paths were placed through the centre of the precipitation pattern with the length of the paths equal to the length of the 50 mm isohyetal contour. Most of the tracks are observed through southern and central Alberta along the continental divide, with very few storm tracks observed in northern Alberta.

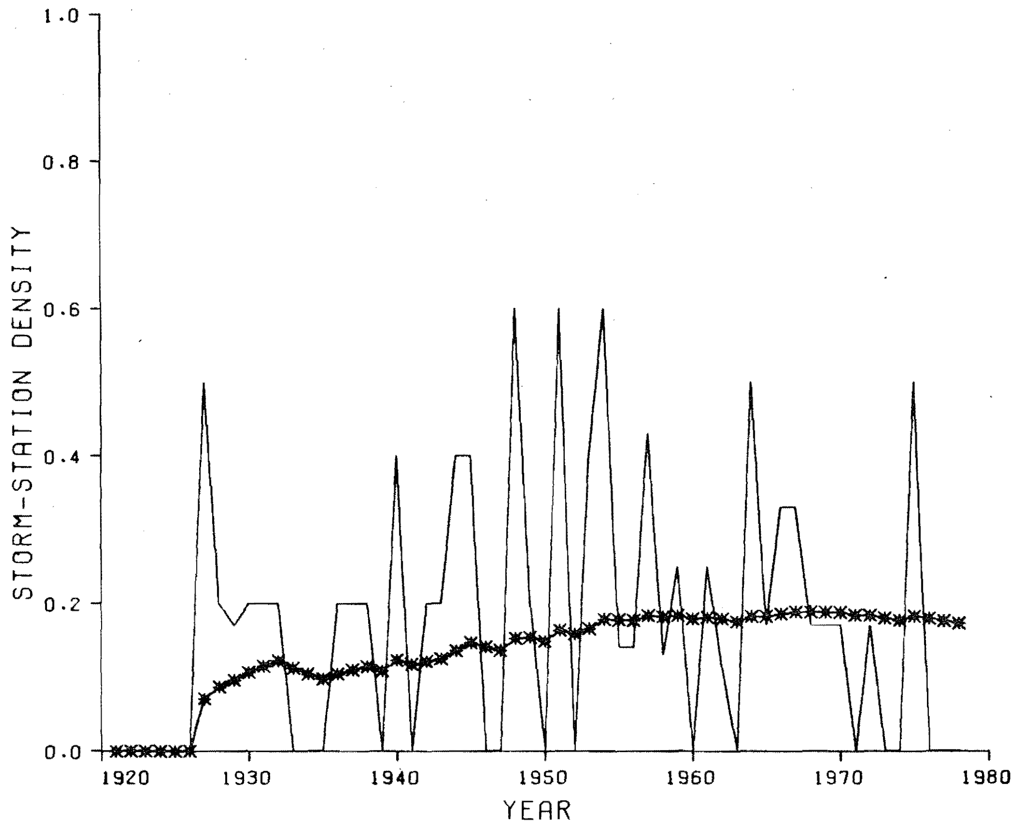


Figure 17 An example of a spatial block exhibiting the "stable" effect in the cumulative average of the storm-station density ratio.

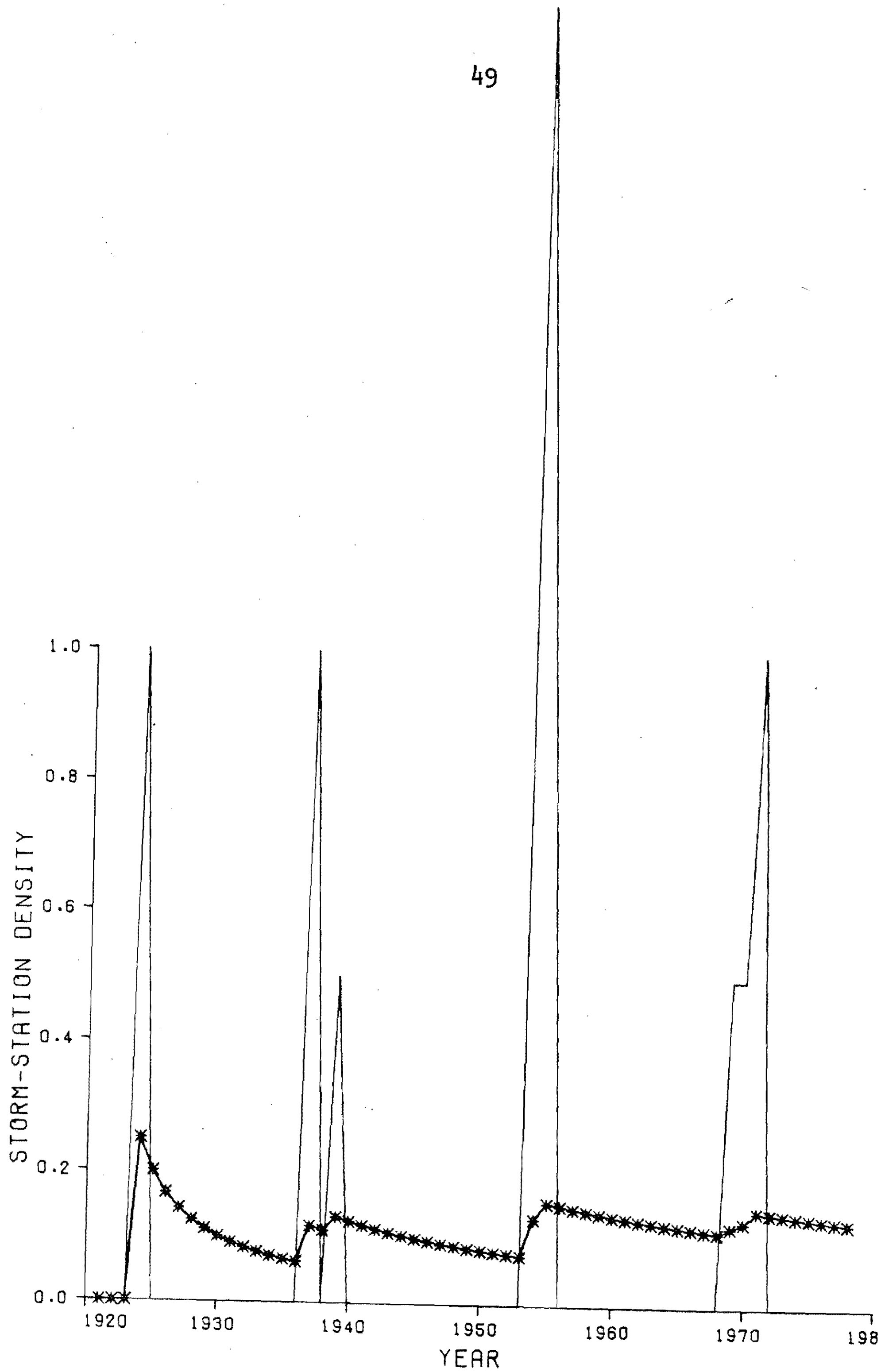


Figure 18 An example of a spatial block exhibiting the "unstable" effect in the cumulative average of the storm-station density ratio.

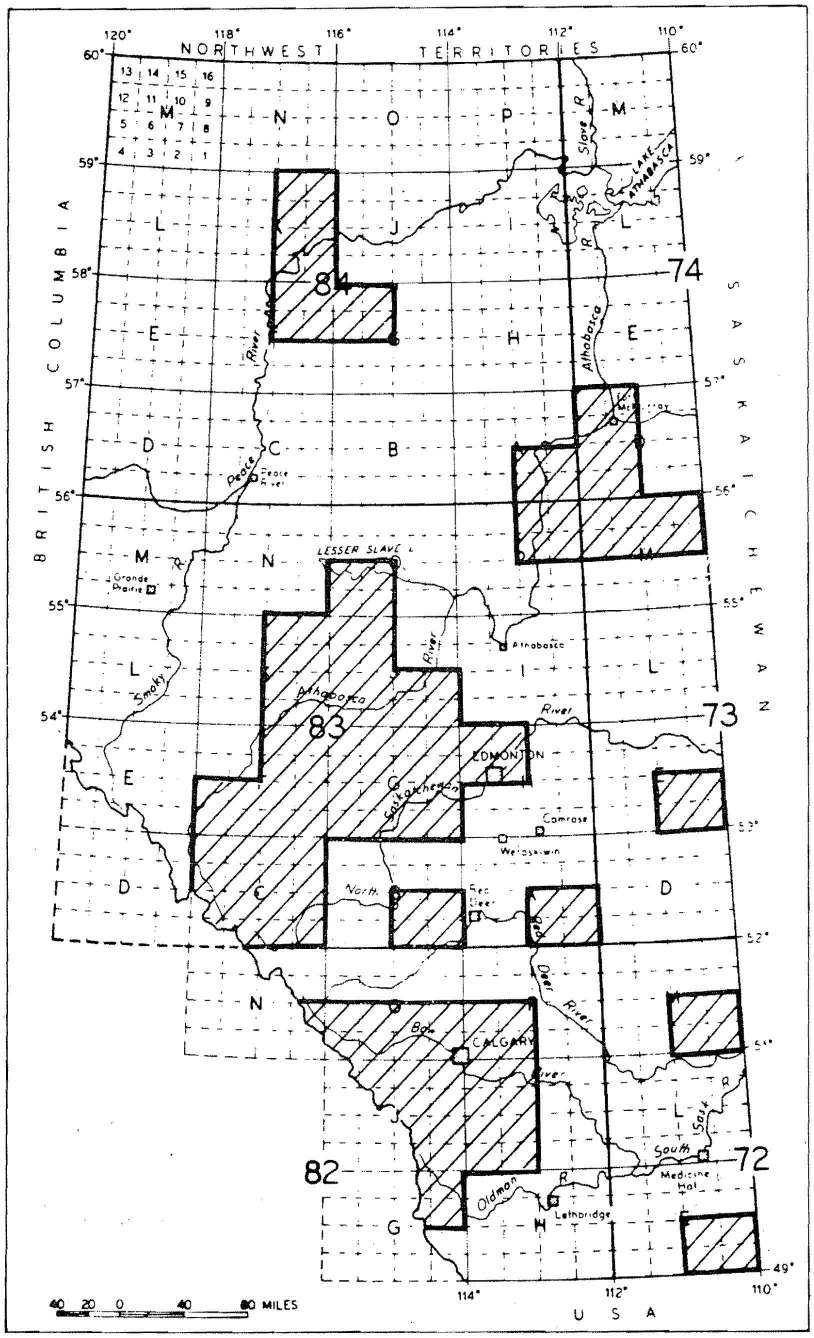


Figure 19 Spatial distribution of regions in Alberta with high variability in storm occurrence.

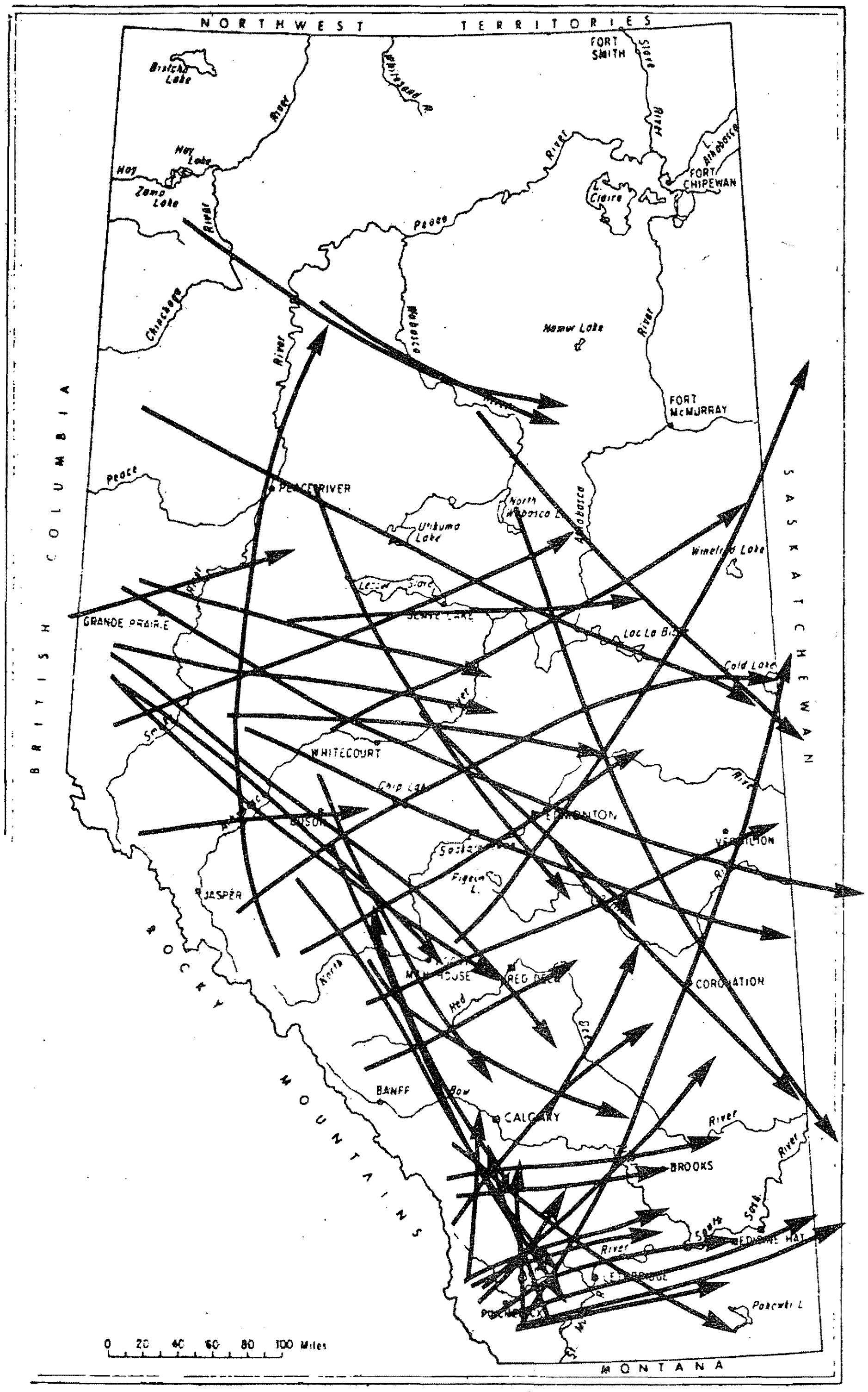


Figure 20 Mean precipitation pattern tracks of rainstorms which produced a depth of 150 mm or more during their lifetime (1921 to 1978).

2.7 CLASSIFICATION OF SEVERE RAINSTORMS

The severe rainstorms were also classified into the two main categories (Cold Low and Cold Trough Storms), with a number of sub-categories, according to Burrows (1966). The classification scheme given by Burrows is listed in Table 2. Of the 34 rainstorms producing 150 mm or more precipitation, 85% of the storms were of the Type I group, with the remainder being of the Type IIA category. Of the 29 storms in the Type I group, 15 (52%) were identified in the IA sub-class, 5 (17%) in the IB sub-class, and 9 (31%) in the ID sub-class. No IC or IIB sub-class storms were identified in the 34 rainstorms examined. The results show that the majority of the severe storms in Alberta are produced by cold low systems.

2.8 SUMMARY

The precipitation data were collected by a network of weather stations which has varied in density from its incorporation. Although the density remained low until the 1960's, it is doubtful whether any severe storms (greater than 150 mm in depth) were missed by the network in the area from central Alberta south to the U.S. border. The analysis of point measurements of maximum depth of the 611 rainstorms (1921-1978) showed that, on the average, about 11 storms occur each year with depths greater than 50 mm, and that the number of rainstorms decreases logarithmically with increased depth category. Over 50% of the rainstorms occur in June and July, with only a small percentage in April (5.6) and September (10.1). The greatest frequency of occurrence is observed in the Waterton Lakes Park area (just about 1 per year), with relatively high frequencies along the continental divide and decreasing eastward along the foothills and plains of Alberta. Two belts of secondary maxima are observed through

Table 2 Classification of rainstorm systems (according to Burrows) (1966)

Type I:	Cold Low Storms	
	IA	Rapid cyclogenesis east of Rocky Mountains due to a cold low originating in the Gulf of Alaska.
	IB	Combined overrunning and cold low effects without rapid cyclogenesis.
	IC	Cold lows that remain on the coast.
	ID	Cold lows which formed in the southwestern U.S.
TYPE II:	Cold Trough Storms	
	IIA	Cold troughs moving from the west coast or the north.
	IIB	Cold troughs from a deep cold low over Hudson Bay.

central Alberta; one through the Edson-Edmonton area, and a second from west of Drayton Valley to the Sundre area.

Like the analysis of point measurements of maximum depth, the results of the average depth showed that the greatest frequency of occurrence is that in the Waterton Lakes Park area with probability of 2.0 (1:2 year event) for depths 50 mm and more; 0.38 (1:3 year event) for depths 100 mm or more; and 0.09 (1:10 year event) for depths 150 mm or more. A decrease in the frequency of occurrence is observed along the continental divide, with a number of pockets of maxima in central Alberta. Seasonally the greatest frequencies are observed in June for southern Alberta and in July for central Alberta. Severe storms are observed to occur in four main regions (or belts) of the province: the first extends through southern Alberta, just south of Calgary; the second in central Alberta from south of Edson to the Edmonton region; the third from Lesser Slave Lake to the Fort McMurray area; and the fourth around the Fort Chipeywan area.

3. ESTIMATE OF PMP BY PHYSICAL METHOD

The United States Weather Bureau developed a physical approach to obtaining an estimate of the probable maximum precipitation. This method has now been accepted internationally (W.M.O. 1973) and is also called the "meteorological" or "traditional" method by various authors. The method is indirect and is based on the analysis and maximization of the largest rainstorms that occurred during the period of rainfall records. It assumes that the amount of rainfall from a storm depends on two independent factors: 1) the moisture content of the air mass; and 2) the efficiency of the rain-producing system. The procedure used for maximizing observed storm rainfall to estimate the PMP is discussed in the next sections and involves moisture adjustments, storm transposition, and envelopment[1]. By employing this procedure for 61 rainstorms, estimates of the PMP were obtained for six river basins in Alberta (South Saskatchewan, Bow, Red Deer, North Saskatchewan, Athabasca, and Peace River basins) and the results are presented (see also Appendix 8.3).

3.1 ESTIMATE OF ATMOSPHERIC MOISTURE

For production of precipitation, the moisture in the lower layers of the atmosphere is extremely important (Schwarz 1967; U.S. Dept. of Commerce, Weather Bureau 1960). Theoretical computations show that, for excessive rain, air originally near the surface reaches the top of the layer from which precipitation is falling within an hour or so. In the case of severe thunderstorms, surface air may reach the top in a matter of minutes.

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[1] A process in which the largest value is selected from a set of data for a given area, and a smooth curve drawn through the largest values.

The most realistic assumption seems to be that the air ascends dry-adiabatically to the saturation level and thence moist-adiabatically. Thus hydrometeorologists generally postulate a saturated pseudo-adiabatic atmosphere for extreme storms. To maximize the moisture of a storm, two saturation adiabats are required. The first gives a measure of the vertical temperature distribution in the storm to be maximized, while the second is the warmest saturation adiabat to be expected at the same place and time of year as the storm. In meteorology these two saturation adiabats are identified by the wet-bulb potential temperature, which corresponds with the dew point temperature at the 1 000 mb level. Tests by the U.S. Dept. of Commerce, Weather Bureau (1960) have shown that storm and extreme values of precipitable water may be approximated by estimates based on surface dew points when saturation and pseudo-adiabatic conditions are assumed. Hence surface dew points are used in identifying the storm saturation adiabat in maximizing the moisture content of the storm. Both storm and maximum dew points are reduced pseudo-adiabatically to the 1 000 mb level by use of Figure 21, so that dew points observed at stations of different elevations are comparable.

As the moisture has an appreciable effect on the storm, precipitation must be that which persists for hours rather than minutes. Also, any single observation of dew-point may be considerably in error. Hence, for estimating storm and probable maximum moisture, the conventional procedure is to use dew-point values on two or more consecutive measurements separated by a reasonable time interval. The adopted procedure is to use the so-called highest persisting 12-hour dew point temperature. This is the highest value equalled or exceeded by all observations during a 12-hour period. For example, for the following series of dew points observed at 3-hour intervals, the highest persisting

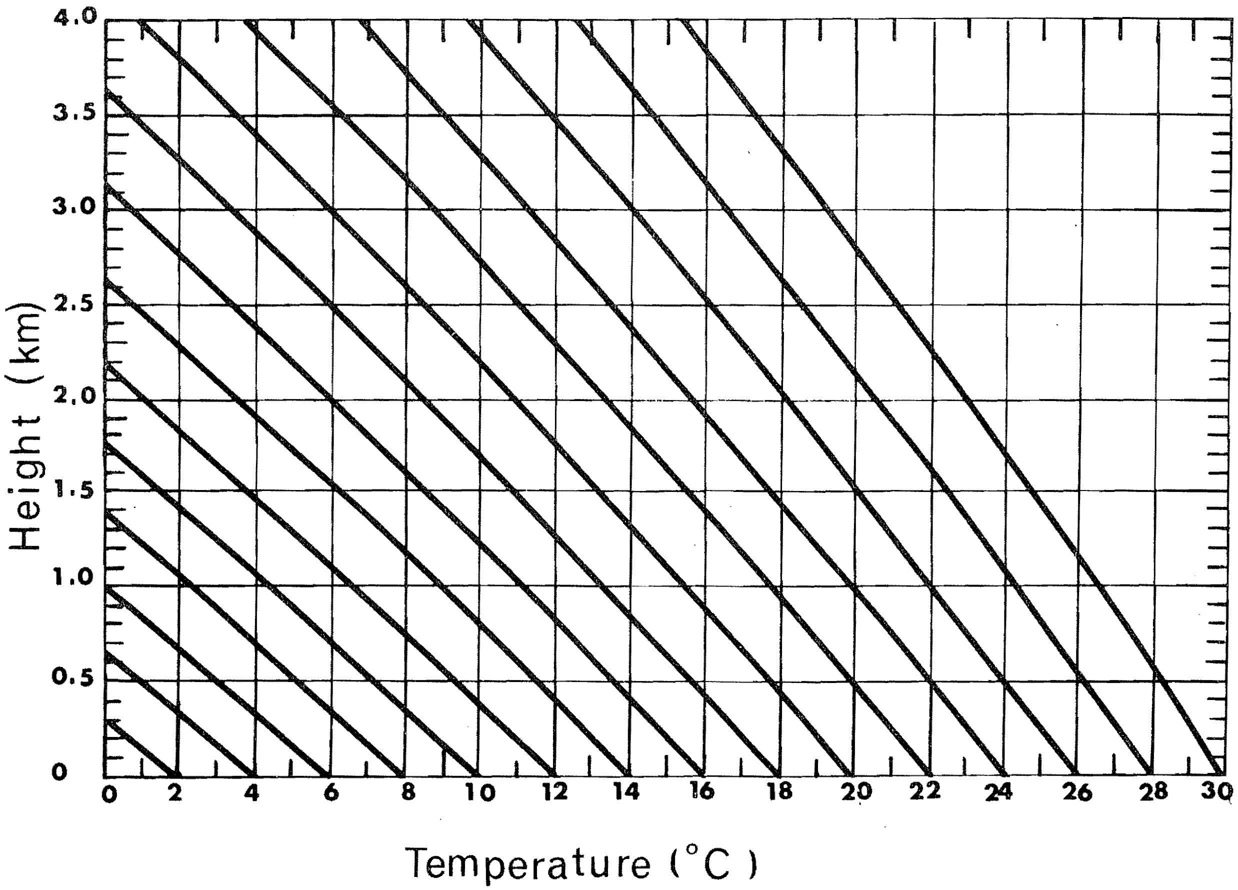

Figure 21 Pseudo-adiabatic diagram for dew-point reduction to 1 000 mb at height zero (W.M.O. 1973).

12-hour dew point is 15°C, which is obtained from the period 15 to 03:

Time:	00	03	06	09	12	15	18	21	00	03	06	09
Dew point (°C):	13	11	11	12	14	15	15	16	16	16	14	14

It is from the maximum persisting 12-hour 1 000 mb dew point temperatures that the maximum values of atmospheric water vapour used for storm maximization are estimated. These dew points are obtained for stations in the basin. Since numerous estimates of PMP are required, for each station an enveloping curve of semi-monthly recorded maximum persisting 12-hour dew points were produced. (An example for Pincher Creek is shown in Figure 22, while the graphs for the other stations are given in Appendix 8.3). With the aid of these curves, moisture adjustments are made on the basis of the maximum persisting 12-hour dew point for the same time of year as the storm occurrence. Thus, for example, maximum dew point indicated by a May value (and not that in September, for instance) would be used to maximize a May storm. Also prepared were monthly maps of recorded maximum persisting 12-hour 1 000 mb dew points which not only served as a convenient source of maximum dew points but also aided in maintaining consistency between estimates for various basins. The maps were prepared by using the monthly maximum recorded 12-hour dew point values, adjusting them to the 1 000 mb level, plotting them at the locations of the observing stations, and drawing smooth isopleths. An example of such a map is shown in Figure 23 for the month of June in Alberta; the maps for the other months are given in Appendix 8.3.

Before an estimate of the moisture maximization is obtained, it is necessary to find the amount of precipitable water available from the storm as well as the potential maximum amount produced at the station. The amount of precipitable

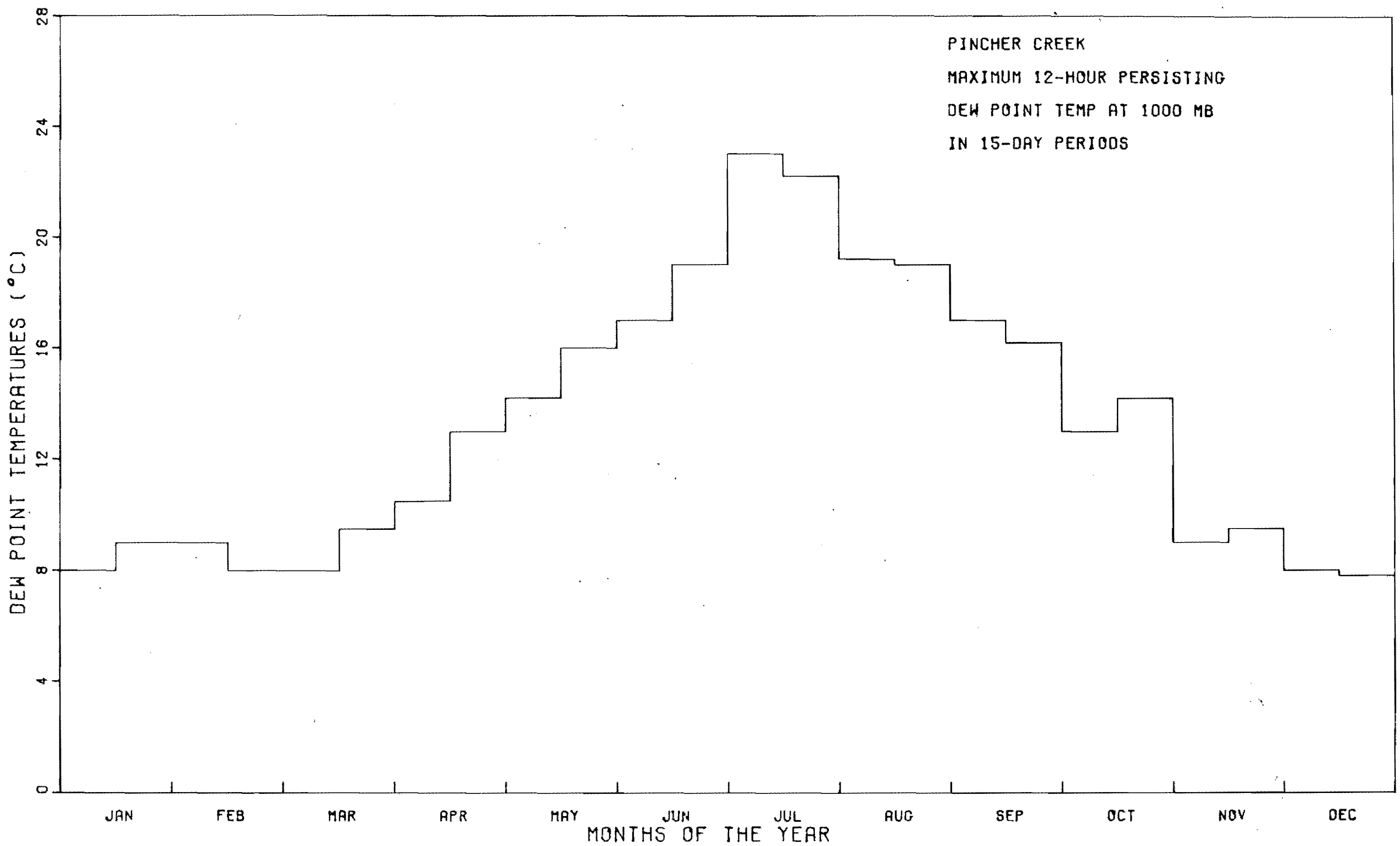

Figure 22 Maximum recorded 12-hour persisting dew point temperatures at 1 000 mb for Pincher Creek

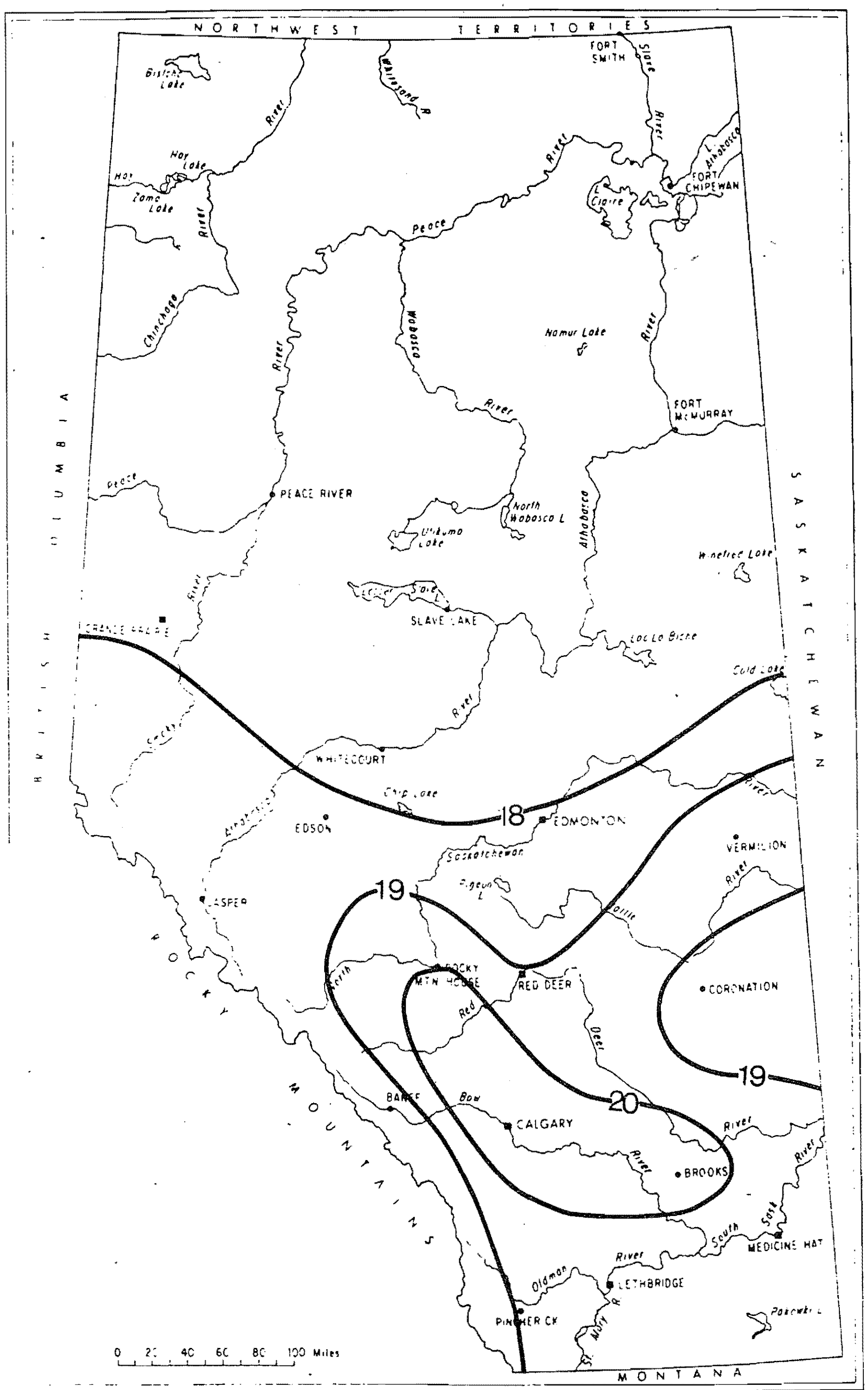

Figure 23 Isoplets of maximum 12-hour persisting dew point temperatures for June.

water, W (cm) can be computed by the general formula:

$$W = \frac{\bar{q}\Delta p}{g\rho} \tag{2}$$

where $\bar{q}$ is the mean specific humidity in gkg^{-1} of a layer of moist air; Δp the depth of the layer in mb; g the acceleration of gravity in $cm \cdot sec^{-2}$); and ρ the density of water (equal to $1\ g \cdot cm^{-3}$). For convenience, equation (2) has been precomputed by the U.S. Dept. of Commerce, Weather Bureau (1951) and is usually listed as tables or in nomogram form. Two tables are given in Apprndix 8.3. Table 5 presents values of precipitable water (mm) between the 1 000 mb surface and various pressure levels up to 300 mb in a saturated pseudo-adiabatic atmosphere as a function of the 1 000 mb dew point. Table 6 presents values of precipitable water (mm) for layers between 1 000 mb surface, assumed to be at zero elevation, and various heights up to 8 km. The 300 mb level is accepted generally as the top of the storm, but it makes little difference which level from 400 mb on up is selected, as there is very little moisture at those heights, and the effect on the moisture adjustment is negligible.

3.2 MOISTURE MAXIMIZATION

Moisture maximization of rainstorms in place[1], consists of multiplying the observed storm rainfall amounts by the ratio (r_m) of the maximum precipitable water (W_m) indicated for the storm location to the precipitable water (W_s) estimated for the storm, or expressed in equation form:

$$r_m = W_m/W_s \tag{3}$$

[1] i.e., without change in location. Storm transposition requires a further moisture adjustment.

For example, if the representative persisting 12-hour 1 000 mb storm dew point is 18°C and the maximum is 22°C, and the rain area is at an elevation of 1 000 m above mean sea level with no intervening topographic barrier between the rain area and moisture source the moisture maximizating ratio, (r_m) can be computed as follows:

Maximum precipitable water (W_m):

Precipitable water between 1 000 mb and 300 mb at 22°C (Table 5) :	62 mm
Precipitable water between 1 000 mb and 1 000 m at 22°C (Table 6) :	17 mm
W_m = 62-17 = 45 mm	

Precipitable water for storm (W_s):

Precipitable water between 1 000 mb and 300 mb at 18°C (Table 5) :	44 mm
Precipitable water between 1 000 mb and 1 000 m at 18°C (Table 6) :	13 mm
W_s = 44-13 = 31 mm	

The moisture maximizing ratio (r_m) is 45/31 or 1.45.

3.3 STORM TRANSPOSITION

In this study, limited storm transposition[1] was employed. In those few cases, moisture and elevation adjustments were computed before the ratio was multiplied by the storm DAD array of rainfall values.

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[1] The transfer of storms from locations where they occurred to other areas where they could occur is called storm transposition.

The transposition procedure involved the meteorological analysis of the storm to be transposed: i.e., the determination of the limits of transposability, and the application of the proper adjustments for making the modifications required by the change in storm location. In estimating PMP for a specific basin, major storms were examined to determine if they could be transposable to the basin. The storms were then adjusted as required by the geographic features of that particular basin. In the preparation of generalized PMP charts, the boundaries, or limits, of the area of transposability of each major storm were delineated. The limits were governed by the constant lines of maximum persisting 12-hour 1 000 mb dew point temperatures (Figures 23, and 100 to 106) and transposed within these limits. In this study, no elevation adjustments were employed because of the uncertainty as to the effects of relatively small or gradual elevation changes on precipitation. There are differences of opinion as to whether or not elevation adjustments should be made for storm transposition over broad, gradually sloping plains. The W.M.O. (1973) states that, for intense local thunderstorms, no adjustment for elevation is necessary when transposition involves elevation differences of less than about 1 500 m.

To maximize a single storm and transpose it to a basin is a demonstration that a certain precipitation volume could fall over that basin. There is no guarantee that the maximum magnitude of the PMP has been achieved, since no single storm is likely to yield extreme rainfall values for all durations and sizes of area. Hence a procedure of envelopment is used as a final step in estimating the PMP for the basin. The process involves selecting the largest value from any set of data by plotting the maximized rainfall data on graph paper, and drawing a smooth curve through the largest values.

3.4 ESTIMATION OF PMP FOR ALBERTA BASINS

A total of 61 DAD analyses were obtained, 60 from the "Storm Rainfall in Canada" series, and one from Warner (1973). Although a number of river basins and sub-basins exist in Alberta (Alberta Environment 1978), six main basins were considered in this report; namely, South Saskatchewan[1], Bow, Red Deer, North Saskatchewan[2], Athabasca, and Peace River basins (see Figure 24). Graphs showing depth-area curves for a specific duration were plotted for rainstorms which occurred or could be transported[3] to the basin. The figures of the 24-hour rainfall for each basin are used as examples while those for other durations (6-, 12-, 48-, 72-, and 96-hour) are found in Appendix 8.3. The estimates of the PMP shown in the figures are the maximum values calculated in each of the basins. Since most of the basins cover large surface areas, the maximum estimates cannot be expected to be appropriate for the whole basin. The spatial variations of the 24- and 48-hour PMP estimates are discussed in Section 3.6.

3.4.1 South Saskatchewan River Basin

The South Saskatchewan River basin (including the Oldman and Pakowki Lake basins) is about 45 500 km^2 in area, and this region experiences the greatest frequency of occurrence of rainstorms in Alberta. Altogether, 21 rainstorms were maximized and transported to this basin and the results for the 24-hour rainfall are given in Figure 25. The letters of the alphabet were used to denote the various storms. The 7 to 8 June 1964

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[1] This river basin includes the Oldman, and Pakowki Lake.
[2] This river basin includes the North Saskatchewan, Battle River and Manito basins.
[3] Storms occurring in regions with similar meteorological and topographic limits.

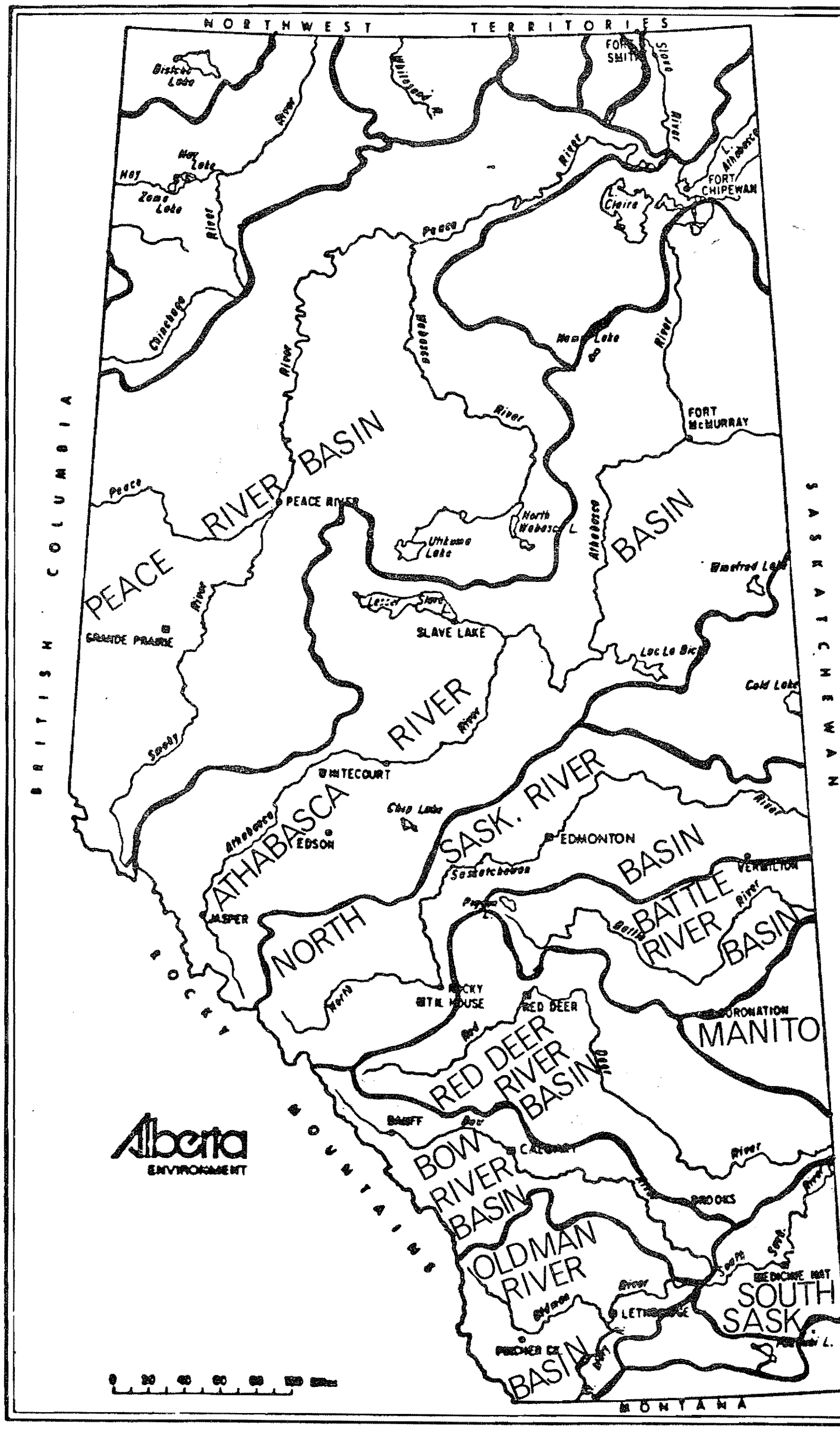

Figure 24 River basins and sub-basins used.

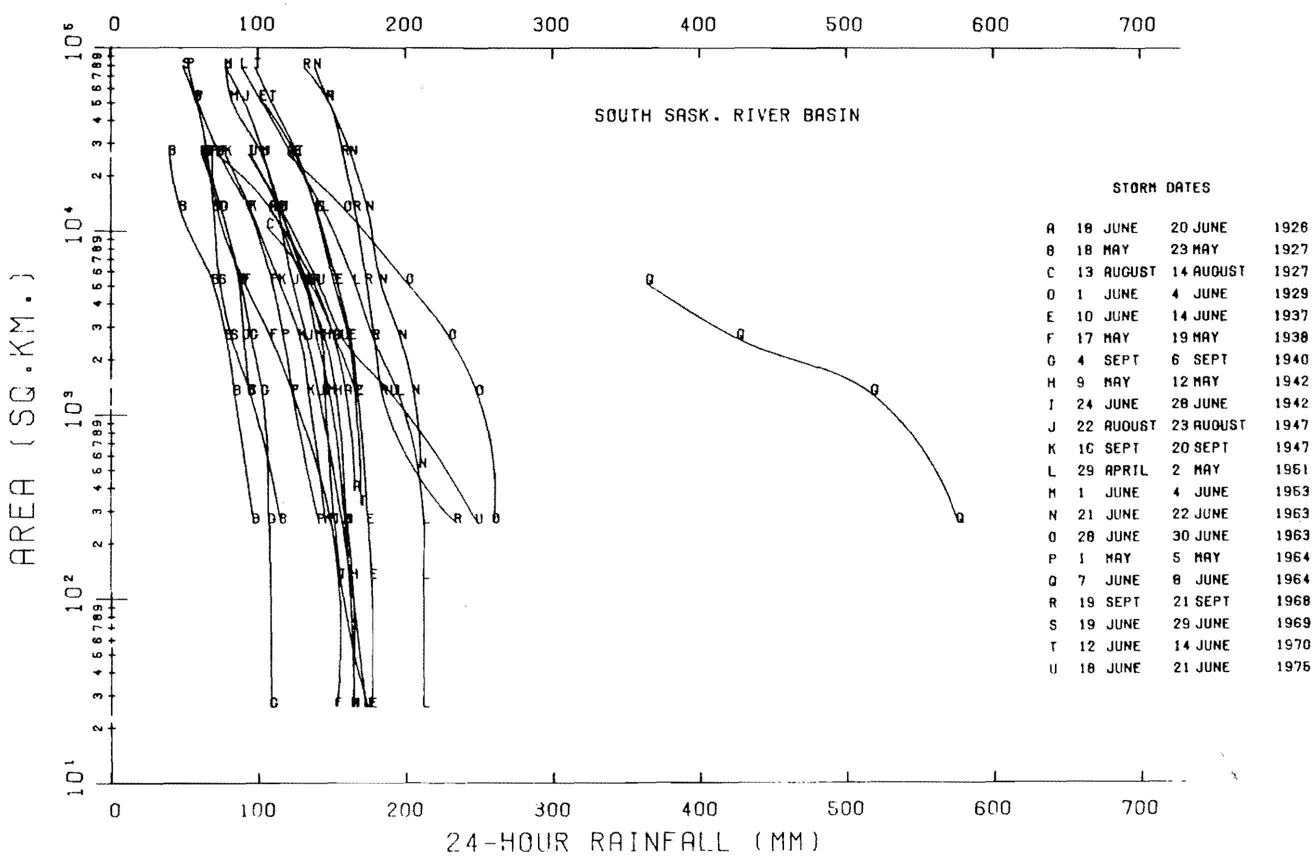

Figure 25 Depth-area curves of maximized 24-hour PMP for the South Saskatchewan River basin.

rainstorm produced the greatest amount of precipitation for a given area in the last 50 years in this basin, and is prominent among the storms in Figure 25. Except for this storm, the other storms are conjested at a much lower PMP, between the 100 and 300 mm depths of precipitation. The maximum estimated PMP for this basin is due to the 7 to 8 June 1964 storm and is 575 mm for a 260 km^2 area, decreasing to 364 mm for a 5 180 km^2 area.

Similarly results for 6-, 12-, 48-, 72-, and 96-hours rainfall were plotted (Appendix 8.3) and, for these as well as for 24-hour rainfall (Figure 25), a curve through the maximum rainfall values was drawn. The resulting curves are given in Figure 26 for this basin. In this figure, as well as for others where envelopes of curves were drawn, the letters of the alphabet are used for a given duration. For each duration, a smooth line through these points was plotted at the following available area coordinates: 25.9 km^2; 259 km^2; 1 295 km^2; 2 590 km^2; 12 950 km^2; 25 900 km^2 and 51 800 km^2. In cases where the coordinates exceed the area of the basin, the storms were so large in area that they not only covered most of the basin but regions of other basins. For areas less than 10 000 km^2, a large increase in the estimated PMP is usually observed between the 12- and the 48-hour durations. In this basin, there is very little difference in the average depth of rainfall for durations 48-hour and longer (e.g., 72- and 96-hour). Compared to some of the other basins, which are presented next, this basin has the largest estimates of the PMP for a given area and duration.

3.4.2 Bow River Basin

The Bow River basin is the smallest of the six basins examined in this report with an approximate area of 25 600 km^2. Through this basin a number of large rainstorms have occurred, but none with as heavy a depth of precipitation as the 7 to

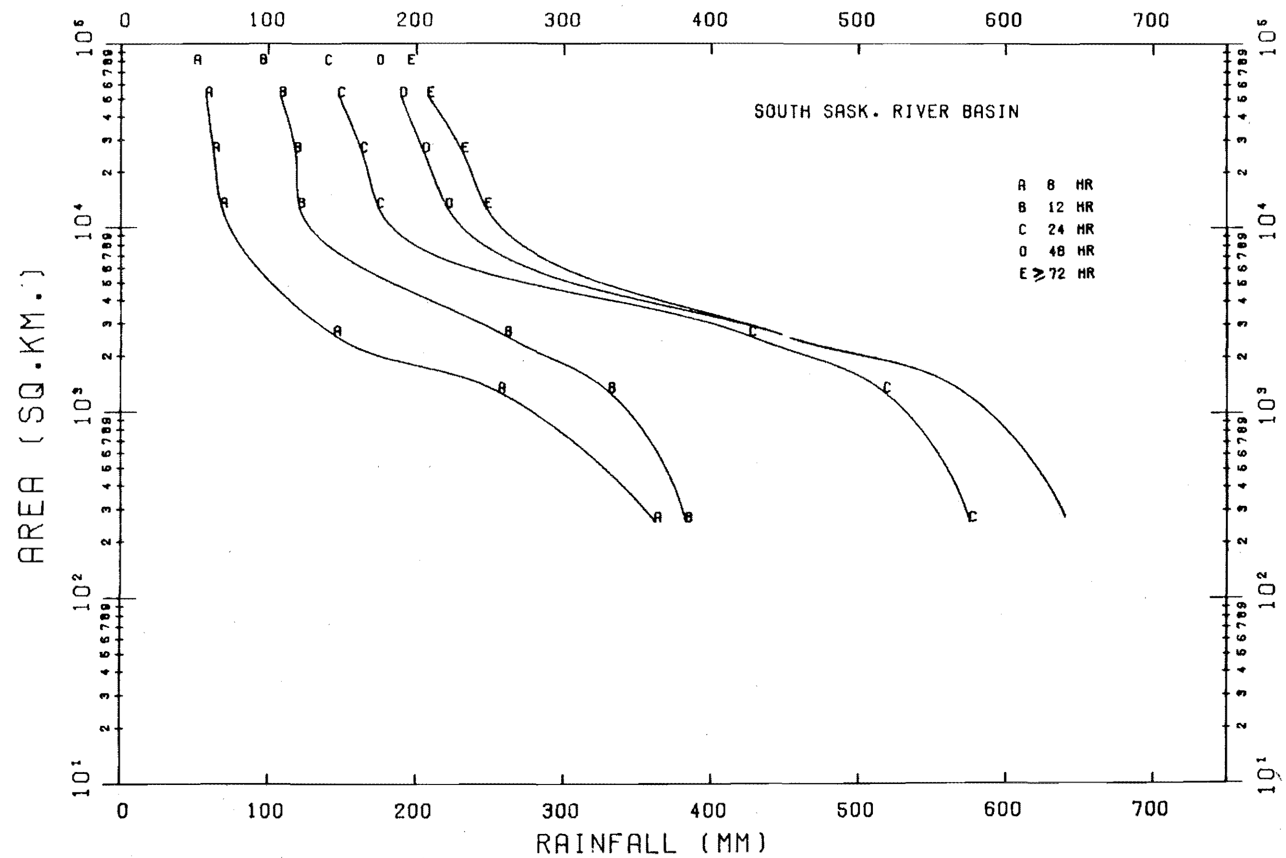

Figure 26 Enveloping DAD curves of PMP for the South Saskatchewan River basin.

8 June 1964 rainstorm in the South Saskatchewan River basin. The 17 available rainstorms which occurred or which were transported to the basin were maximized and the estimates of the 24-hour PMP are shown in Figure 27. The largest estimates of the 24-hour PMP for areas less than 10 000 km^2 were obtained for the 28 to 30 June 1963 storm (Storm L in Figure 27) with an average maximized depth of 260 mm for a 259 km^2 area and a depth of 201 mm for a 5180 km^2 area. The remainder of the storms had lower estimates of the PMP with the majority of these between 100 and 200 mm in depth. The enveloping curves for this basin are shown in Figure 28.

In Figure 28, the 48-, 72-, and 96-hour curves coincide for areas less than 10 000 km^2. Again, as for the South Saskatchewan River basin, the greatest differences in the estimate of the PMP occur between the 12- and the 24-hour durations, while the least differences are found for durations 48-hour and longer. Compared to the other curves, the 24- and the 48-hour durations exhibit a relatively large increase in the estimate of the PMP for decrease in area from 10 000 km^2 to 1 000 km^2. Even with a 96-hour duration, the greatest estimate of the PMP for this basin is about 340 mm for an area of 260 km^2 (Figure 28).

3.4.3 Red Deer River Basin

The third basin for which estimates of the PMP were made was the Red Deer River basin, with an approximate area of 46 800 km^2. The estimates of the 24-hour PMP for the 22 rainstorms examined are shown in Figure 29. For areas less than 1 000 km^2, the largest estimates of the 24-hour PMP were calculated in the 12 to 16 July 1937 storm, while for areas greater than 2 000 km^2 the storm of 14 to 17 June 1973 produced the largest estimates. Most of the rainstorms affecting this basin had 24-hour PMP estimates between 100 and 300 mm, similar to that calculated for the Bow River basin. Only a few storms (Storms,

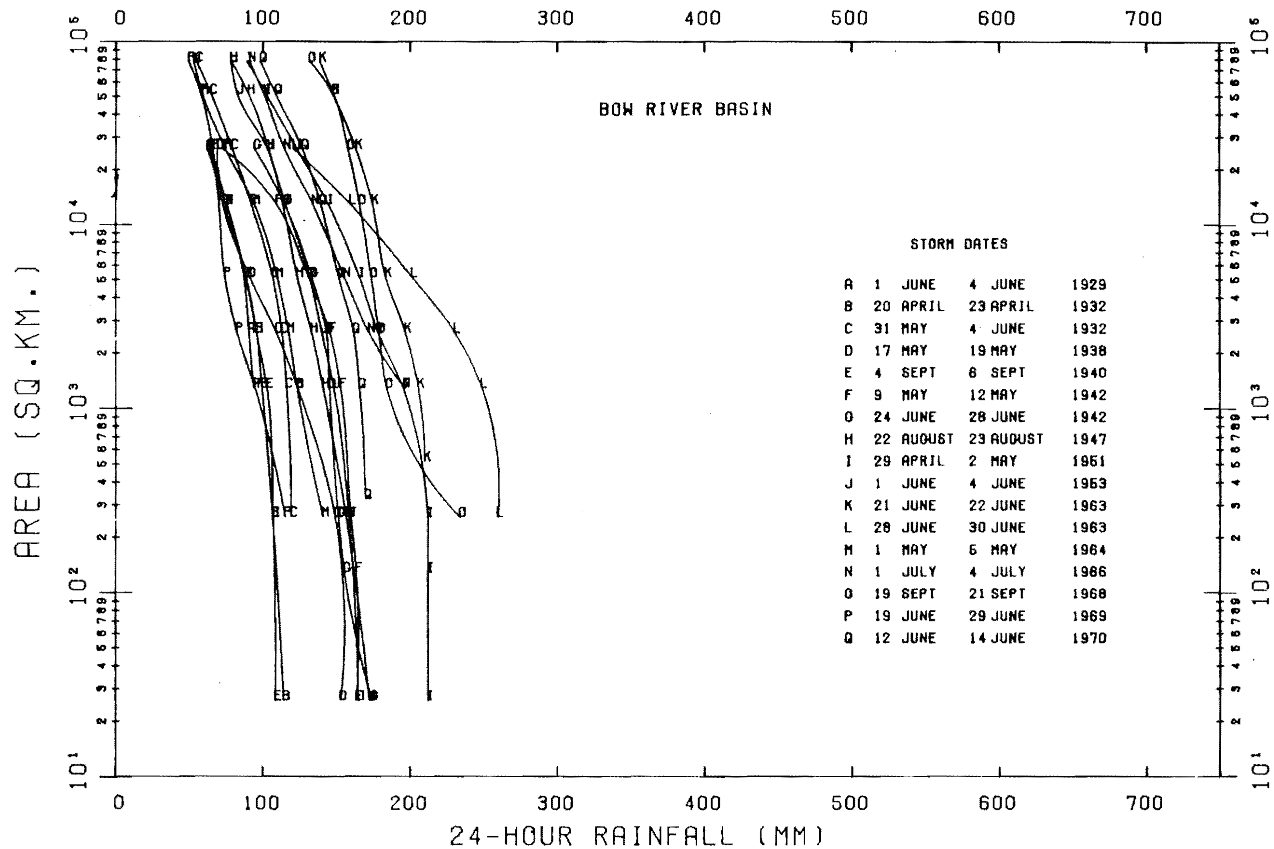

Figure 27 Depth-area curves of maximized 24-hour PMP for the Bow River basin.

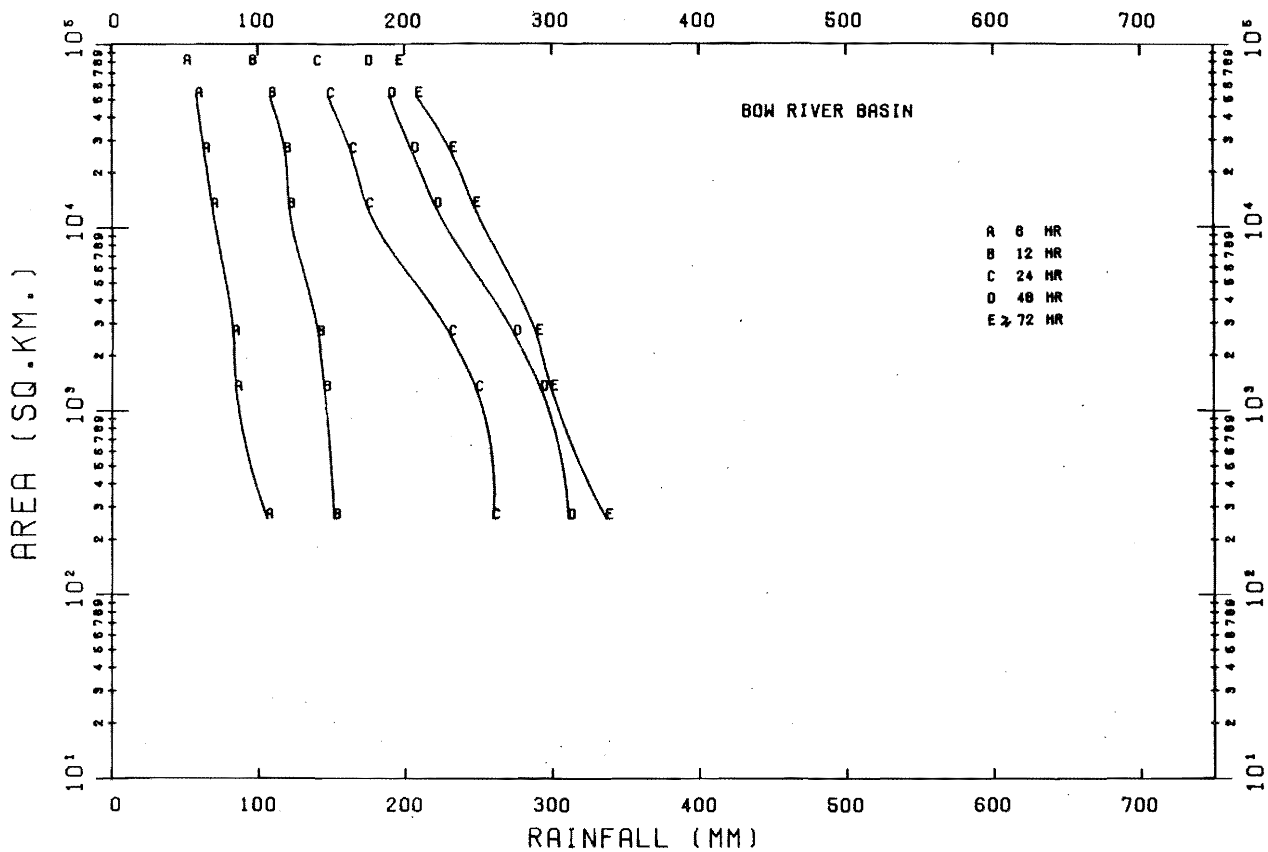

Figure 28 Enveloping DAD curves of PMP for the Bow River basin.

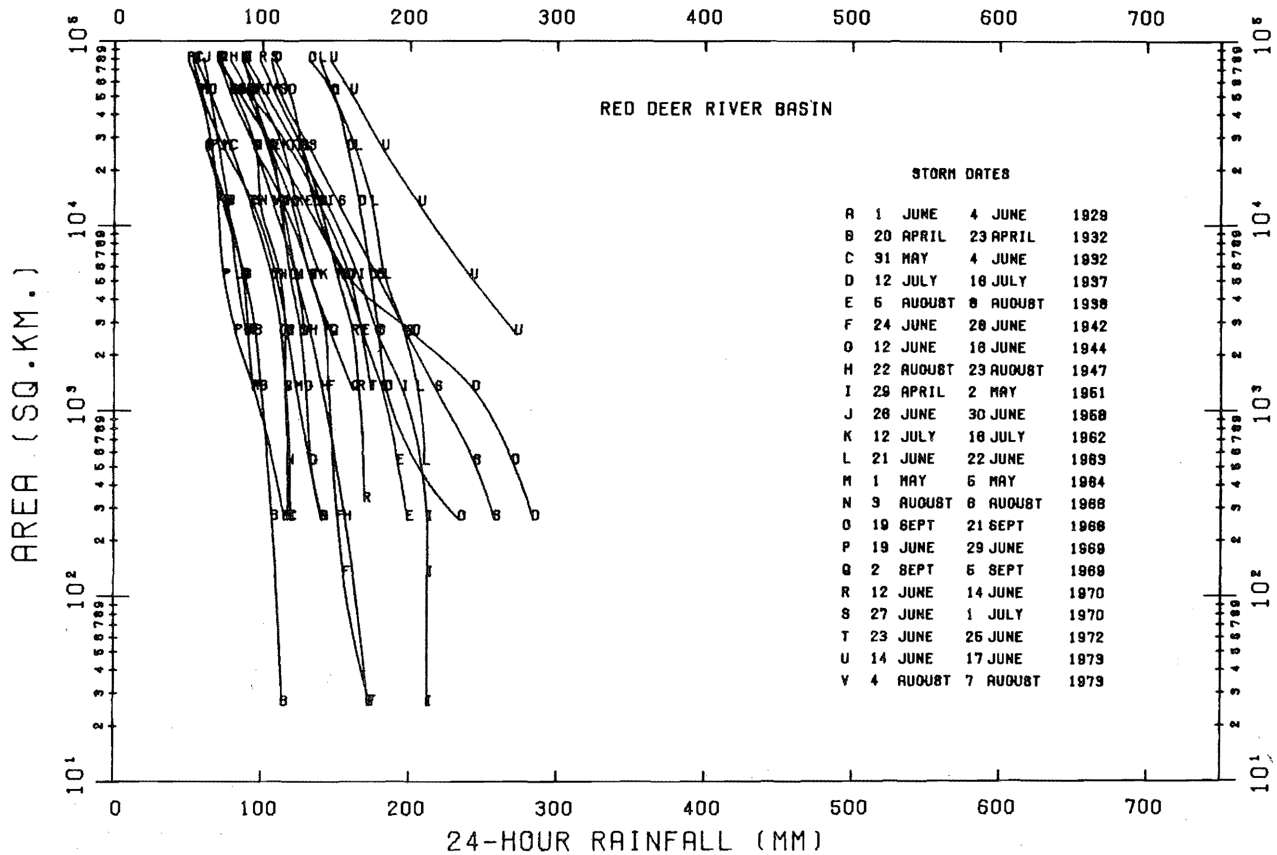

Figure 29 Depth-area curves of maximized 24-hour PMP for the Red Deer River basin.

D, S, and U in Figure 29) showed a rapid rise in the estimated PMP with decrease in area; the majority of the storms exhibited a gradual increase for the same decrease in area.

Figure 30 contains the enveloping DAD curves for this basin. Again the large difference in estimates of the PMP observed for the other basins between the 12- and 24-hour duration is noted. No 96-hour durations are presented in this figure since these are the same as the 72-hour durations. The estimates of the PMP for areas less than 10 000 km^2 were larger for the Red Deer River basin (Figure 30) than the Bow River basin (Figure 28) for all durations. This is probably because the storms occurring in this basin are farther north from the continental divide, hence more mature and result in a greater depth at the surface. Few estimates below 1 000 km^2 area were available from the DAD analyses. Also of note is the rapid increase in the average depths with decrease in area size, especially from about 20 000 km^2 to 1 000 km^2.

3.4.4 North Saskatchewan River Basin

In the analysis, three river basins (North Saskatchewan, Battle River and Manito) were combined under the title of the North Saskatchewan River basin. The total combined area is 93 000 km^2, of which the North Saskatchewan occupies 61%, the Battle River 27% and the Manito 12%. Estimates of the 24-hour PMP were made on a total of 28 storms and these are shown in Figure 31. The storm with the greatest PMP estimates occurred from the 22 to 24 July 1960 (denoted by the letter L in Figure 31) with a calculated value of about 300 mm of rainfall for the 500 km^2 area. A sharp rise in the 24-hour PMP estimate of a number of storms is probably because these are thunderstorms. The envelope curves of DAD of the estimates of PMP for the six durations are shown in Figure 32. The estimates for this river

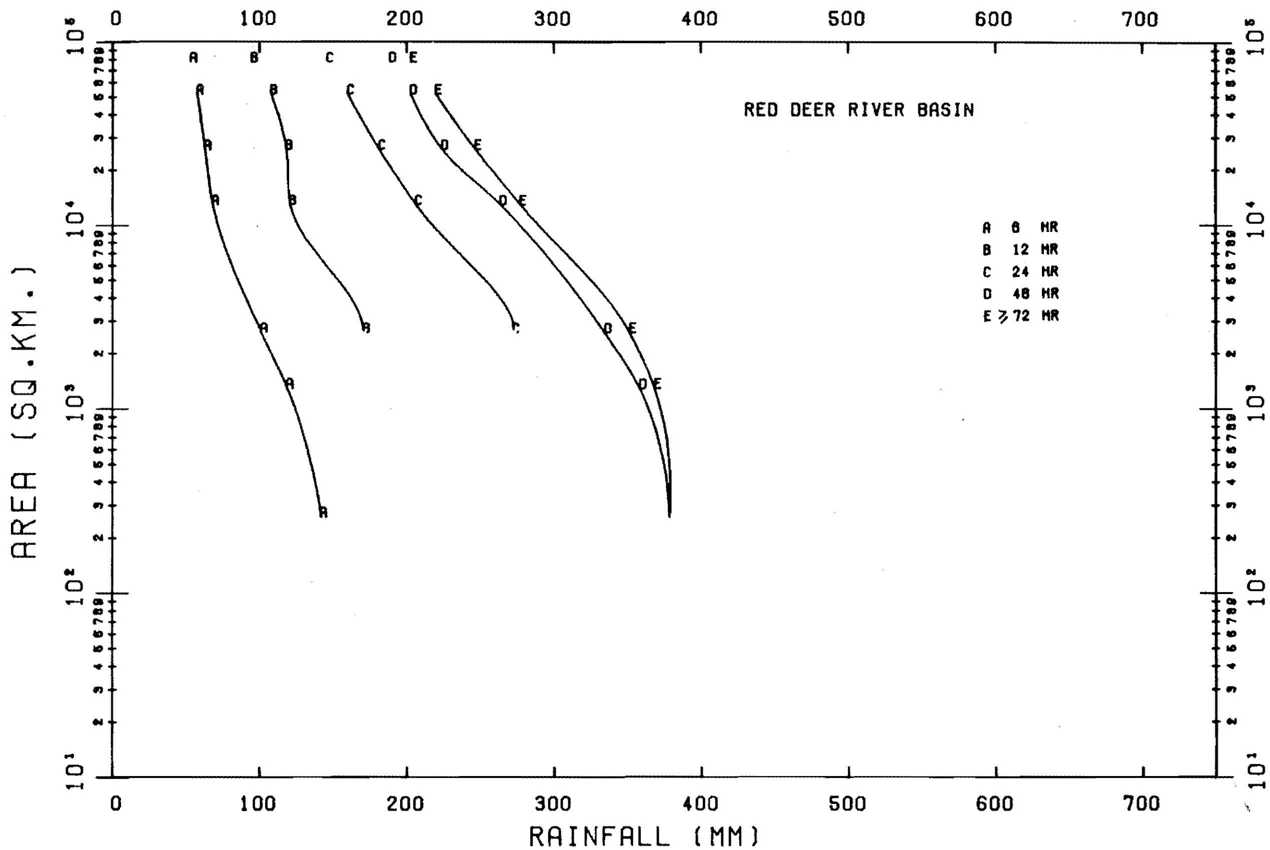

Figure 30 Enveloping DAD curves of PMP for the Red Deer River basin.

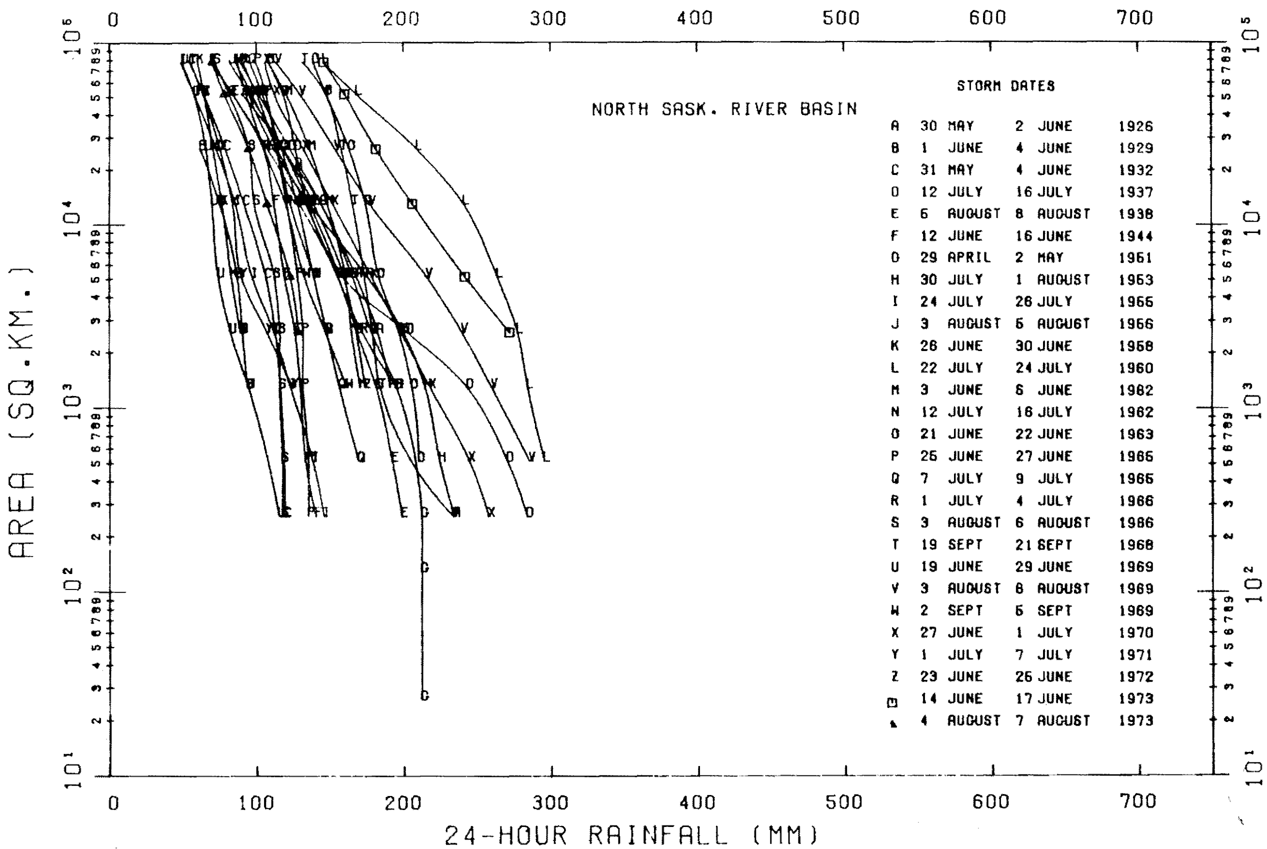

Figure 31 Depth-area curves of maximized 24-hour PMP for the North Saskatchewan River basin.

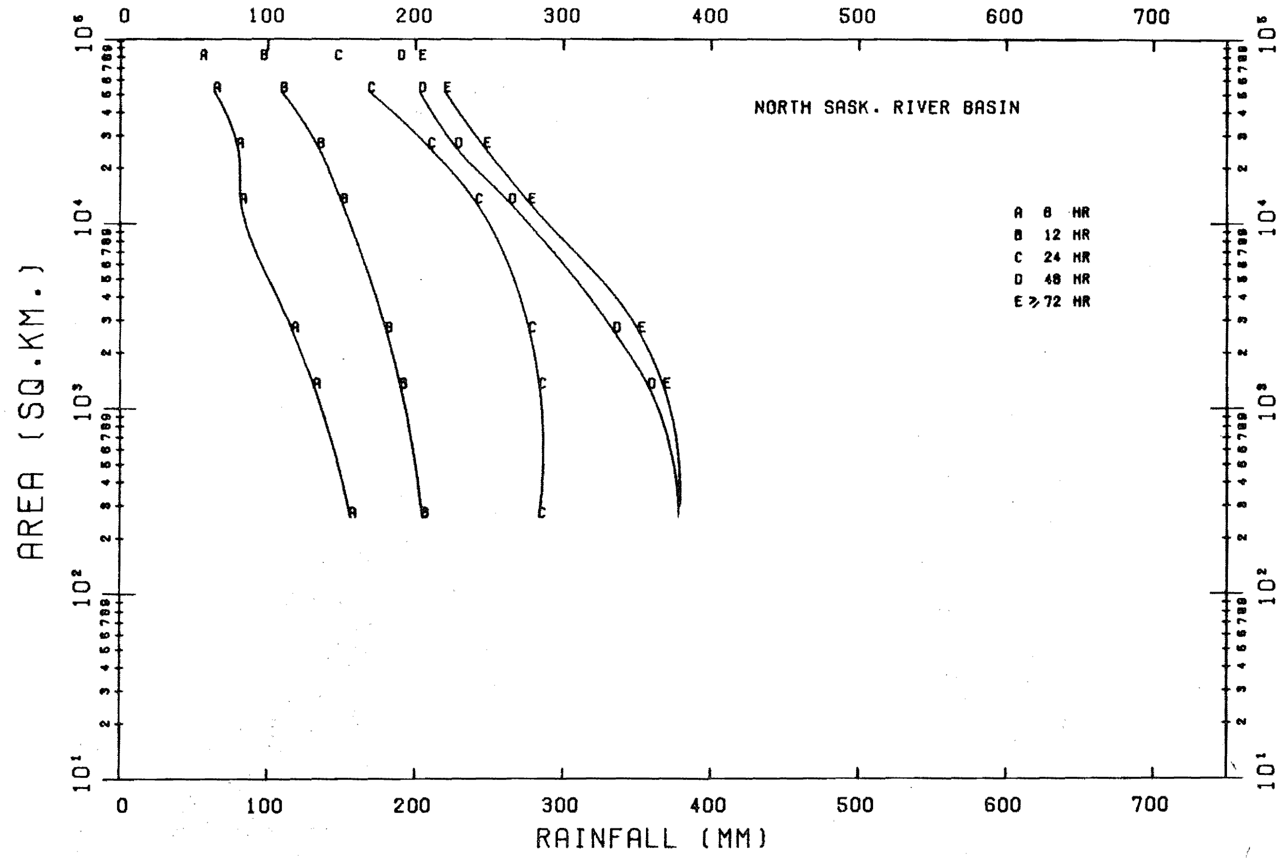

Figure 32 Enveloping DAD curves of estimates of PMP for the North Saskatchewan River basin.

basin are just slightly larger than those for the Red Deer River basin for all durations. As is the Red Deer River basin, an increase in the PMP estimate with decrease in area is observed. This seems to be characteristic of basins in central and northern Alberta. The greatest estimates obtained in this basin were about 380 mm for an area of about 260 km^2 (durations of 48-hour and longer).

3.4.5. Athabasca River Basin

The Athabasca River basin is approximately 144 700 km^2 in area and extends from the Rocky Mountains at Jasper to the Saskatchewan border. A total of 29 storms were maximized for this basin and the estimated 24-hour PMP are shown in Figure 33. The storm of 22 to 24 July 1960, which was considered transportable to the North Saskatchewan River basin and which dominated the estimates for that basin, also has the greatest estimates in this basin. An estimate of about 300 mm seems to be the largest PMP for a 500 km^2 area in basins north of the Bow River basin. The DAD curves of estimates of the PMP for the Athabasca River basin are shown in Figure 34. The curves for the various durations in this figure are similar in magnitude to those observed for the North Saskatchewan River basin, except with slightly larger values in the PMP.

3.4.6 Peace River Basin

The last and largest in area of the river basins examined was the Peace River basin, with an area of approximately 172 700 km^2. A total of 21 rainstorms were maximized and curves of the 24-hour PMP estimates given in Figure 35. The storm which was estimated to have the greatest PMP was the one that occurred from the 27 to 28 June 1964, with an average estimated amount of

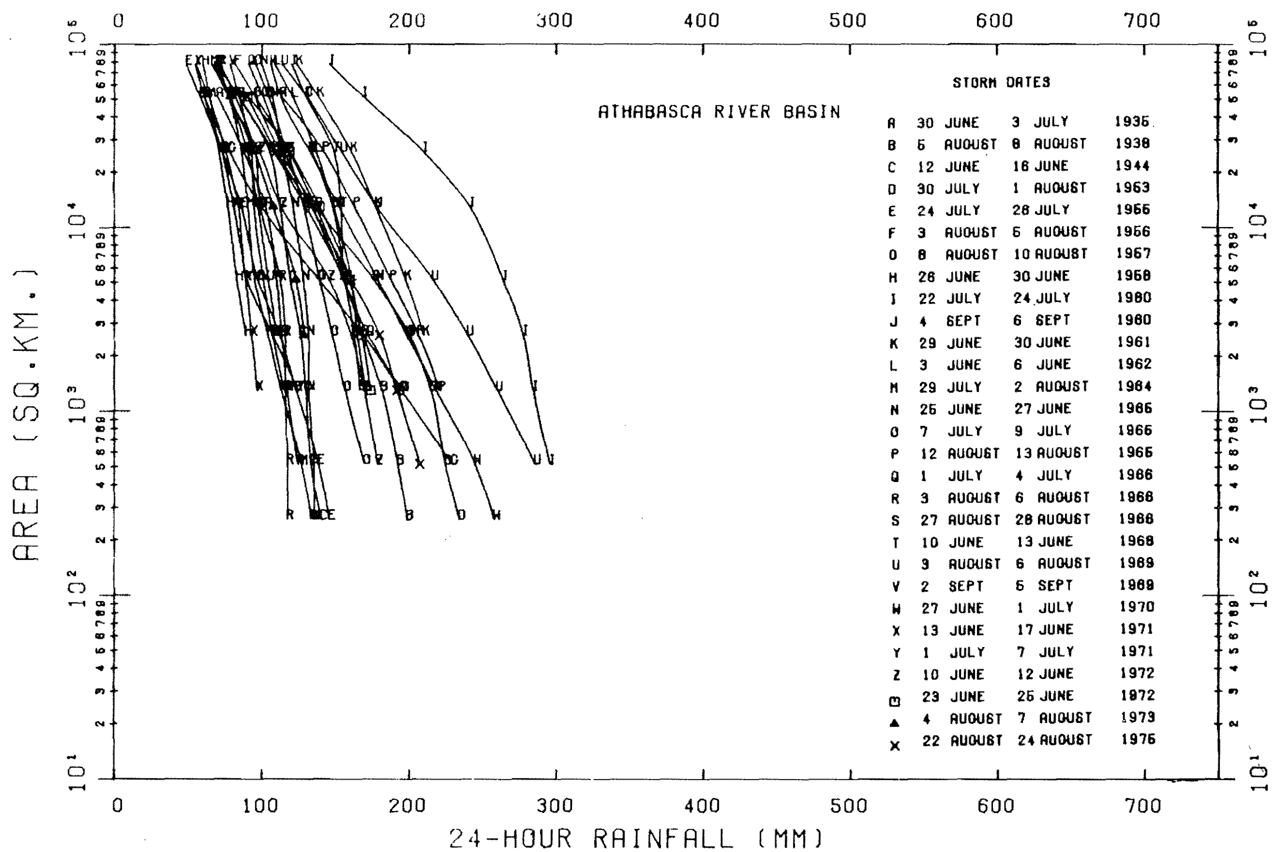

Figure 33 Depth-area curves of maximized 24-hour PMP for the Athabasca River basin.

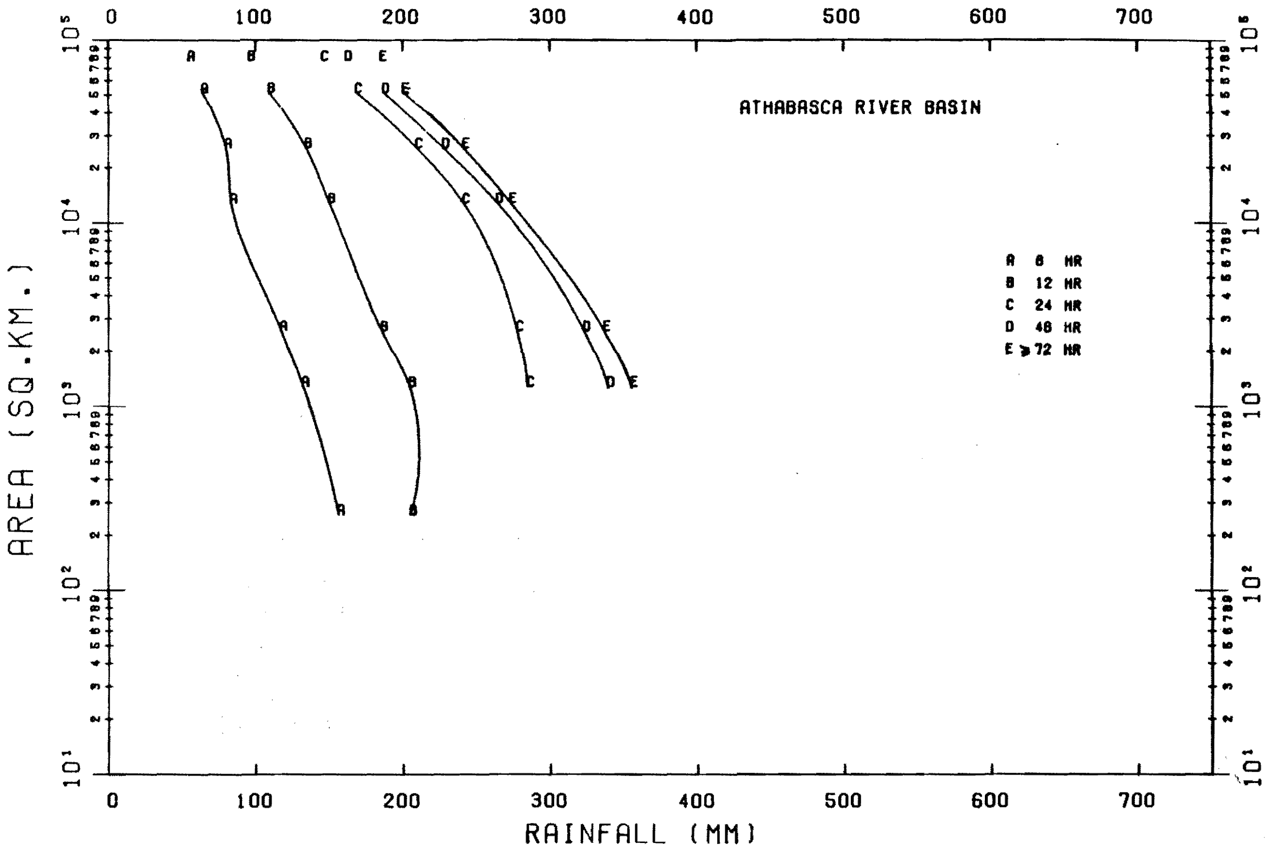

Figure 34 Enveloping DAD curves of PMP for the Athabasca River basin.

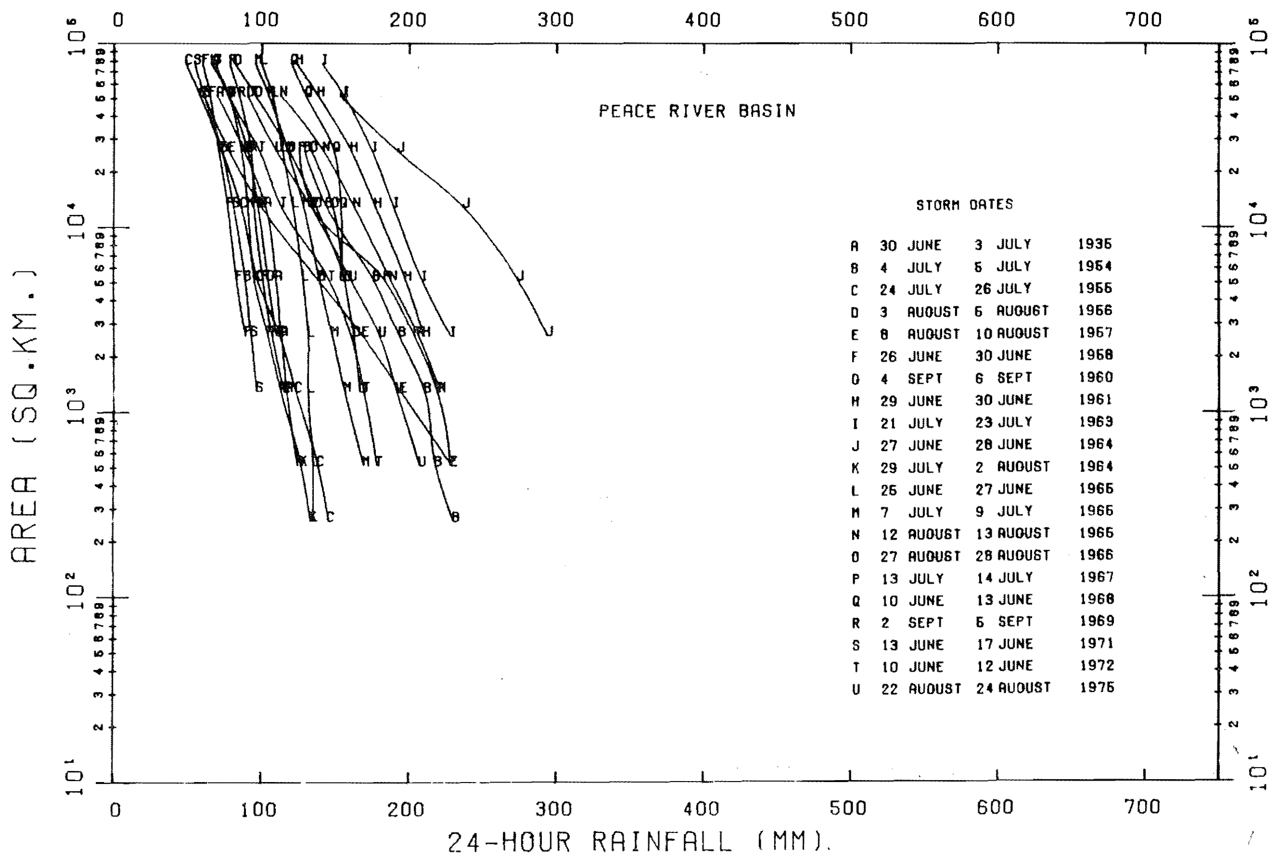

Figure 35 Depth-area curves of maximized 24-hour PMP for the Peace River basin.

about 300 mm of precipitation in an area of 2 600 km^2. The curves follow a similar pattern to those observed in the North Saskatchewan and Athabasca River basins. Figure 36 shows the enveloping DAD curves for the six durations. Like the figures of enveloping DAD curves for the other basins, a large increase in depth is observed between the 12- and 24-hour durations. Very little increase in the PMP is observed for durations 24-hour and longer.

3.5 MONTHLY VARIATION OF THE ESTIMATED PMP FOR ALBERTA RIVER BASINS

For each of the six basins and for each month from April to September, figures of enveloping DAD curves were produced and these are given in Appendix 8.3. In some basins (South Saskatchewan, Athabasca, and Peace), for certain months DAD was not available, hence, no enveloping curves are given. On each graph, six durations (6-, 12-, 24-, 48-, 72-, and 96-hour) denoted by letters from A to F were plotted. For durations 48 hours and longer, some curves coincide, hence, 4 or 5 curves appear in the figure.

A comparison of the enveloped DAD curves on a monthly basis showed very little difference in the estimates of the PMP in April for the four basins (South Saskatchewan, Bow, Red Deer, and North Saskatchewan). The estimates ranged from about 100 mm precipitation for the 6-hour to about 300 mm for the 96-hour duration (for a 260 km^2 area). No April or May estimates of the PMP were made for the Athabasca and Peace River basins. In May, for areas less than 10 000 km^2, a decrease is noted in the estimates compared to the April figures, with the Red Deer River basin having the smallest estimates. Overall, no great difference is observed in May between the four river basins mentioned above. In June, the South Saskatchewan River basin has the largest

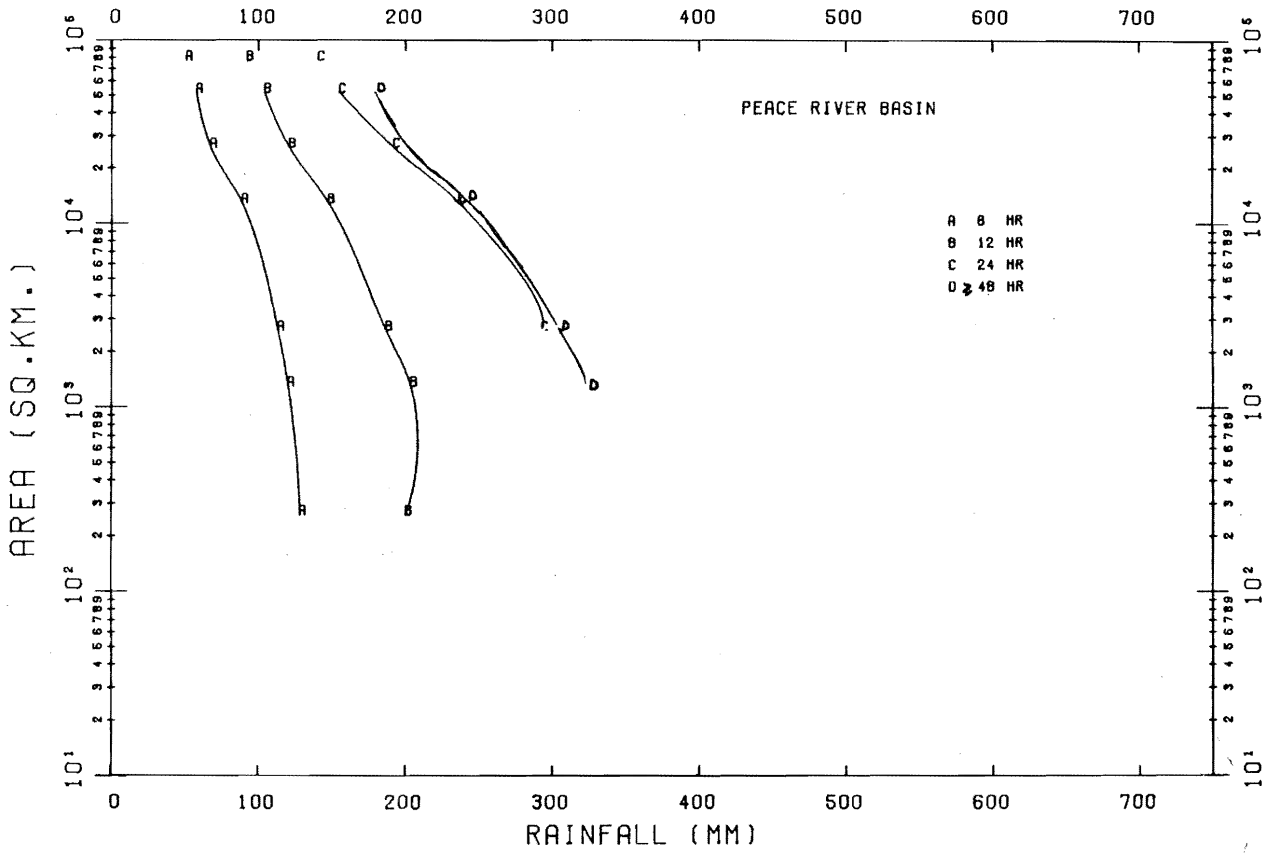

Figure 36 Enveloping DAD curves of PMP for the Peace River basin.

estimates of the PMP in the province (especially for areas less than 10 000 km^2), with an average depth of 380 mm for the 6-hour duration and the depth increases to a maximum value of 642 mm for the 96-hour duration. For this month, the Peace River basin ranks second to the South Saskatchewan River basin in the magnitude of the estimates, the other basins being lower in the PMP. The estimates for June are higher than those for April or May in these basins. In July the largest estimates are found in the basins located in central Alberta and a decrease is observed for basins to the south and to the north. Except for the central Alberta basins, the remaining estimates for the other basins are comparable with those obtained in May. In August the largest estimates of the PMP are found in central and northern Alberta with basins in the southern portion having relatively low values. A reverse trend is observed in September, where the largest estimates of the PMP are found in the southern basins of the province with a decrease in the magnitude toward the northern basins.

3.6 SPATIAL VARIATION OF THE ESTIMATED PMP FOR ALBERTA RIVER BASINS

The estimates of the PMP shown in Figures 25 to 36 and Figure 107 to 142 (Appendix 8.3) are the maximum values calculated for each river basin. Since many of the river basins cover large surface areas, the PMP also varies spatially in each basin. The extent of the spatial variation for the 24-hour and the 48-hour estimated PMP is shown in Figures 37 and 38 respectively.

The 24-hour estimated PMP (Figure 37) exhibits the largest decreases of the PMP in the South Saskatchewan River basin, where PMP values over 500 mm observed in the western portions of the river basin (in the Waterton Lakes Park area) decrease to about 100 mm (in the eastern portions of the river

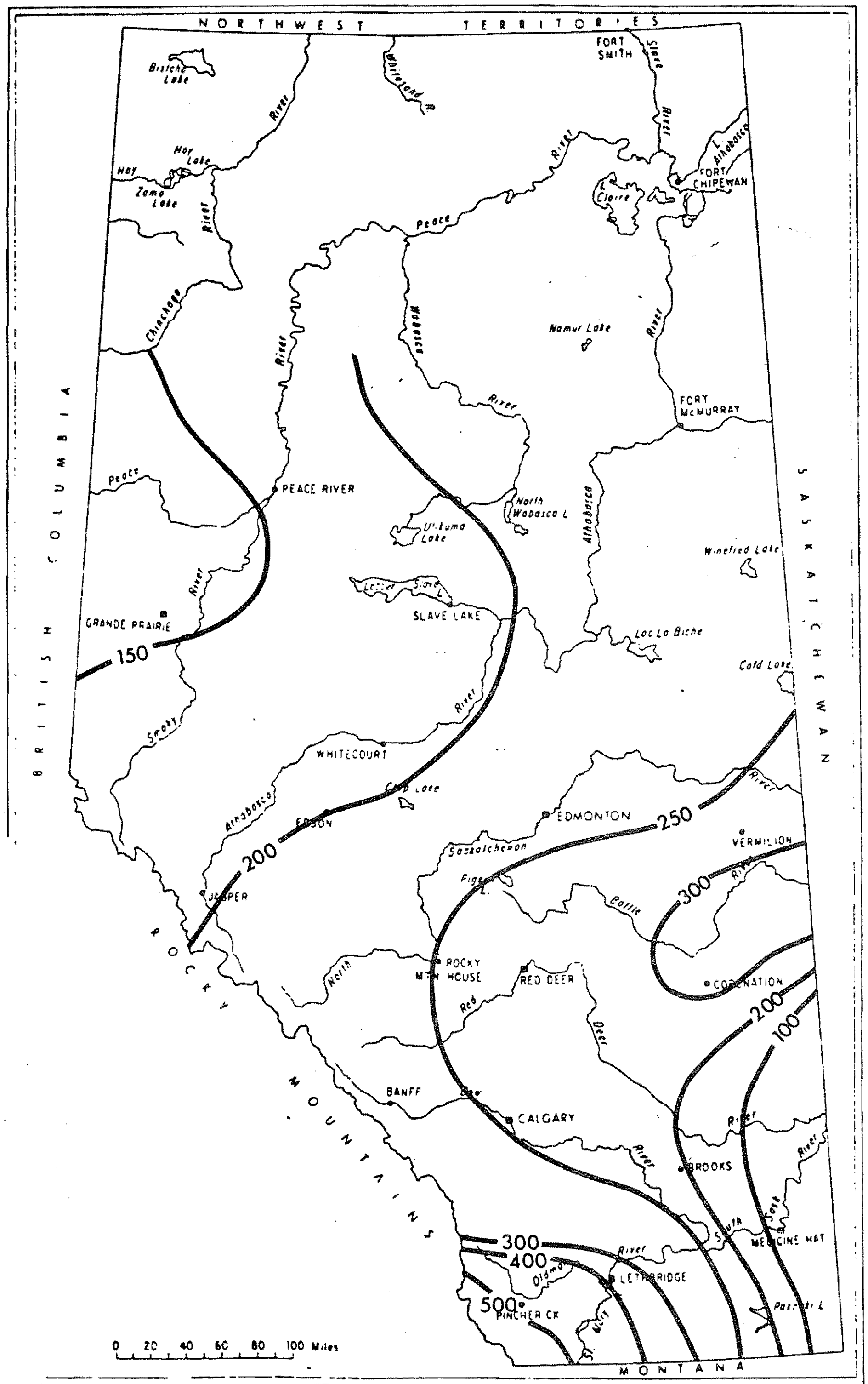

Figure 37 Spatial variation of the maximized 24-hour PMP.

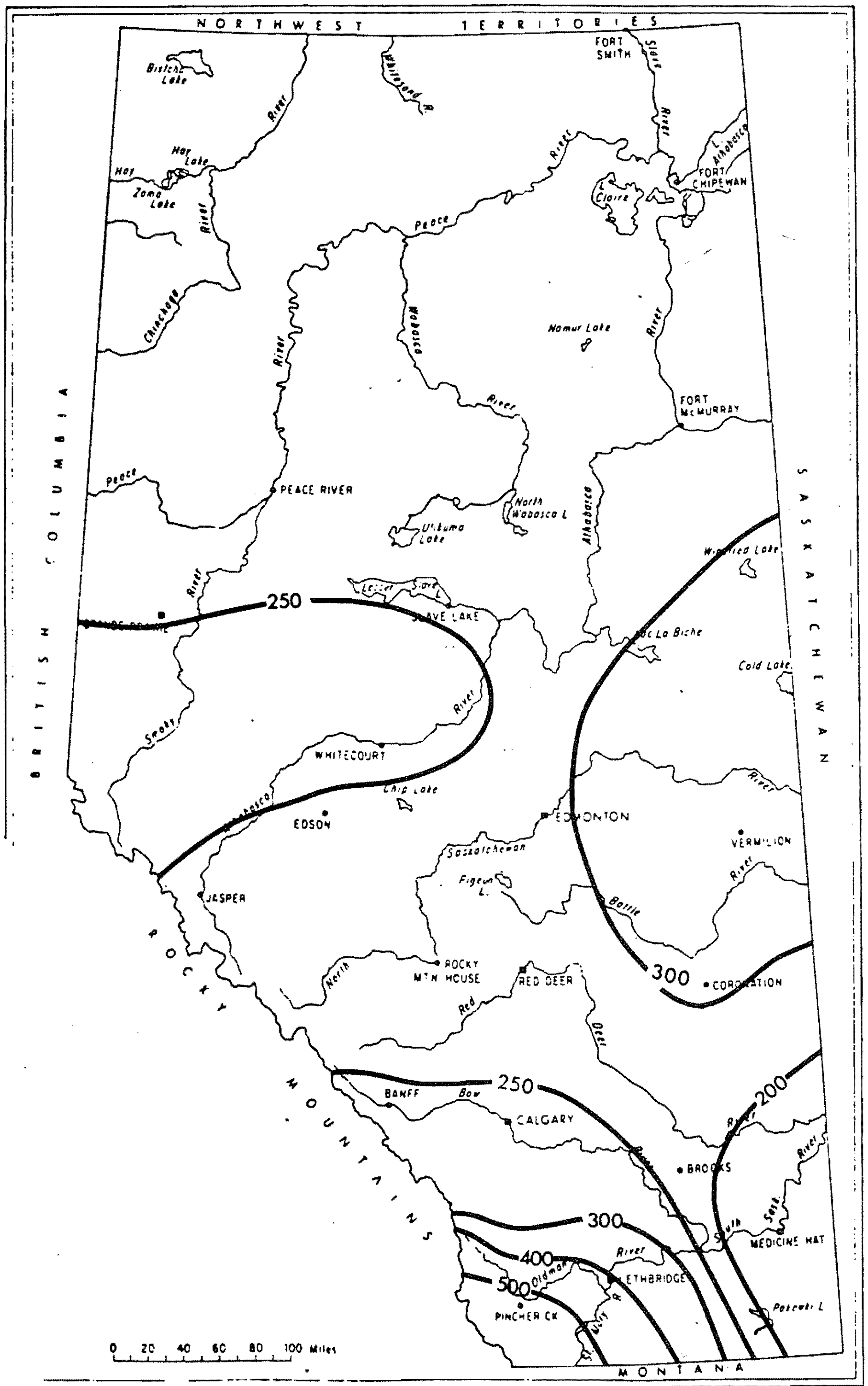

Figure 38 Spatial variation of the maximized 48-hour PMP.

basin-Pakowki Lake area). A west-east decrease in the PMP is also observed in the Red Deer River basin, where estimates of about 250 mm in the Rocky Mountain House area decrease to about 100 mm north of Brooks. The three basins north of Red Deer show very little west-east variations in the 24-hour maximized PMP.

The spatial variations of the 48-hour maximum PMP (Figure 38) also show large decreases in the PMP in the South Saskatchewan River basin. Spatially there is very little west-east variation (about 25%) in the Bow and Red Deer River basins, and about 35% in the North Saskatchewan, Athabasca and Peace River basins.

3.7 SUMMARY

Overall no consistent increasing or decreasing pattern was observed between April and September in the estimates of the PMP for the basins. The maximum estimates of the PMP seem to occur in June for the basins in the southern portion of the province, while in central and northern Alberta the maximum estimates were found to occur in July. The minimum estimates of the PMP were observed to occur in August for the Bow and South Saskatchewan, in May for the Red Deer and North Saskatchewan, and in September for the Athabasca and Peace River basins. For a 260 km^2 area, the largest estimates of the 6-hour PMP observed in the province were those in June in the South Saskatchewan River basin with a maximum depth of about 380 mm, while for a 96-hour PMP (again in June in the South Saskatchewan River basin) the maximum depth was 642 mm.

Large spatial variability from west to east (about 80%) in the 24-hour maximum estimated PMP is exhibited in the South Saskatchewan River basin. Similar variability is also noted in this basin for the 48-hour maximum estimated PMP. The river basins north of the South Saskatchewan River basin show some west-east variations in the maximum PMP, but this is small (up to 35% of the maximum value) compared to that observed in the South Saskatchewan River basin.

4. ESTIMATE OF PMP BY STATISTICAL METHOD

Statistical procedures for estimating PMP may be used wherever sufficient precipitation data are available, and are useful for making estimates, or where other meteorological data, such as dew point and wind records, are lacking. The procedure used in this report is that developed by Hershfield (1961, 1965), and even though it is not the only approach, it is one which has received the widest acceptance. Its convenience lies in that it requires considerably less time to apply than does the "physical" approach, with little understanding of meteorology. However, a major shortcoming is that it yields only point values of PMP and thus requires area-reduction curves for adjusting the point values to various sizes of area. The procedure was employed to all first-order stations within the six basins considered in this report, and the results are presented after a development of the technique.

4.1 STATISTICAL PROCEDURES

The procedure as developed and modified by Hershfield (1961, 1965) is based on the general frequency equation given by Chow (1951):

$$X_t = \overline{X}_n + K\,S_n \tag{4}$$

where X_t is the rainfall for return period t; $\overline{X}_n$ and S_n are respectively the mean and standard deviation of a series of n annual maxima; and K is a common statistical variable which varies both with the different frequency distributions fitting extreme-value hydrologic data and the return period of event n. Hershfield substituted X_m, the maximum observed rainfall for X_t, and K_m for K. K_m is then the number of standard deviations to be added to $\overline{X}_n$ to obtain X_m. Thus equation (4) becomes:

$$X_m = \overline{X}_n + K_m S_n \qquad (5)$$

To obtain a value for variable K_m, Hershfield first computed for each station the mean and standard deviation by the conventional procedures, however in the computations he omitted the maximum observed rainfall. Then he substituted these values for $\overline{X}_n$ and S_n in equation (5) as well as the maximum observed rainfall for X_m, to solve for K_m. This is equivalent to observing the maximum event after the values of the basic statistics have been established. From records of 24-hour rainfall for some 2 600 stations, Hershfield computed that the greatest value of K_m for all stations was 15. Using similar computations and employing storm transposition for all first-order Alberta stations, a maximum value of 9.6 (for K_m) for 24-hour rainfall was calculated. The distribution of the mean annual maximum rainfall for 24-hour rainfall for Alberta stations as a function of K_m is shown in Figure 39. The distributions for 48-, 72-, and 96-hour rainfalls are given in Appendix 8.4, with the maximum value of K_m of 11.3 for the 48-hour, and 12.3 for the 72-hour rainfalls. Before the PMP can be computed, a number of adjustments are required to the mean and standard deviation for maximum observed event and sample size.

4.1.1 Adjustment of $\overline{X}_n$ and S_n for Maximum Observed Event

Hershfield (1961) stated that extreme rainfall amounts of rare magnitude, (with return periods of 500 or more years) are found to have occurred at some time during a much shorter period of record (such as 30 years). Such rare events, or outliers, may

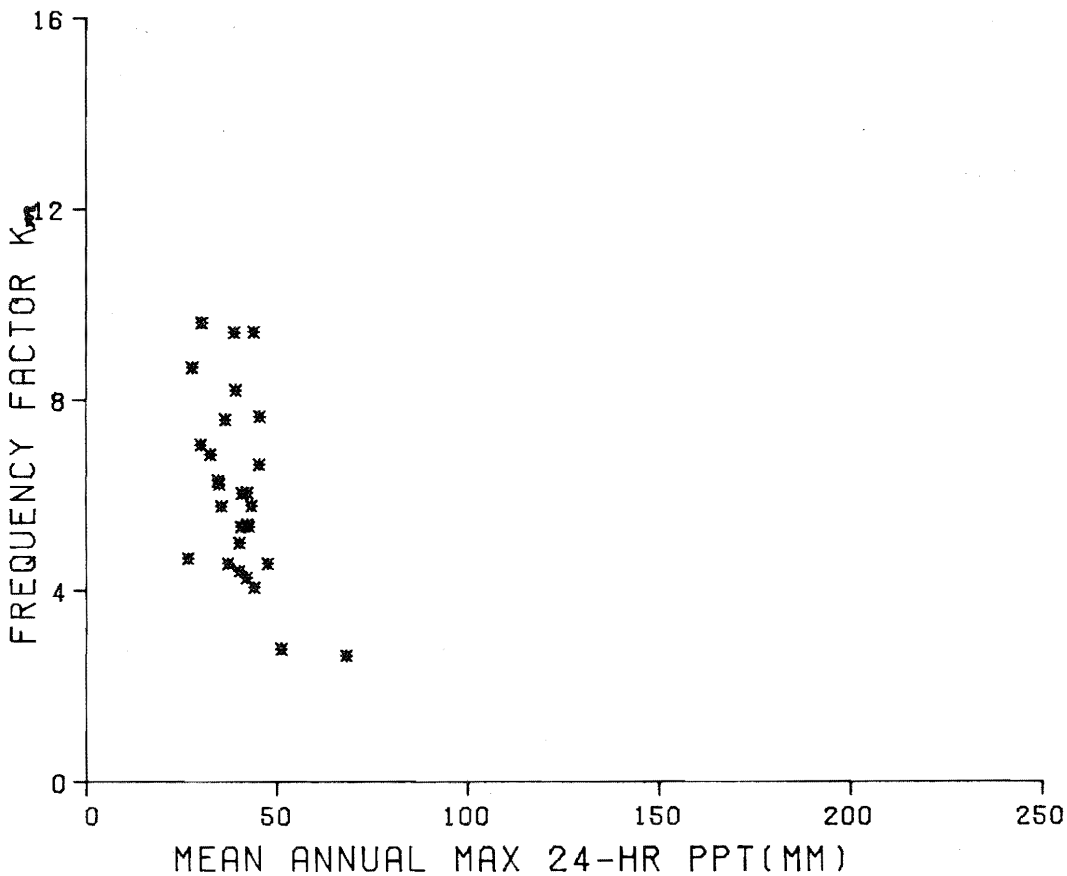

Figure 39 K_m as a function of mean of annual series for 24-hour rainfall for Alberta first-order weather stations.

have an appreciable effect on the mean ($\overline{X}_n$) and standard deviation (S_n) of the annual series. The magnitude of the effect is less for long records than for short, and it varies with the rarity of the event. This effect has been studied by Hershfield (1961) using hypothetical series of varying length, and the relationship of the maximum observed event on the mean is shown in Figure 40. Similarly, Figure 41 shows the relationship of maximum observed events on the standard deviation. In these figures, X_{n-m} and S_{n-m} refer respectively to the mean and standard deviation of the annual series computed after excluding the maximum item in the series. In both diagrams, the relationships consider only the effect of the maximum observed event, and no consideration was given to other anomalous-appearing observations.

4.1.2 Adjustment of $\overline{X}_n$ and S_n for Sample Size

The mean ($\overline{X}_n$) of the annual series may tend to increase with length of record, because the frequency distribution of rainfall extremes is skewed to the right so that there is a greater chance of getting a larger than a small extreme as length of record increases. Using data from 198 key weather stations, and adjusting for an outlier according to the relationship of Figure 39, Hershfield (1961) determined the average ratios of 50-year mean to 10-, 15-, 20-, and 30-year means, and the adjustment necessary for length of record is shown in Figure 42. In his computations, the statistics from the 50-year records were used as a standard to adjust those from shorter records. A comparison of a small number of available greater than 50-year means with the 50-year means showed only a negligible difference. Similarily, the adjustment necessary in the standard deviation for length of record was computed and the results shown on Figure 42. The effect of the record length is much more pronounced on the magnitude of the standard deviation than the mean. The

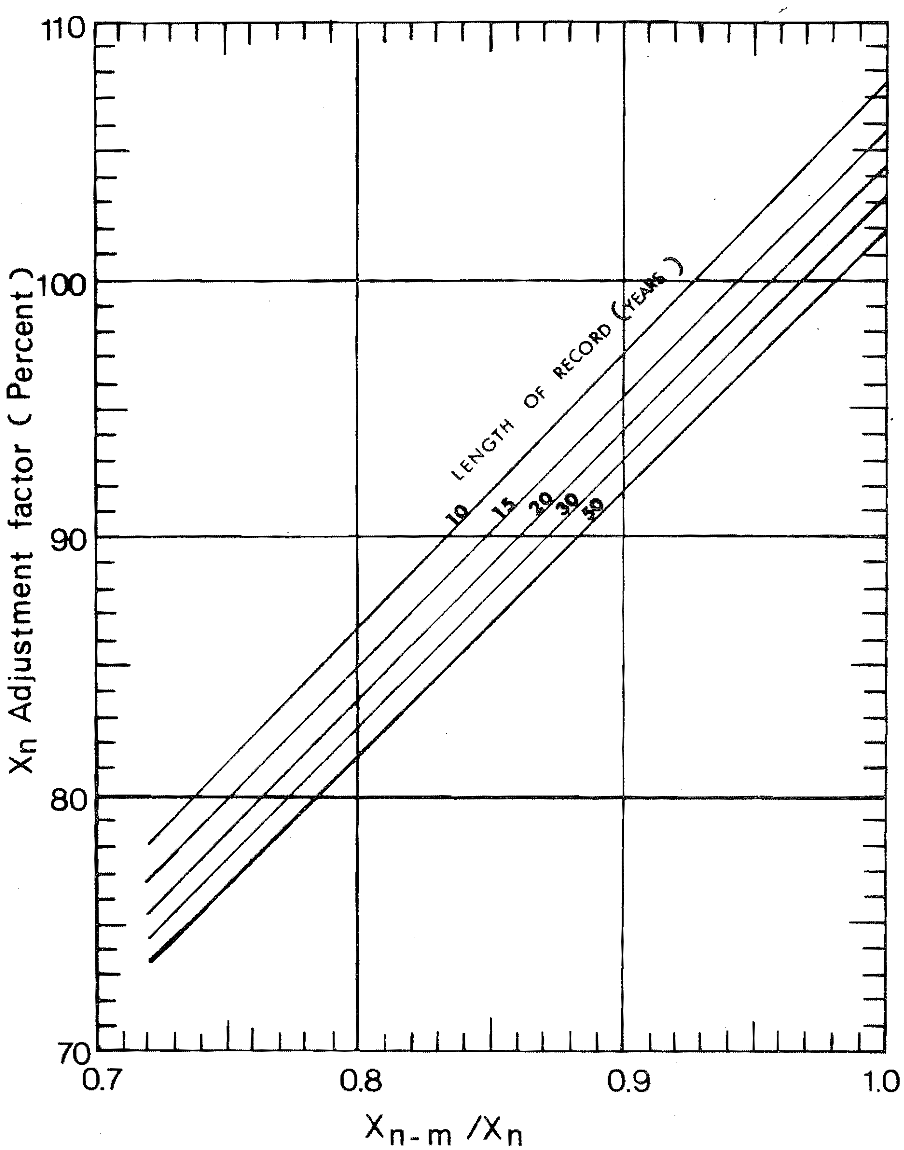

Figure 40 Adjustment of mean of annual series for maximum observed rainfall (Hershfield 1961).

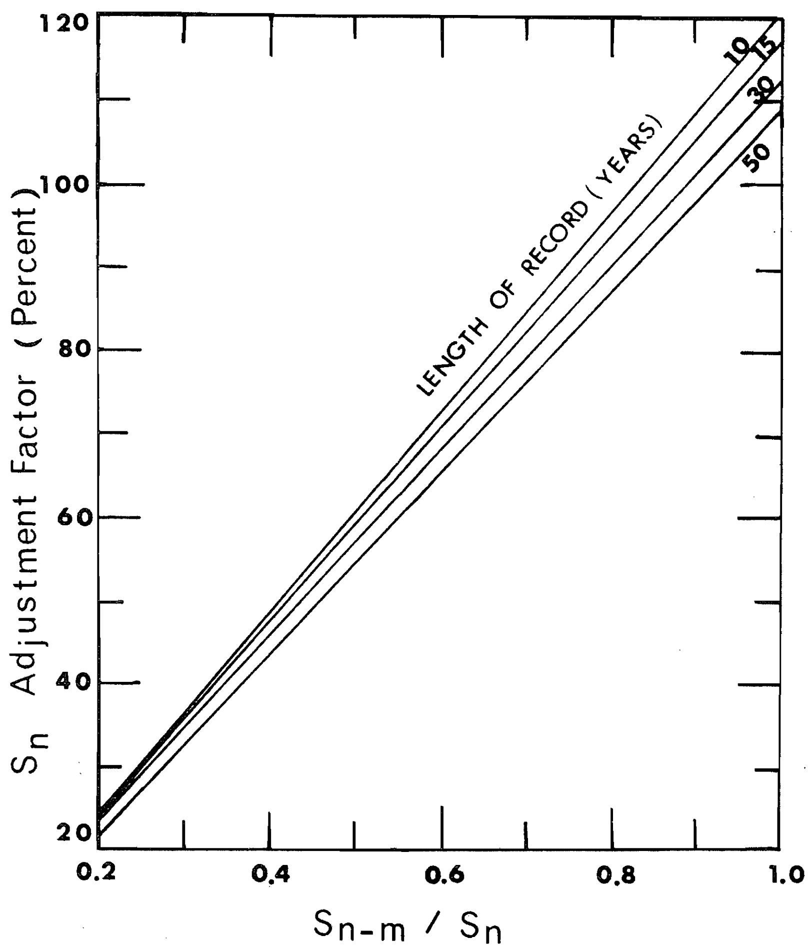

Figure 41 Adjustment of standard deviation of annual series for maximum observed rainfall (Hershfield 1961).

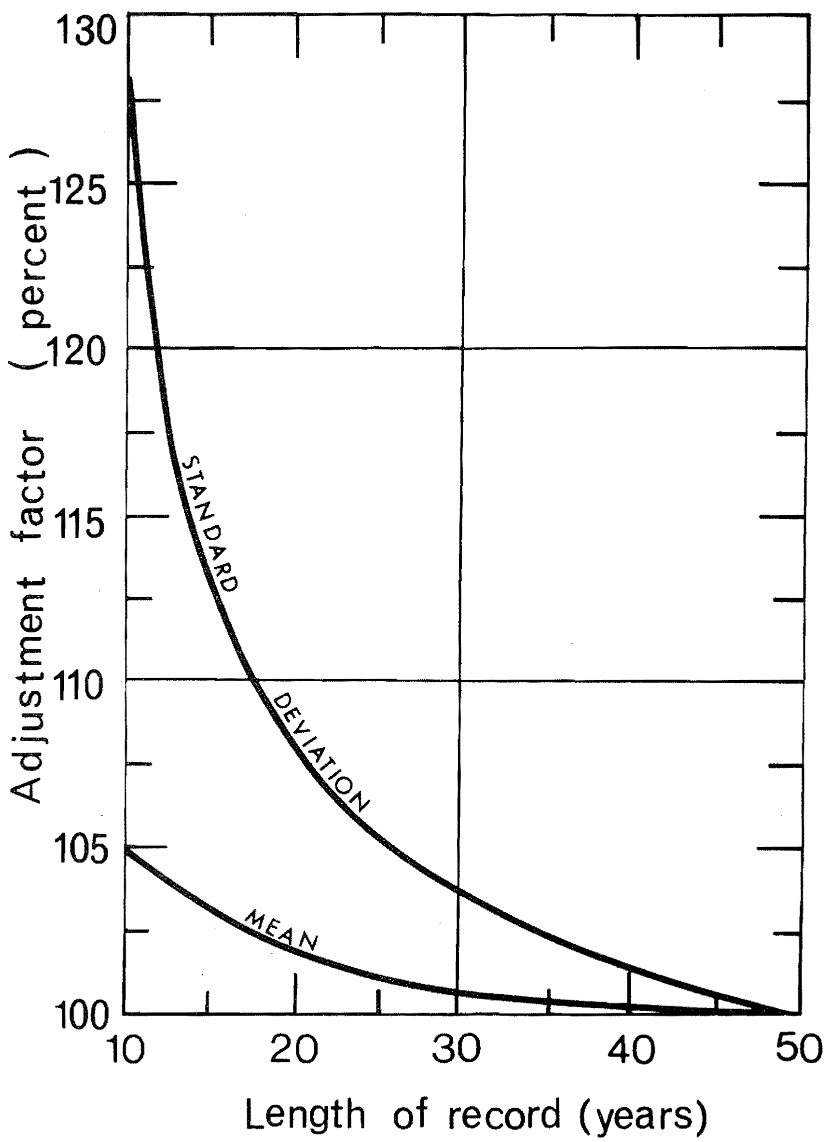

Figure 42 Adjustment of mean and standard deviation of annual series for length of record (Hershfield 1961).

few longer records than 50 years indicate adjustment only slightly different from that for the 50-year records.

4.1.3 Adjustment for Fixed Observational Time Intervals

Precipitation data usually are recorded on a fixed time interval; e.g., hourly, six-hourly, or daily. Such data rarely yield the true maximum rainfall amounts for the indicated durations. As an example, the annual maximum observational day amount is very likely to be appreciably less than the annual maximum 24-hour amount determined from intervals of 1440 consecutive minutes unrestricted by any particular observation time. Studies by Weiss (1964) indicate that multiplying the results of a frequency analysis of annual maximum rainfall amounts for a single fixed time interval of any duration from 1 to 24 hours by 1.13 will yield values closely approximating those to be obtained from an analysis based on true maxima. Hence, the PMP values yielded by the statistical procedure should be multiplied by 1.13 if data for single fixed time intervals are used in compiling the annual series. Figure 43 shows the lesser adjustments necessary when durations are determined from two or more fixed time intervals. As an example, maximum 24-hour amounts determined from 24 consecutive 1-hour rainfall increments require an adjustment by a factor of 1.01.

4.1.4 Area-Reduction Curves

As was mentioned previously (Section 4.0), a major shortcoming of the statistical procedure is that it yields only point values of PMP and thus requires area-reduction curves for adjusting the point values to various sizes of area. A number of variations of deptharea relationship (Court 1961) exist. The curves used in this study were those developed by McKay (1965)

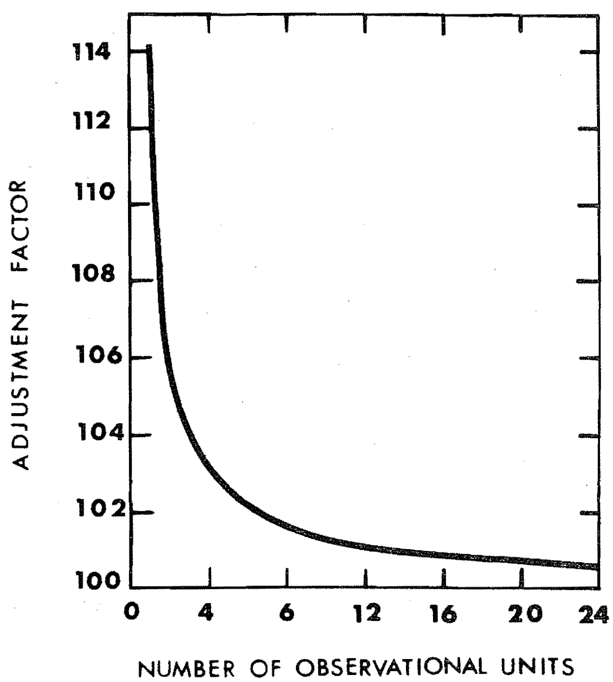

Figure 43 Average adjustment of fixed interval precipitation amounts for number of observational units within the interval (Weiss 1964).

for the prairie provinces and given in Figure 44. It shows curves relating point values to areas in excess of 100 000 km^2. For rainfall, point values are often assumed to be applicable to areas up to 25 km^2 without reduction.

4.2 ESTIMATE OF PMP FOR ALBERTA BASINS

For each year of record, maximum 24-hour rainfall was calculated for a total of 27 first-order weather stations in Alberta. Using this data, statistical estimates were computed using the procedure developed by Hershfield (1965) and described above. The maximum value of K_m was computed for 24-hour extreme rainfalls to be 9.6. This is much lower than the value of 15 given by Hershfield for rainstorms from all over the world. A number of authors (Bruce and Sporns 1963; Bruce et al. 1965) have used K_m equal to 15 in their statistical estimation of the PMP for their studies of selective Canadian basins, and they obtained good agreement between the estimated results and the results obtained using the physical approach. The value of K_m equal to 15 is, of course, an upper limit, and is slightly higher than the 9.6 (for 24-hour rainfall) calculated in this study. In the computation of the statistical estimate of the PMP, the 24-hour extreme rainfalls for the individual stations were adjusted for maximum depth in the storm.

The data from the 27 weather stations were grouped according to the six river basins outlined in Figure 24. The results of the 24-hour rainfall for each basin are used as examples in the main part of the report, other durations (i.e., 48-, 72-, and 96-hour) are found in Appendix 8.4.

In the South Saskatchewan River basin, precipitation extremes from five stations were maximized and the 24-hour enveloping-depth-area curves of the estimated PMP are shown in Figure 45.

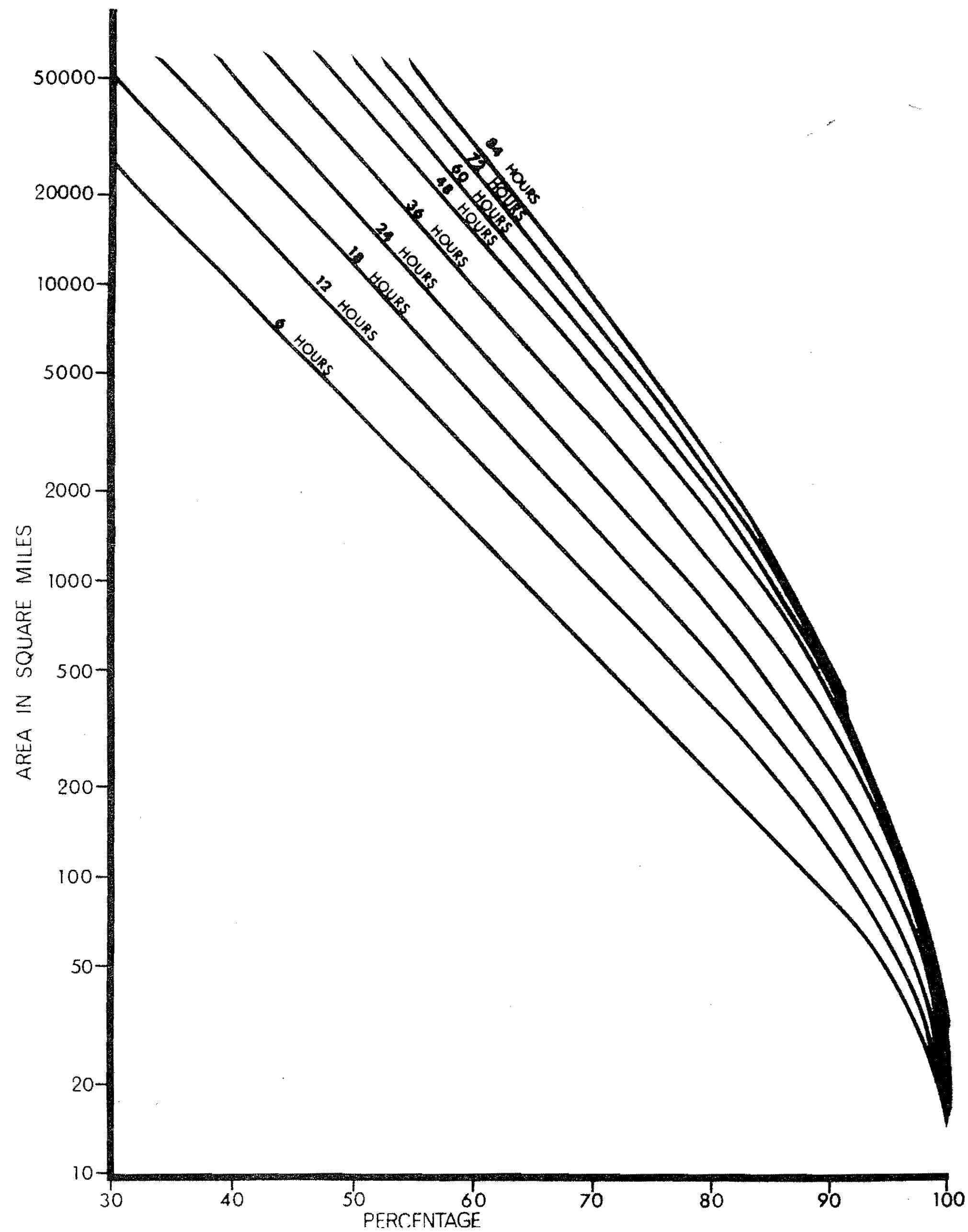

Figure 44 Depth-area, or area-reduction curves (McKay 1965).

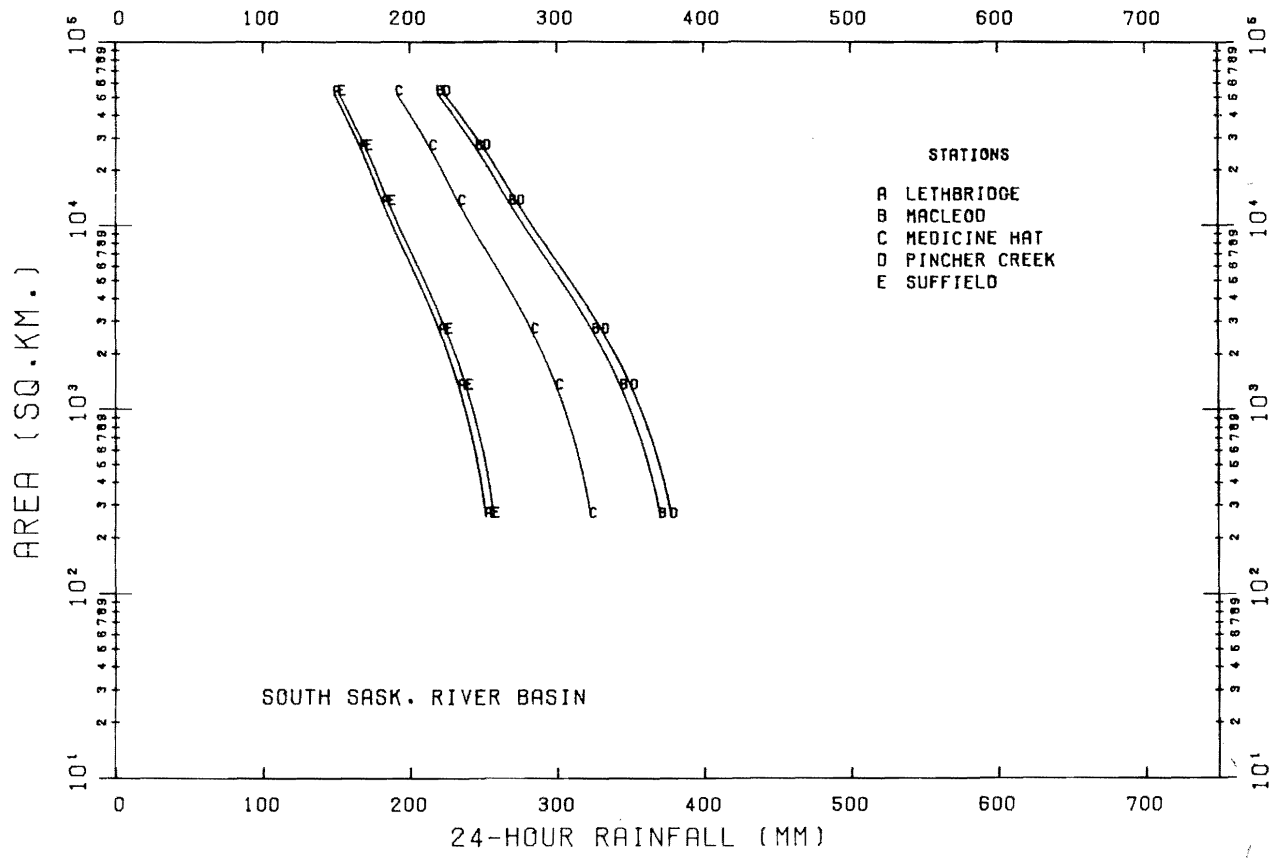

Figure 45 24-hour enveloping depth-area curves of statistically estimated PMP for the South Saskatchewan River basin.

The largest values of the PMP of the five stations were calculated for Pincher Creek; however, these estimates are much lower (for areas less than 5 000 km^2) and much higher (for areas greater than 5 000 km^2) than the estimates obtained by the physical approach (Figure 25) for the South Saskatchewan River basin. The differences in the estimates are due to the severe storm of 7 to 8 June 1964. This storm had its heaviest reported depths in the Waterton Lakes Park area, even though Pincher Creek is relatively near to Waterton Lakes Park, very little precipitation was received at this station. Hence the severity of this storm would have very little effect on the estimated PMP using the statistical approach. If the storm of 7 to 8 June 1964 is not included in the physical analysis, the estimates of the PMP using the statistical approach are comparable to the results obtained by the physical procedure.

In the Bow River basin three stations were used in obtaining the statistical estimates of the PMP, with Calgary showing the greatest PMP estimates (Figure 46). The estimates are about 75 mm higher than those obtained by the physical approach (for areas of about 250 km^2 to 10 000 km^2). Similarly the statistical estimates for Brooks are higher in value than those by the physical approach. Banff, on the other hand, is about 50 mm lower for 250 km^2 area and about 25 mm lower for 10 000 km^2 area, showing the spatial variability noted in Section 3.

Similarly, the 24-hour statistical estimates for the Red Deer (Figure 47), North Saskatchewan (Figure 48), and Athabasca (Figure 49) River basins show higher estimates than those obtained by the physical approach. Estimates for the Peace River basin (Figure 50) on the other hand are lower by the statistical than was obtained from the meteorological approach. The statistical estimates are higher by an average rainfall of about 50 mm for

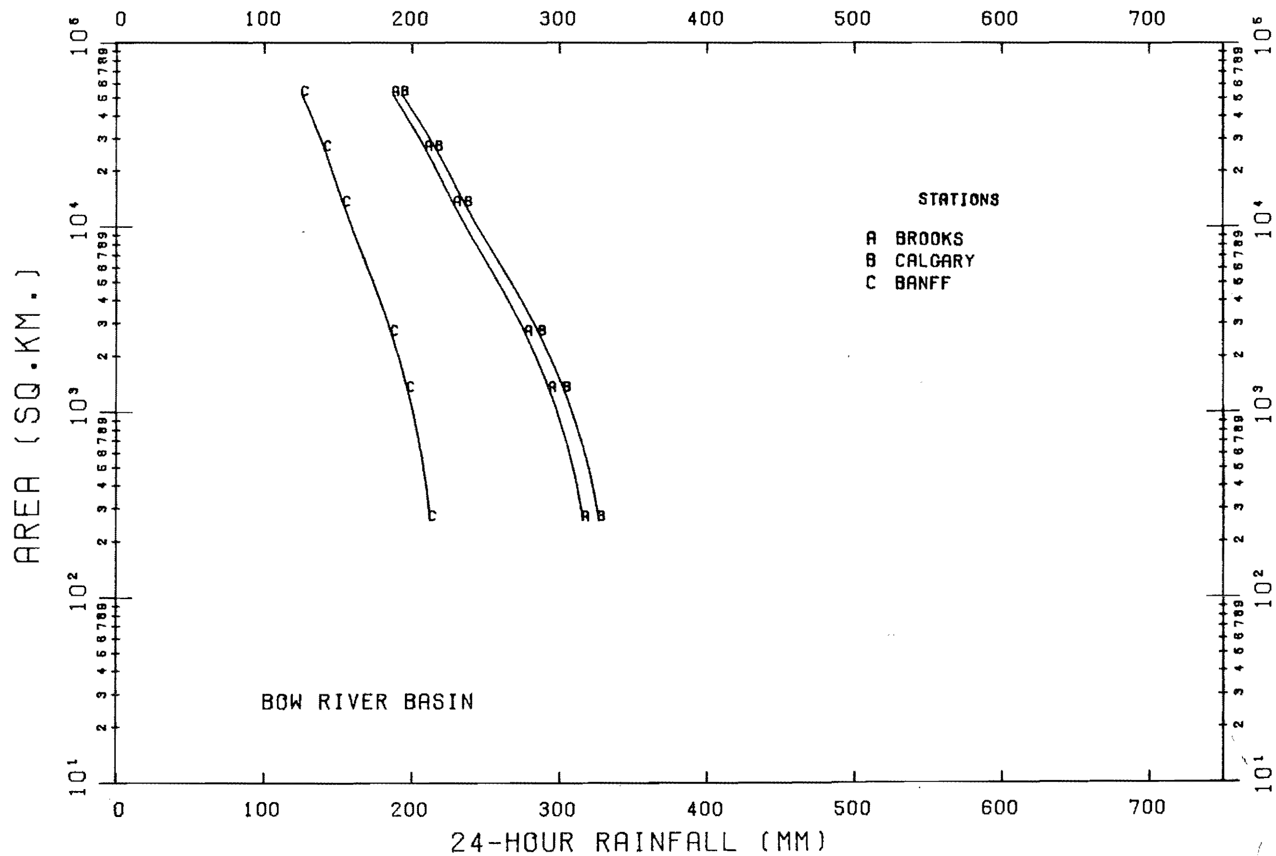

Figure 46 24-hour enveloping depth-area curves of statistically estimated PMP for the Bow River basin.

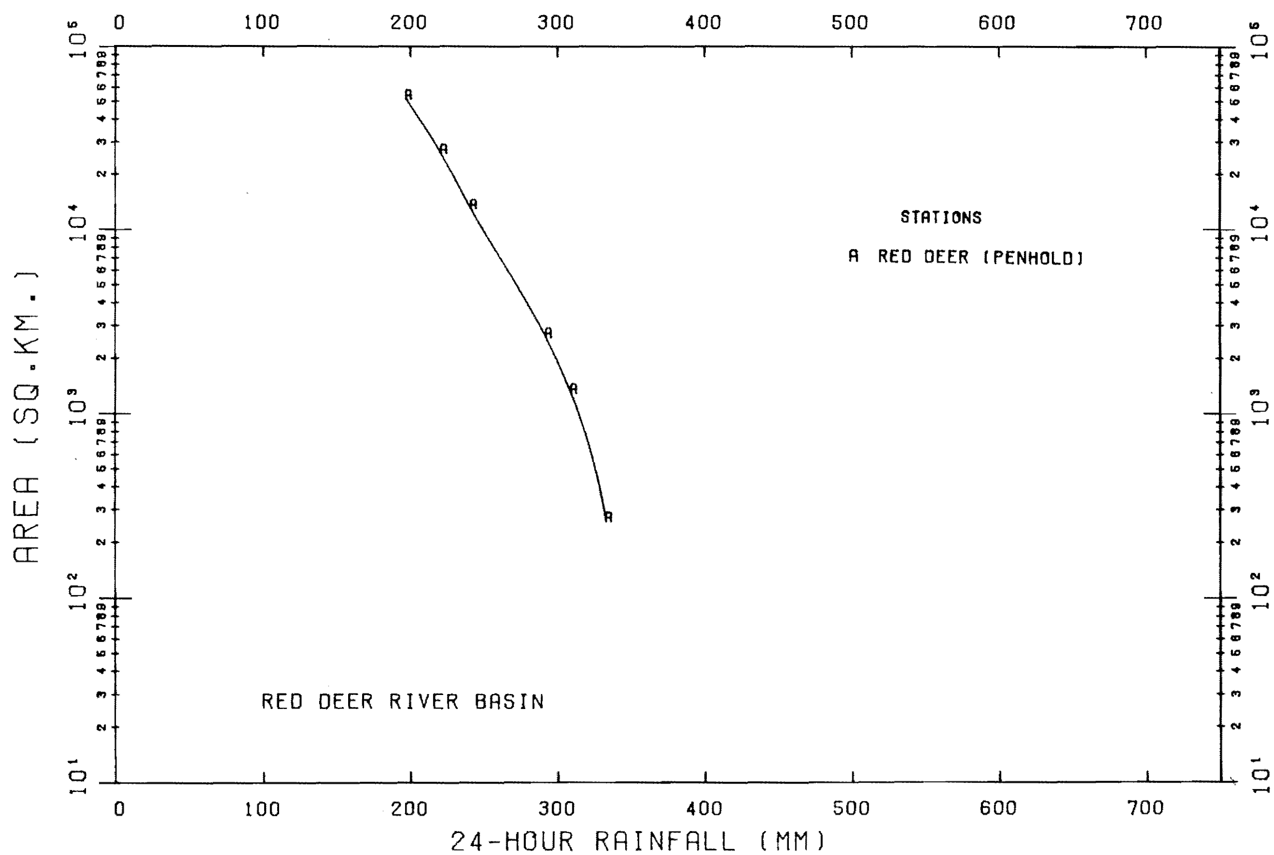

Figure 47 24-hour enveloping depth-area curves of statistically estimated PMP for the Red Deer River basin.

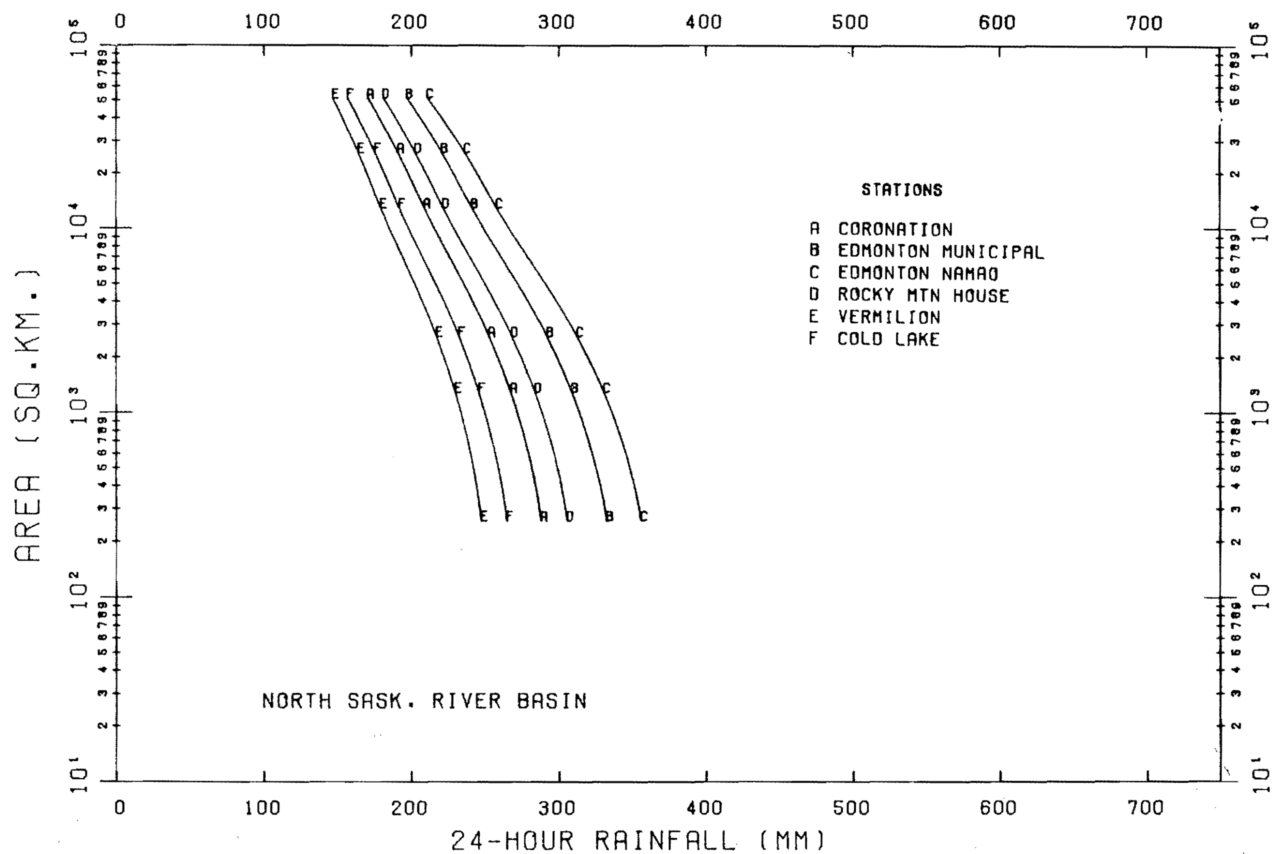

Figure 48 24-hour enveloping depth-area curves of statistically estimated PMP for the North Saskatchewan River basin.

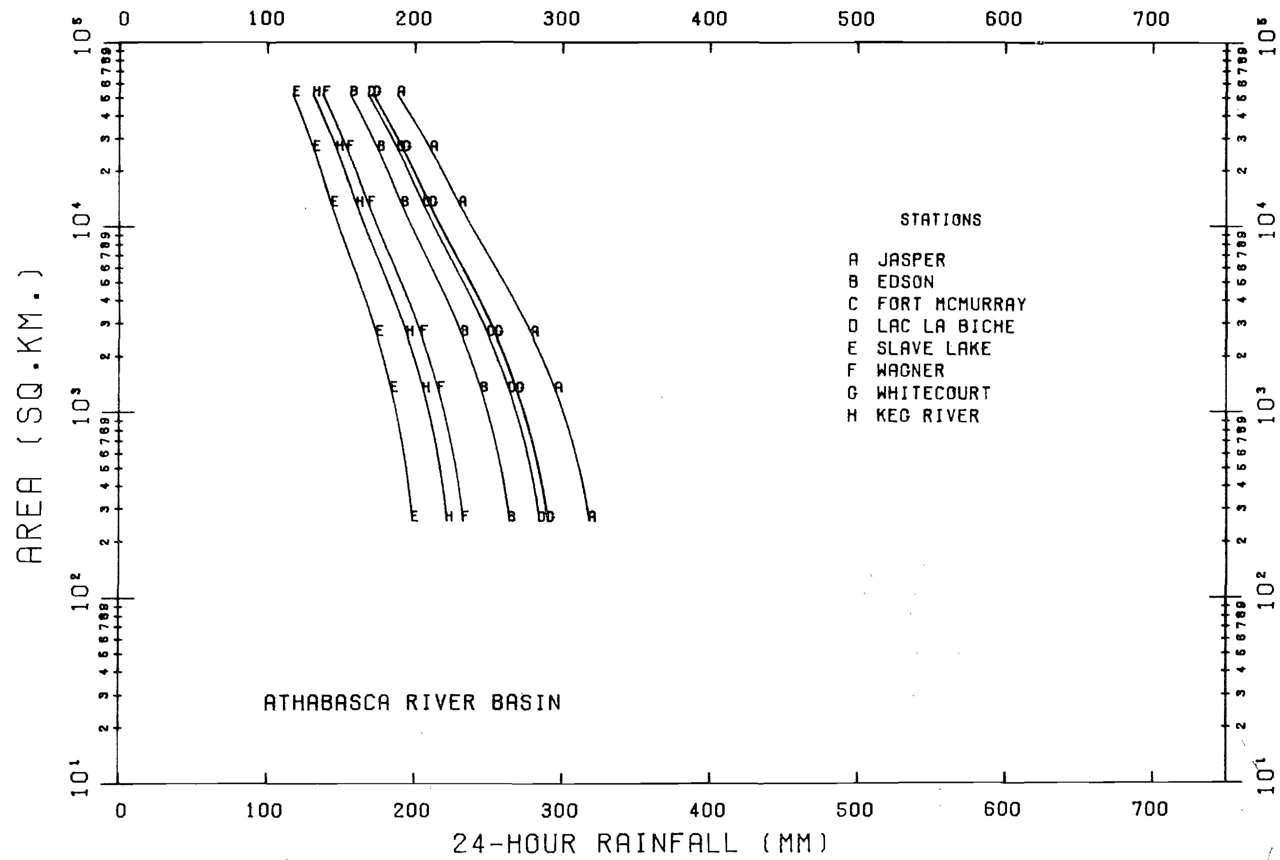

Figure 49 24-hour enveloping depth-area curves of statistically estimated PMP for the Athabasca River basin.

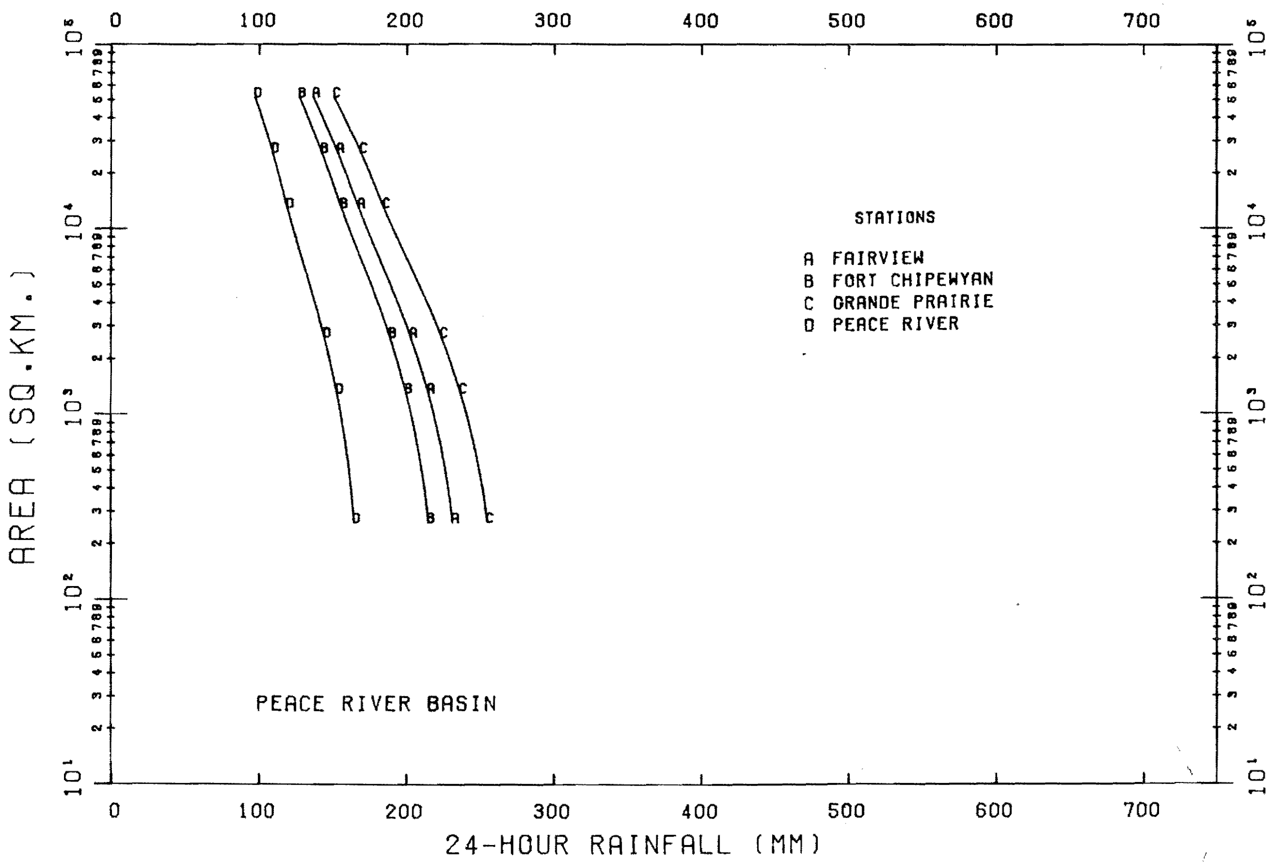

Figure 50 24-hour enveloping depth-area curves of statistically estimated PMP for the Peace River basin.

areas of about 250 km^2. By comparing the 48-, 72- and 96-hour (Appendix 8.4, Figures 177 to 194) statistical estimates of the PMP with those computed by the physical approach (Figures 90 to 100), the same conclusion can be reached, that is, that the statistical estimates of the PMP are higher in most cases than those obtained by the physical approach, and the differences are about 50 mm (for areas of about 250 km^2).

4.3 SUMMARY

The statistical method as developed by Hershfield, even though it is a convenient approach for estimating PMP, produced results which were higher than those calculated by the physical approach. The major shortcoming in this approach is that the maximum rainfall for the station is not necessarily the maximum depth of the storm. For the 27 first-order stations examined (for the six river basins), the maximum K_m that was calculated was 9.6 (as compared to a world value of 15 obtained by Hershfield). The statistical estimates were about 50 mm higher (for areas of about 250 km^2) in the six river basins. The largest estimates were obtained for the South Saskatchewan River basin, as were also obtained by the physical approach. The statistical estimates of the PMP exhibit spatial variability between stations as was also observed in the results from the meteorological approach.

5. SNOWMELT

5.1 INTRODUCTION

Extreme floods in Alberta result from major rainstorms, rapid snowmelt of significant duration, or a combination of these two factors. It is this latter aspect, namely the occurrence of a major rainstorm in combination with rapid snowmelt, that is examined in this section. Although such a combination is rare in Alberta, an occurrence of this nature could produce extreme severe flooding. A documented example of such an occurrence is the 7 to 8 June 1964 rainstorm (Warner 1973) which occurred in the headwaters of many streams in southwestern Alberta. The St. Mary Snow Survey (Warner 1973) recorded a very ripe snow on 29 April 1964 at Mount Allen, with the mean snow depth equal to 110.6 inches (281 cm) and the water equivalent to 50.8 inches (129 cm). In Alberta, along the continental divide, the occurrence of a rain-on-snow event is highly favourable since snow has been observed as late as the first week of June in this area. Although there exists a high potential for a rain-on-snow event, the occurrence of such an event which would produce severe flooding is rare (1:100 year event), since other hydrological and meteorological conditions must occur simultaneously.

In this section, figures of the occurrence of the snowpack and the maximum snow depth are given for basins in Alberta. This gives the maximum snow depth available for a rain-on-snow event and helps in establishing a factor needed in the "generalized snowmelt equations". The effects of snowmelt on flooding is an extensive topic requiring use of the generalized snowmelt equations, and is beyond the scope of this report. However, to obtain an insight to the extent of this topic, a review of the indexes needed in the snowmelt equations are examined for the rain-on-snow event.

5.2 PROBABLE MAXIMUM SNOWPACK

The critical snowmelt floods are the result of rapid snowmelt of significant duration or the combination of a major rainstorm with rapid snowmelt (a rain-on-snow event). It is believed by investigators (McKay 1965) that these probably occur when the spring thaw was much delayed, and following a season of major snow accumulation. It was, therefore, desirable to estimate the latest possible time a snowpack was observed on the surface. It was also desirable to obtain the winter maximum snowfall, and the maximum depth of the snowpack at various times through the rainstorm period.

In Alberta, climatological records, collected by AES, are the only readily available source of data from which an estimate on the snowpack can be made. The few snow survey records are of insufficient time period for estimation. In the past century, few observers reported the actual depth of snow cover, with most records expressed in the form of remarks on whether the sleighing was good, fair, or poor. In 1902, an attempt was made to publish snow depth for the last day of each month for certain stations. There are many omissions in these observations, and only a limited number of stations give a nearly continuous record. It was not until the beginning of 1933 that the observing program at first-order stations was expanded to include the depth of the snow on the ground each Monday morning as well as on the last day of the month. No further changes in the observing program occurred until 1 January 1941 when the Meteorological Service of Canada (now AES) began to use a new synoptic code adopted for the worldwide exchange of weather information. In the code, provision was made for reporting the daily depth of snow on the ground. These observations made it possible to determine for the first time the number of days each year on which the ground at a particular station was covered by snow. These measurements of the depth of the snow on the ground at the first-order observing stations were made according to the following instructions (Potter 1965a):

> "The total depth of snow on the ground shall be recorded in whole inches by making a series of measurements and taking the average. The area for taking the measurement shall be chosen with a view to avoiding drifts. Care should be taken to insure that the total depth is measured, including the depth of any layers of ice which are present."

Since many of the first-order observing stations are located at airports, the measurements are mainly representative of exposed sites, and not of sheltered or forest locations.

In southern Alberta east of the foothills, the occurrence of the first snow cover is usually in late September, however the date varies considerably from year to year. Snow cover in this region and in the foothill country near Calgary does not normally persist throughout the winter. It may melt at any time under chinook conditions. The variability in the date of the first snow cover in the Peace River country is somewhat similar to that in the foothills where the snow cover has formed in the middle of August on some occasions, or has been delayed until late November, with the most likely date of occurrence near the middle of October.

In southern Alberta, the snow cover may disappear completely at any time during the winter. In this region, and throughout most of the remaining agricultural areas of the province, the snow cover is not likely to persist beyond the first week of April, thus minimizing the probability of the occurrence of a rain-on-snow event. Late snowfalls in some years have given temporary snow cover during the second and third weeks of May over most of the prairies, and as late as early June in the foothills (Figure 51). In the Peace River country, the snow

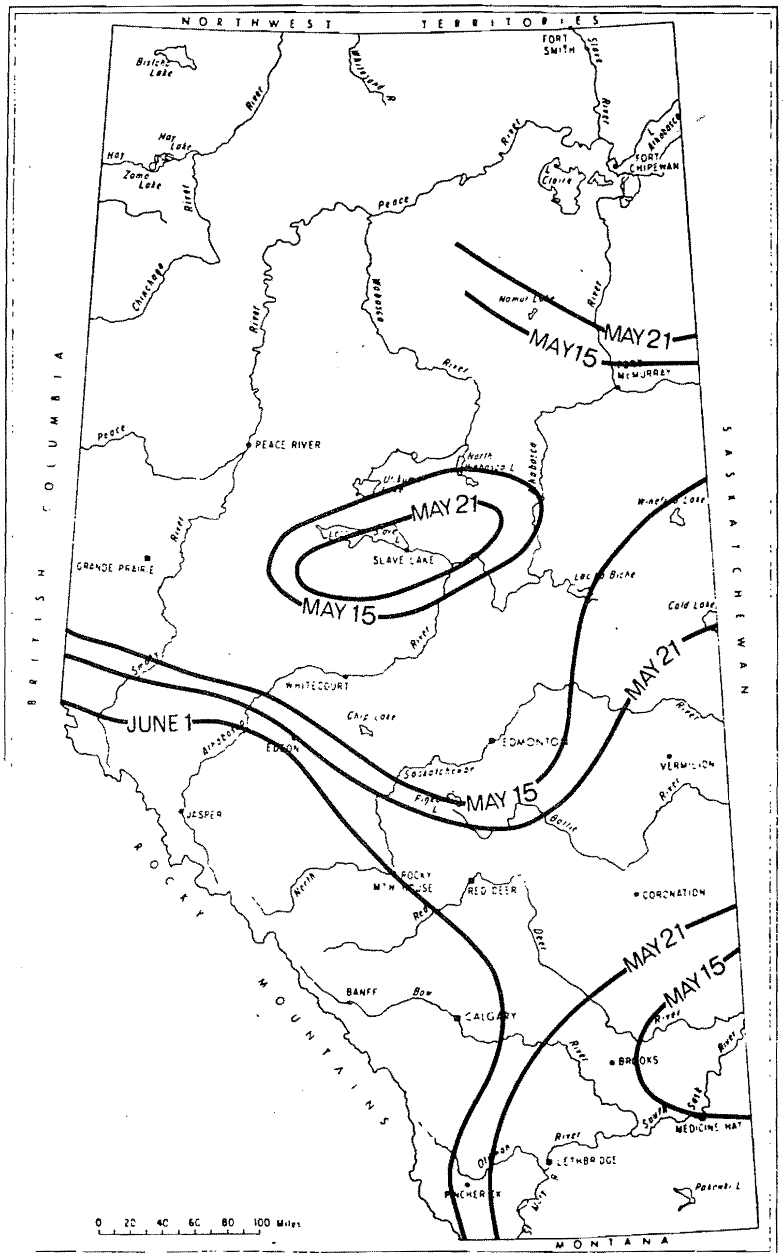

Figure 51 Date of last snow cover of 1 inch (25 mm) or more for Alberta.

cover usually melts by the middle of April, with the date of the last snow cover quite variable, from early in April to as late as the first week in May.

The greatest amount of snow cover (in inches) on 31 March is shown in Figure 52, while that for 30 April in Figure 53. Figure 52 shows that the greatest depths are usually observed in the foothills (around Banff) and in northern Alberta (north of Edmonton). A month later on 30 April much of the snow cover has melted with maximum values observed around the Banff-Rocky Mountain House area. Snowdepth information alone, does not provide a good measure of the water equivalent of the snowpack, because of the variability of snow density. Estimates of an average density for snowpacks have been made by various authors (McKay 1965, 1968; Church 1941; U.S. Corps of Engineers 1956) from relationships between density and time, vegetative cover, wind, and temperature. These are very approximate, and must be used with caution since slight errors in an assumed density may result in significant errors in the estimated water equivalent.

The snow cover is formed by crystals of varied shape and density. As snow ages, it is subjected to climatic conditions which alter its form and density. The cover may be quite heterogeneous, containing ice planes and snow layers of varied density.

Results of average densities obtained during snow survey[1] were found to be similar for a given location and time from one winter to the next. This is particularly true during the melt-period in spring. Well-drained, ripe snow tends to have a density of about 0.35. The density of a pack was observed by Church (1941) to rise as high as 0.49 when runoff began, and then dropped to 0.37 with drainage. The U.S. Corps of Engineers (1956) found that, with a freeze-thaw cycle in the spring,

[1] The density measured during snow surveys is a vertically averaged value, which integrates the effects of seasonal heat exchanges, wind and percolation of melt water.

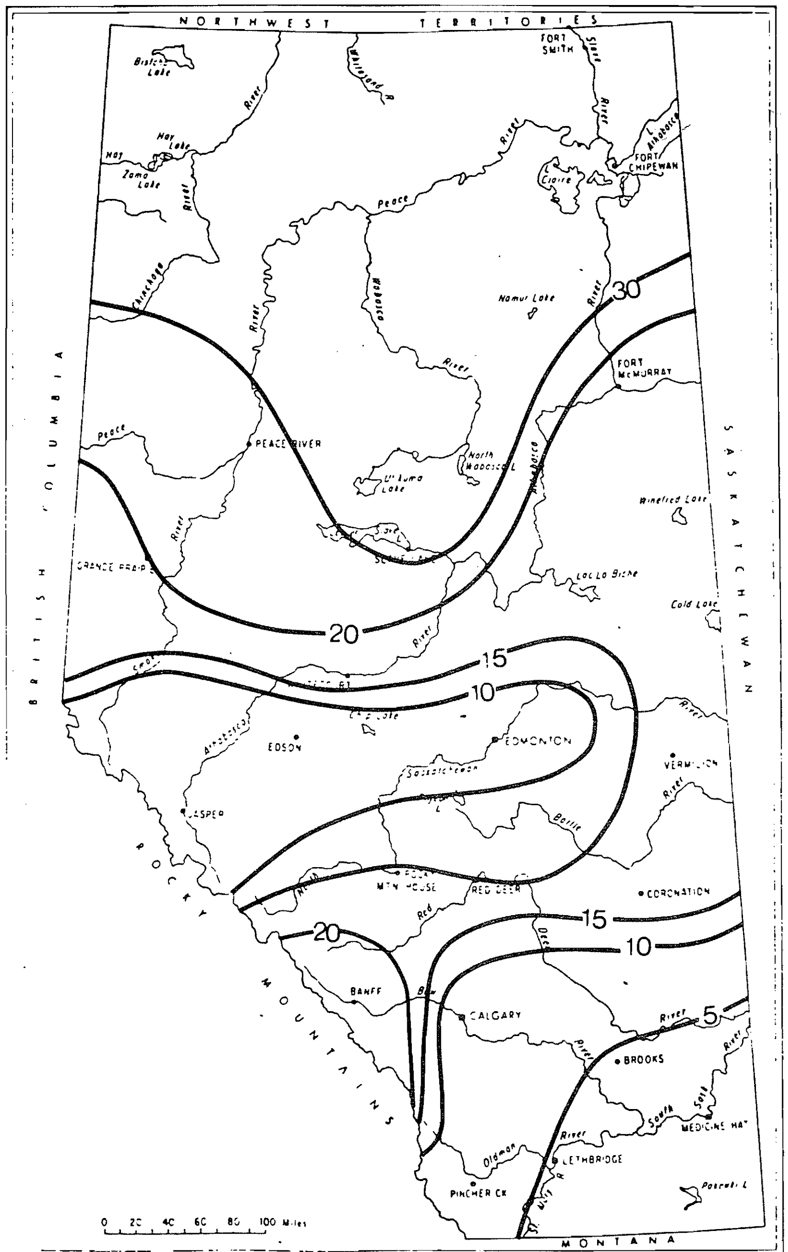

Figure 52 Greatest depth of snow cover (in inches) observed on 31 March.

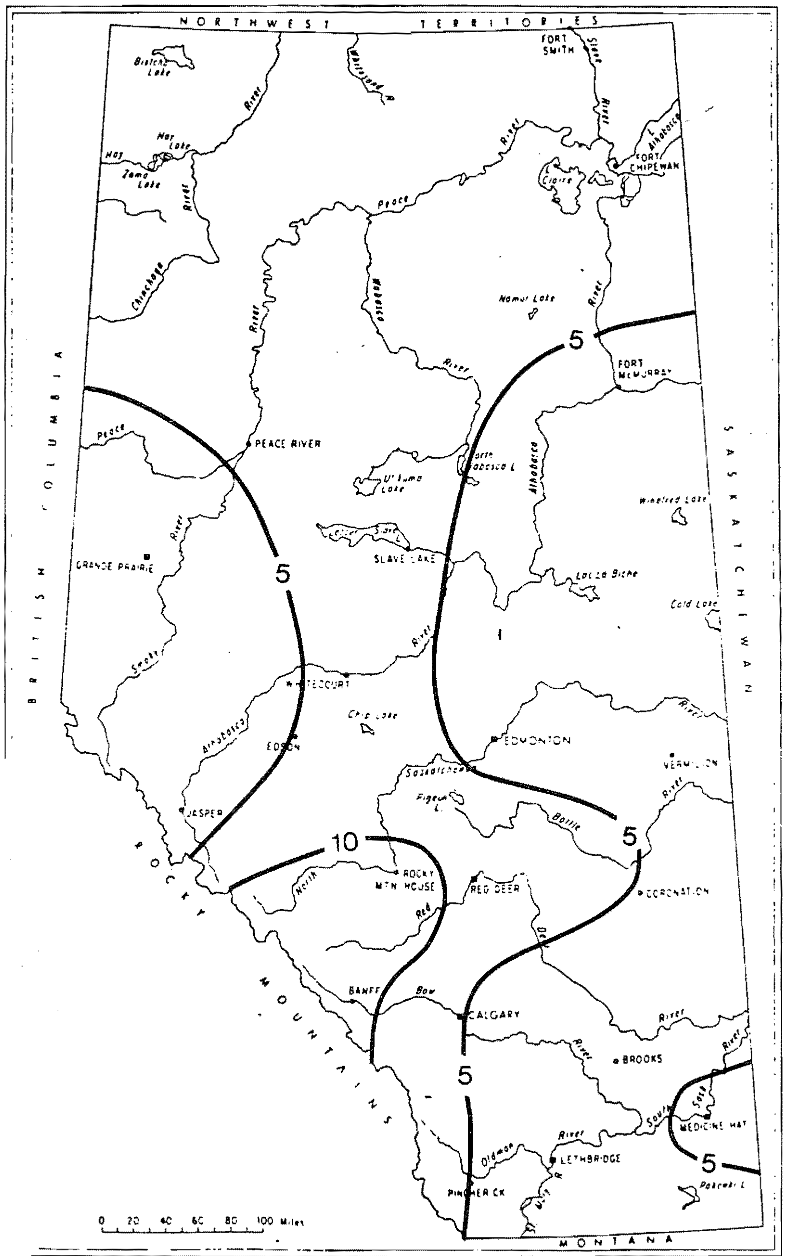

Figure 53 Greatest depth of snow cover (in inches) observed on 30 April.

shallow packs become alternately drained and primed with liquid water, and the density varied from about 0.40 to 0.48. McKay (1968) examined average densities of snow covers in the prairie provinces, and observed appreciable differences in the densities in the alpine zone of the Rockies compared to those in Saskatchewan. The seasonal variation in the average snow density for diverse locations in the prairie provinces is shown in Figure 54. The author also examined density variations within homogeneous zones for 1956 data, and the results from 23 stations in eastern Saskatchewan are shown in Figure 55 (no results for Alberta were presented). Variations as large as two standard deviations from the mean were observed, with values as high as 0.40 noted at some locations. The results presented in Figure 54 show that the maximum average snow density for the eastern Rockies is about 0.27. This result seems low compared to results from outside of Alberta and hence further investigations are needed to define this quantity spatially for Alberta. The potential rate of melt increases as spring advances. Most serious floods occur, therefore, when the snowmelt is delayed as late as possible, and when the pack is heavy. Snowmelt rates are determined by an energy balance which varies seasonally and with vegetative cover. The equations developed at Central Sierra Snow Laboratory (CSSL), Soda Springs, California to calculate the snowmelt rates are examined next.

5.3 SNOWMELT RATE EQUATIONS

Snowmelt is the overall result of many different processes of heat transfer. The rigorous determination of snowmelt amounts is quite complex and beyond the scope of this report. The general equation for total basin melt during rain as developed by the U.S. Corps of Engineers has five components:

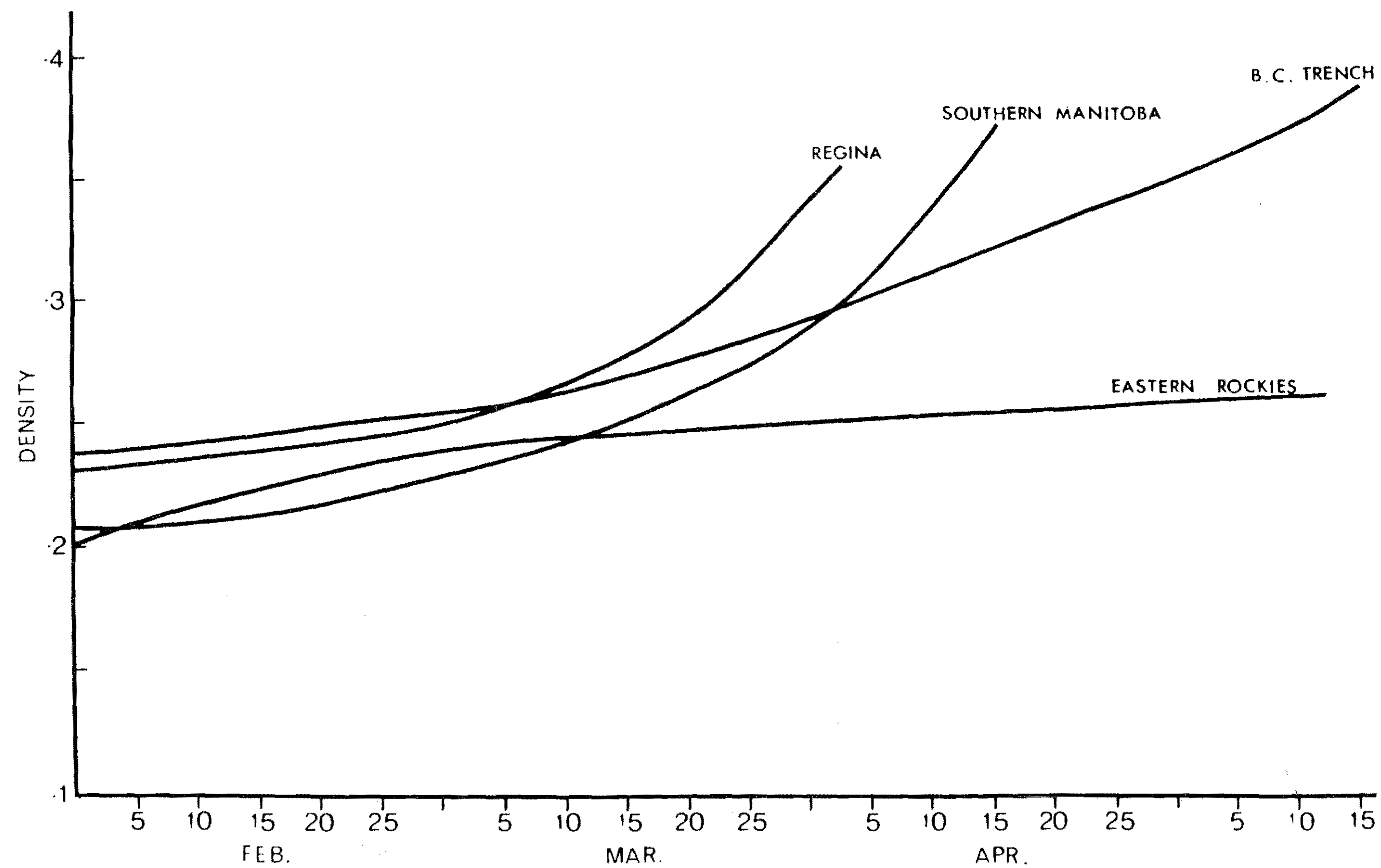

Figure 54 Seasonal variation in average snow density (McKay 1968).

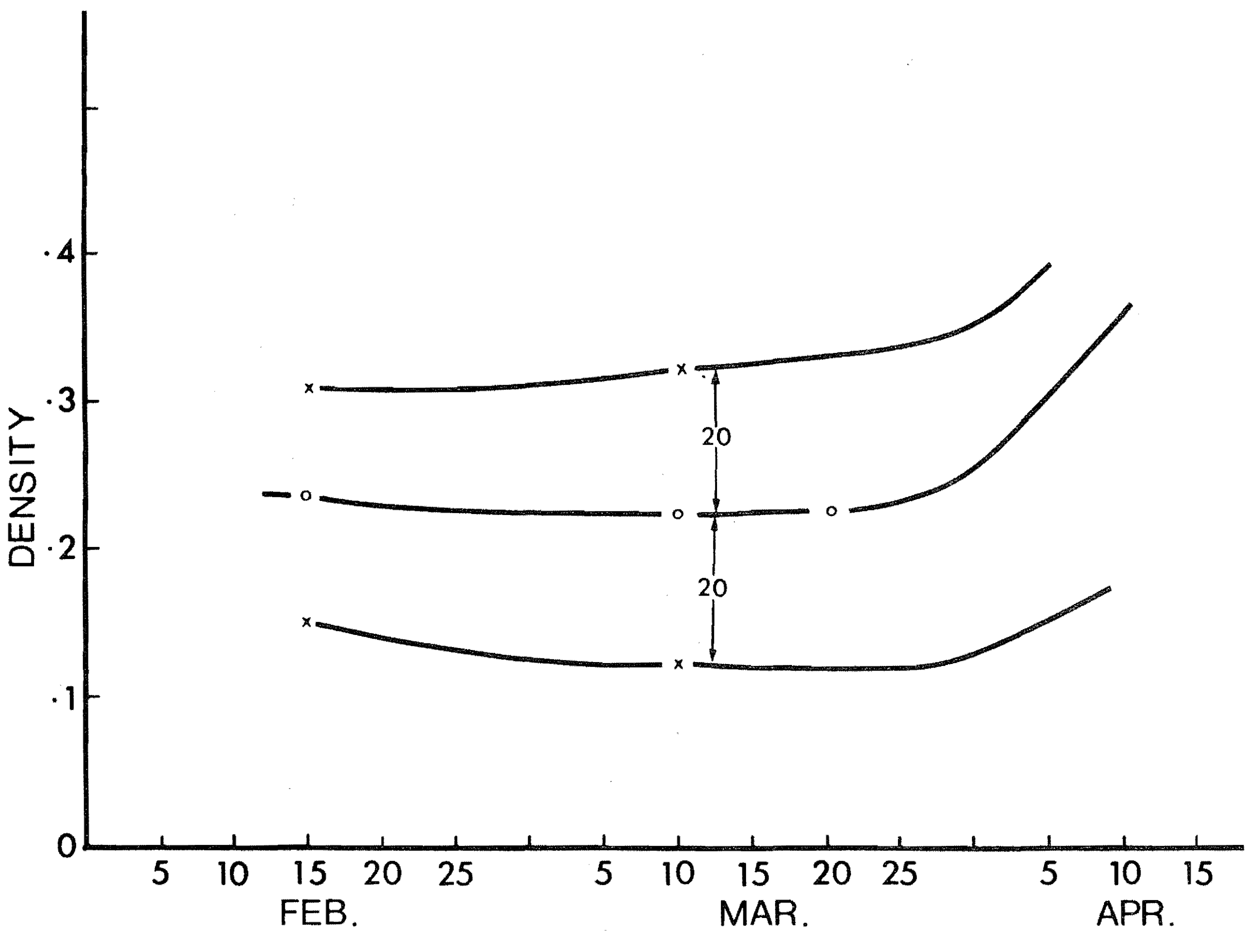

Figure 55 Variation of snowpack density for eastern Saskatchewan from 23 locations in 1956 (McKay 1968).

$$M = M_{rs} + M_{rl} + M_{ce} + M_g + M_p \qquad (6)$$

where M is the total daily snowmelt in inches per day, M_{rs} is the snowmelt by shortwave radiation, M_{rl} the snowmelt by longwave radiation, M_{ce} the melt due to convective condensation, M_g the melt from ground heat, and M_p the melt by transfer of heat from rain.

The snowmelt by shortwave radiation, M_{rs}, is relatively unimportant during periods of rain-on-snow. Studies in United States of incident radiation during these periods show that it is reasonable to assume a constant daily average of 40 longleys for an open area with an average albedo of the snow surface of 65%. The resulting net snowmelt is 0.07 inches per day (1.78 mm per day). For forested areas it may be less, depending on the areal extent and density of forest cover. No studies have been made in Alberta to verify these numbers.

The U.S. Corps of Engineers estimated the longwave radiation during periods of significant precipitation by considering the theoretical exchange of blackbody radiation between the snow surface and the forest canopy or low clouds. For the rain-on-snow conditions, this was expressed as a linear relationship in terms of air temperature and the snow surface temperature of 32°F by

$$M_{rl} = 0.029(T_a - 32) \qquad (7)$$

where M_{rl} is the melt in inches per day resulting from net longwave radiation exchange, and T_a is the air temperature in degrees F.

The snowmelt by the transfer of heat from rain, M_p, was expressed in terms of average daily rainfall rate and free air temperature by the equation

$$M_p = 0.007P_r (T_a - 32) \qquad (8)$$

where M_p is the daily snowmelt from rain, P_r is the daily precipitation in inches, and T_a the air temperature in degrees F.

The snowmelt from ground heat, M_g, was estimated at 0.02 inches per day (0.51 mm per day).

The convective-condensation term M_{ce}, was represented by three equations for varying environments:

(1) for melt at a point in the open:

$$M_{ce} = 0.0084v(T_a - 32) \qquad (9)$$

(2) for basin melt from open or partly forested areas:

$$M_{ce} = (k)0.0084v(T_a - 32) \qquad (10)$$

(3) for heavily forested areas:

$$M_{ce} = 0.045(T_a - 32) \qquad (11)$$

where T_a is the temperature of saturated air at the 10-foot (305 cm) level in degrees F, v is the wind speed at the 50-foot (1 524 cm) level in miles per hour, and k is a basin constant, considering the conditions of measurement with respect to average basin topographic characteristics and exposure to wind. Corrections for elevations represented only about 5% of the total melt and hence were not included in the equation. Conversion to different observation levels of temperature and wind from those specified in the above equations may be accomplished using a power law expression. Increased turbulence due to rain should tend to increase M_{ce}. Thus experiments are needed to determine the effect of rain on both the temperature and wind profiles near the surface.

Combination of the terms in Equation (6) for environmental conditions leads to the following equations:

(1) for open or partly forested basin areas,

$$M = (0.029 + 0.0084kv + 0.007P_r)\ (T_a - 32) + 0.09 \qquad (12)$$

and

(2) for heavily forested areas,

$$M = (0.074 + 0.007P_r)\ (T_a - 32) + 0.05 \qquad (13)$$

These are the equations used by McKay (1965) in computing snowmelt for the Paddle River, Alberta study. The value of k varies from about 0.2 for densely forested areas to slightly over 1.0 for exposed ridges or mountain passes.

The coefficients in Equations (12) and (13) were determined by the U.S. Corps of Engineers for a specific basin; for other basins subject to different meteorological conditions the values of the coefficients may be different. For Alberta basins this has not yet been investigated and can serve as a research topic. To obtain an estimate of the contributions of snowmelt to the total water released, it is assumed that the two equations (12 and 13) and the appropriate coefficients can be applied to basins in Alberta. To compute the maximum melt from rainfall, instead of P (the daily precipitation) in Equations (12) and (13), the greatest PMP for each basin (as described in Section 3 and given in Figures 142, 144, 148, 149, 154, 155, 160, and 161) was substituted in the equations. The basin constant, k, for maximum melt was assigned the value 1.0 (McKay 1965). The basin constant varies within the basin, and a value of 1.0 is not necessarily representative for the entire basin. This parameter has received little attention in the literature and needs to be defined for Alberta basins. Since 24-hour snowmelts were desired, the mean daily temperature and average wind speed as given in Table 3 were used in the computations for the four basins.

The Athabasca and Peace River basins were not included in the table since no estimates were available of the PMP for these basins in April and May. The average wind speed is given in miles per hour (since the equations were developed for this unit) and in kilometres per hour, while the mean daily temperature is in degrees Fahrenheit and Celsius. The values given in Table 3 were extracted for the first-order weather stations from the temperature and wind data summaries published by AES (1975a and 1975b respectively). No data were readily available for the first two weeks of June, therefore this month was omitted from Table 3. The use of the mean daily temperature and the average wind speed are of course open to question, for they are not the best parameters; however of the readily available quantities they are probably the most realistic. As the critical snowmelt floods are the result of rapid snowmelt of significant duration, air temperature and wind speeds must be those which persist for hours rather than minutes, and therefore the use of averages or means would be more appropriate than maximum or peak values (which usually last for short durations). Using the values given in Table 3 in Equations (12) and (13), snowmelt was computed for open or partly forested basin and for heavily forested areas. The results of these computations are summarized in Table 4. The results given in Table 4 are just slightly higher than the melt rates obtained by McKay (1968) for similar forest coverage in the Paddle River study. The daily snowmelt is twice as great in May as in April, and this is mainly because of the warmer temperatures. The amount of snowmelt in an open or partly forested area is from 1.5 to about 2.0 times that calculated in a heavily forested area. At the rates given in Table 4, it would take approximately

Table 3 Values of air temperature and wind speed used in the snowmelt equations for Alberta basins

Basin	Average Wind Speed				Mean Daily Temperature			
	April		May		April		May	
	mph	km/h	mph	km/h	°F	°C	°F	°C
South Sask.	20	32	19	31	38	3.3	48	8.9
Bow	17	27	16	26	38	3.3	49	9.4
Red Deer	16	26	15	24	38	3.3	49	9.4
North Sask.	14	22	13	21	37	2.8	50	10.0

Table 4 Daily snowmelt (mm/day) computed by the snowmelt equations for open or partly forested basin and for heavily forested areas

Basin	Snowmelt for Open or Partly Forested Basin mm/day		Snowmelt for Heavily Forested Areas mm/day	
	April	May	April	May
South Sask.	42	96	22	49
Bow	37	90	21	51
Red Deer	36	84	21	50
North Sask.	38	88	24	57

5 days to melt the greatest depths observed in the South Saskatchewan River basin in April, and about one day in May. This assumes that the maximum snowpack is very ripe with a maximum density of 0.46. In the headwaters of the Bow River basin, the period is twice that calculated for the South Saskatchewan River basin (i.e., about 10 days for April and two days in May) since here the maximum snowpack is about twice as thick. The other two basins (Red Deer and North Saskatchewan) would have time periods similar to that calculated for the South Saskatchewan River basin.

The amount of water released in a 24-hour snowmelt for a 255 km^2 area and an open or partly forested area is about 25% of the estimated PMP in April for the South Saskatchewan River basin. This number increases to about 50% in May. For a heavily forested area in this basin, the values are about half of that calculated for the open or partly forested areas (i.e., about 10% in April and about 25% in May). In this basin, comparing to the estimated PMP for June, even the largest snowmelt rate (i.e., 96 mm per day for an open or partly forested area) is small (i.e., about 25%). For the other basins, similar results were calculated. Thus the total water released from the occurrence of a rain-on-snow event is about 25% more than that of the rain without snow event in April, and about 50% more in May.

Thus far the total water released has been estimated. To obtain the probable maximum flood, these estimates can be related to the basin snowmelt runoff, which can be obtained from hydrograph analysis. So far the discussion has been restricted to point melt rates. Basin-wide snowmelt rates present further complications. Variations in areal snow cover complicate the problem, while at the same time the progressive retreat of the snowline results in a change in the mean elevation of the snow-covered area. In addition, only a part of the snow-covered area may be contributing to snowmelt and, as the southerly exposed open areas become bare of snow first, the more sheltered areas are left to produce the last of the snowmelt. Thus, basinwide snowmelt is difficult to evaluate. In order to evaluate basinwide snowmelt properly, it is necessary that a complete water balance be made for the area such that the snowmelt can be determined relative to the other causes of runoff. Moreover, it is necessary that the areal extent of the snowpack be known.

6. SUMMARY AND TOPICS OF FUTURE RESEARCH

The importance of meteorological and climatological phenomena in their relationship to hydrological problems, particularly flooding from major rainstorms, has been recognized for many years. Probable maximum precipitation estimates have been used in the design of structures. Although the literature is abundant with PMP estimates for most U.S. river basins, very little work has been published for river basins in Alberta. Hence, one of the main objectives of this study was to examine the climatology and meteorology of rainstorms, and provide PMP estimates for river basins in Alberta.

To understand the spatial and temporal distribution of PMP, rainstorms (their location, time of occurrence, and severity), which may contribute to extreme flooding, were identified. In this report a total of 611 rainstorms with depths 50 mm and more from 1921 to 1978 were identified from all readily available data sources. The analysis of point measurements of maximum depth showed that, on the average, about 11 storms occur each year with depths greater than 50 mm, and that the number of rainstorms decreases logarithmically with increased depth category. Over 50% of the rainstorms occur in June and July, with only a small percentage in April (5.6) and September (10.1). The greatest frequency of occurrence is observed in the Waterton Lakes Park area (just about 1 per year), with relatively high frequencies along the continental divide and decreasing eastward along the foothills and plains of Alberta. Two belts of secondary maxima are observed through central Alberta; one through the Edson-Edmonton area, and a second from west of Drayton Valley to the Sundre area.

Like the analysis of point measurements of maximum depth, the results of the average depth showed that the greatest frequencies of occurrences are those in the Waterton Lakes Park area with probability of 2.0 (twice a year) for depths 50 mm and more; 0.38 (1:3 year event) for depths 100 mm and more; and 0.09 (1:10 year event) for depths 150 mm and more. Seasonally, the greatest frequencies are observed in June for southern Alberta and in July for central Alberta. Severe storms (150 mm and greater in depth) are observed to occur in four main regions (or belts) of the province: 1) through southern Alberta, just south of Calgary; 2) in central Alberta from south of Edson to the Edmonton region; 3) from Lesser Slave Lake to the Fort McMurray area; and 4) around the Fort Chipeywan area.

For all severe rainstorms where a DAD analysis was available, a PMP was estimated for the six river basins based on meteorological consideration of available moisture. The maximum estimates of the PMP seem to occur in June for the basins in the southern portion of the province, while in central and northern Alberta the maximum estimates were found to occur in July. For a 260 km^2 area, the largest estimates of the 6-hour PMP observed in the province were those in June in the South Saskatchewan River basin with a maximum depth of about 380 mm, while for a 96-hour PMP (again in June in the South Saskatchewan River basin) the maximum depth was 642 mm. Spatial variability of the PMP is observed in each of the river basins with the largest decrease of the maximum PMP is recorded in the South Saskatchewan River basin. Here at the eastern edges of the basin the PMP estimates are about 80% lower than those calculated at the western edges. Presented in this report are the enveloping 6-, 12-, 24-, 48-, 72-, and 96-hour curves of PMP from April to September for the six river basins.

A second method of estimating the PMP, using the statistical technique developed by Hershfield, was also applied to 27 first-order stations. These estimates were about 50 mm higher (for areas of about 250 km^2) in the six river basins. The largest estimates by this technique also were obtained in the

South Saskatchewan River basin. The spatial variability in the estimate also is noted between stations in each basin using the statistical technique.

In Alberta, along the continental divide, the occurrence of a rain-on-snow event is highly favourable since snow has been observed as late as the first week of June in this area. The effects of snowmelt on flooding is an extensive topic, and not well understood for Alberta rainstorms. Thus this is an area where a greater emphasis in future research needs to be placed.

6.1 TOPICS OF FUTURE RESEARCH

Probably the first topic which can be addressed as a future research project is to determine in detail the number of times the rain-on-snow event has occurred. This requires examination of the occurrence of precipitation events on areal basis, simultaneously with daily areal snow coverage.

The question of the ripeness of the snowpack needs further investigation. As was observed from measurements obtained for the 7 to 8 June 1964 rainstorm, the snowpack was very ripe with a density of 0.46, yet other studies (McKay 1965, 1968) assumed values of about 0.27 in their calculations of snowmelt. The density of snowpacks should be examined temporally and spatially to determine if homogeneous zones exist in Alberta.

Another topic, of a larger scope, is the development of "generalized snowmelt equations" for Alberta zones. To date researchers desiring to obtain an estimate of the snowmelt have assumed that the coefficients developed by the U.S. Corps of Engineers for a specific watershed are applicable to watersheds in Alberta. Since a number of assumptions are needed in developing these coefficients, a detailed study could be conducted to determine the validity of these assumptions. It is possible that the necessary data to verify these assumptions may not exist and hence data collecting networks may have to be initiated.

Probably the most time consuming research topic would be to relate not only the point estimates of the water released but also the basinwide release to the basin runoff. Crude estimates can be made under simplified assumptions. However, in order to evaluate the total water released for the whole basin, a complete water balance is necessary.

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8. APPENDICES

8.1 RAINSTORMS WITH MAXIMUM DEPTHS GREATER THAN 50 mm (1921 to 1978)

This appendix contains a list of 611 rainstorms identified for the period 1921 to 1978 which produced 50 mm and more during their lifetime. The listing contains the date of occurrence, the location, and the greatest depth reported (in inches and millimetres). Rainstorms marked with a star (in front of the date) come from the "Storm Rainfall in Canada" series.

YEAR	DATE				LOCATION OF HEAVIEST RAINFALL	IN	MM
1921	Apr	3	Apr	4	Lacombe (exp. farm)	2.10	53.3
1921	July	1	July	3	Dorenlee (Bashaw)	3.24	82.3
1921	July	17	July	19	Peace River Crossing	3.83	97.3
1921	Aug	25	Aug	25	Peace River Crossing	3.15	80.0
1922	Apr	12	Apr	12	Macleod	3.00	76.2
1922	Apr	27	Apr	29	Pincher Creek	2.57	65.3
1922	May	9	May	10	Dorenlee (Bashaw)	3.12	79.2
1922	Aug	10	Aug	11	Fort Vermilion	2.50	63.5
1922	Aug	12	Aug	13	Nordegg	3.07	78.0
1923	May	25	May	28	Radway	3.31	84.1
*1923	May	30	June	2	Bassano Dam	7.50	190.5
1923	June	12	June	13	Halkirk	2.40	61.0
1923	June	15	June	15	Youngstown	3.05	77.5
1923	June	20	June	23	Pekisko	4.17	105.9
1923	June	26	June	27	Meanook	2.33	59.2
1923	July	1	July	3	Perbeck	2.59	65.8
1923	July	3	July	5	Dunvegan	3.30	83.8
1923	July	18	July	19	Edson	2.39	60.7
1923	July	25	July	25	Lyndon	2.35	59.7
1924	June	6	June	9	Lundbreck	3.60	91.4
1924	June	19	June	19	Pincher Creek	2.57	65.3
1924	July	4	July	6	Vermilion	2.78	70.6
1924	July	15	July	17	Heldar	2.92	74.2
1924	July	27	July	29	Olds	4.30	109.2
1924	Aug	1	Aug	4	Calgary City	3.43	87.1
1924	Aug	7	Aug	8	Pincher Creek	2.25	57.1
1924	Aug	29	Aug	30	Campsie	2.22	56.4
1925	Apr	17	Apr	18	Edmonton	2.21	56.1
1925	Apr	22	Apr	25	Seven Persons	2.50	63.5
1925	May	21	May	22	Hearnleigh (Vulcan P.O.)	2.73	69.3
1925	June	10	June	13	High River	3.78	96.0
1925	July	6	July	7	Wastina Hermaruka	3.61	91.7
1925	July	12	July	12	Fort McMurray	2.20	55.9
1925	Aug	14	Aug	17	Rocky Mtn. House	4.79	121.7
1925	Aug	27	Aug	27	Fort Vermilion	2.07	52.6
1925	Sept	3	Sept.	4	Entrance	2.13	54.1
1925	Sept	8	Sept	9	Campsie	2.95	74.9
1925	Sept	25	Sept	29	Beaver Mines	3.03	77.0
1926	Apr	3	Apr	4	Lyndon	2.55	64.8
*1926	May	29	May	30	Camrose	3.35	85.1
1926	June	8	June	9	Edmonton	3.80	96.5
1926	June	18	June	18	Edmonton	4.48	113.8
*1926	June	18	June	20	Claresholm	4.12	104.6
1926	June	28	June	28	Edmonton	2.02	51.3
1926	July	1	July	2	High River	2.06	52.3
1926	July	17	July	19	Alix	2.36	59.9

YEAR	DATE				LOCATION OF HEAVIEST RAINFALL	IN	MM
1926	Aug	18	Aug	19	Expanse Colee (Vauxhall)	2.44	62.0
1926	Aug	30	Sept	2	Calmar	4.26	108.2
1926	Sept	4	Sept	7	Rocky Mtn. House	4.20	106.7
1927	May	7	May	8	Hanna	2.59	65.8
*1927	May	18	May	23	Foremost	5.78	146.8
1927	May	26	May	28	Dunvegan	2.25	57.1
1927	May	27	May	31	Mountain View	5.19	131.8
1927	July	4	July	6	Fort Smith	3.02	76.7
1927	July	13	July	15	Pincher Creek	3.52	89.4
1927	July	20	July	21	Waterton Park	3.39	86.1
1927	July	30	July	31	Coalspur	2.57	65.3
*1927	Aug	13	Aug	14	Medicine Hat	4.80	121.9
1927	Aug	30	Aug	31	Meanook	2.20	55.9
1927	Sept	10	Sept	10	Bassano	2.27	57.7
1927	Sept	13	Sept	14	Hillspring (Caldwell)	3.13	79.5
1928	May	28	May	29	Viking	2.30	58.4
1928	June	3	June	3	Lundbreck	2.20	55.9
1928	June	6	June	8	Olds	4.50	114.3
1928	June	9	June	9	High River	2.35	59.7
1928	June	15	June	18	Pekisko	3.09	78.5
1928	June	29	July	1	Cowley	3.39	86.1
1928	July	3	July	5	Sion	2.90	73.7
1928	July	29	July	30	Pemukan	2.90	73.7
1928	Aug	24	Aug	27	Waterton Park	3.39	86.1
1929	Apr	29	Apr	30	Pekisko	2.00	50.8
*1929	June	1	June	4	Exshaw	6.51	165.4
1929	July	3	July	3	Fort McMurray	3.48	88.4
1929	July	6	July	7	Waterton Park	2.13	54.1
1929	July	10	July	11	Edmonton	2.96	75.2
1929	July	19	July	21	Peace River Crossing	2.18	55.4
1929	Sept	21	Sept	23	Coalspur	4.19	106.4
1930	Apr	14	Apr	15	Calgary City	2.07	52.6
1930	May	1	May	1	Stettler	2.02	51.3
1930	May	20	May	21	Campsie	2.50	63.5
1930	May	25	May	26	Beaverlodge	2.49	63.2
1930	June	10	June	14	Wabasca	5.40	137.2
1930	June	20	June	22	Vermilion	2.27	57.7
1930	July	18	July	19	Hill Spring (Caldwell)	2.93	74.4
1930	July	25	July	27	Stettler	3.08	78.2
1930	Aug	17	Aug	19	Rocky Mtn House	3.04	77.2
1930	Sept	11	Sept	12	Campsie	4.95	125.7
1930	Sept	14	Sept	14	Campsie	2.25	57.1
1930	Sept	17	Sept	18	Wabasca	2.54	64.5
1930	Sept	21	Sept	23	Campsie	2.75	69.8
1931	May	16	May	18	Kinuso	3.20	81.3

YEAR	DATE				LOCATION OF HEAVIEST RAINFALL	IN	MM
1931	June	9	June	11	Three Hills	2.20	55.9
1931	June	16	June	18	Rocky Mtn House	3.92	99.6
1931	June	29	June	30	Athabasca	5.01	127.3
1931	July	25	July	27	Vermilion	2.99	75.9
1931	July	30	July	31	Groton	2.71	68.8
1931	Aug	3	Aug	4	Vermilion	2.24	56.9
1931	Aug	6	Aug	7	Sedgewick	3.85	97.8
1931	Sept	8	Sept	9	Waterton Park	2.20	55.9
1932	Apr	17	Apr	17	Kinuso	2.55	64.8
*1932	Apr	20	Apr	23	Hillsdown	4.50	114.3
1932	May	21	May	22	Cardston	2.69	68.3
*1932	May	31	June	4	Pekisko	5.86	148.8
1932	June	15	June	17	Winnifred	2.76	70.1
1932	Aug	18	Aug	19	Harmattan	3.51	89.2
1932	Aug	29	Aug	30	Exshaw	2.34	59.4
1932	Sept	9	Sept	9	Calendula Sibbald	2.00	50.8
1932	Sept	17	Sept	18	Glassford	2.27	57.7
1933	May	4	May	4	Campsie	4.20	106.7
1933	May	7	May	9	Campsie	7.85	199.4
1933	May	22	May	22	Campsie	5.56	141.2
1933	June	6	June	9	Duffield	2.90	73.7
1933	June	21	June	22	Coalspur	2.10	53.3
1933	June	22	June	24	Sion	2.90	73.7
1933	June	28	June	29	Glassford	2.85	72.4
1933	July	25	July	27	Elmsworth	2.68	68.1
1933	July	29	July	30	Telfordville	2.43	61.7
1933	Aug	23	Aug	25	Lundbreck	2.40	61.0
1933	Aug	30	Aug	31	Coalspur	2.64	67.1
1933	Sept	15	Sept	17	Buffalo Head Prairie	2.71	68.8
1934	May	20	May	20	Red Deer	2.08	52.8
1934	May	29	May	31	Entrance	2.83	71.9
1934	June	3	June	8	Pincher Creek	7.65	194.3
1934	June	22	June	24	Vermilion	2.85	72.4
1934	June	25	June	27	Medicine Hat	2.50	63.5
1934	July	12	July	13	Kinuso	2.88	73.2
1934	Sept	10	Sept	11	Entrance	3.61	91.7
1934	Sept	21	Sept	23	Macleod	2.48	63.0
1935	May	10	May	11	Entrance	2.97	75.4
1935	May	18	May	18	Elk Island	2.12	53.8
1935	May	22	May	23	Red Deer	2.62	66.5
1935	June	12	June	14	Eckville	3.31	84.1
1935	June	18	June	20	Red Deer	3.64	92.5
*1935	June	30	July	3	Jasper	5.47	138.9
1935	July	6	July	7	Kinuso	2.43	61.7
1935	July	9	July	9	Coalspur	2.63	66.8
1935	July	16	July	17	Gleichen	2.84	72.1

YEAR	DATE		LOCATION OF HEAVIEST RAINFALL	IN	MM
1935	July 27	July 29	Fort McMurray	4.31	109.5
1935	July 31	Aug 1	Red Deer	2.58	65.5
1935	Aug 13	Aug 15	Kinuso	3.55	90.2
1935	Sept 4	Sept 5	Red Deer	2.24	56.9
1936	May 4	May 6	Sion	2.76	70.1
1936	May 20	May 21	Alix	2.27	57.7
1936	May 29	May 31	Nordegg	2.49	63.2
1936	June 6	June 8	Waterton Park	2.98	75.7
1936	July 3	July 4	Bear Lake	2.90	73.7
1936	July 23	July 24	Fort McMurray	2.46	62.5
1936	Aug 12	Aug 15	Coalspur	2.82	71.6
1936	Sept. 10	Sept 14	Bear Lake	3.90	99.1
1937	May 19	May 19	Fort Chipewyan	2.89	73.4
1937	May 22	May 23	Lyndon	2.26	57.4
*1937	June 10	June 14	Waterton Park	6.04	153.4
1937	June 23	June 23	Vegreville	2.02	51.3
*1937	July 12	July 16	Edmonton	6.07	154.2
1937	July 13	July 15	Meanook	3.07	78.0
1937	July 21	July 21	Red Deer	2.16	54.9
1937	July 29	July 30	Heldar	2.12	53.8
1937	Aug 12	Aug 15	Kinuso	4.13	104.9
1937	Sept 20	Sept 22	Red Deer	3.59	91.2
1938	May 1	May 3	Stettler	2.74	69.6
*1938	May 17	May 19	Mountain View	5.10	129.5
1938	June 8	June 9	Athabasca	2.19	55.6
1938	June 25	June 27	Slave Lake	3.44	87.4
1938	July 1	July 3	Hillsdown	3.11	79.0
1938	July 8	July 8	Keg River	2.36	59.9
*1938	Aug 5	Aug 8	Red Deer	7.14	181.4
1938	Aug 18	Aug 19	Nordegg	2.10	53.3
1938	Sept 5	Sept 6	Nordegg	2.10	53.3
1939	May 6	May 6	Macleod	3.02	76.7
1939	May 16	May 20	Edmonton	3.83	97.3
1939	June 3	June 5	Olds	2.69	68.3
1939	June 11	June 16	Pekisko	6.18	157.0
1939	June 22	June 26	Olds	3.24	82.3
1939	July 1	July 1	Drumheller	2.13	54.1
1939	July 15	July 20	Whitecourt Forestry	5.86	148.8
1939	Sept 10	Sept 10	Carrot Creek Forestry	2.43	61.7
1940	Apr 20	Apr 24	Hillspring (Caldwell)	5.16	131.1
1940	Apr 29	Apr 29	Edson	2.01	51.1
1940	July 7	July 8	Strathmore	2.16	54.9
1940	July 15	July 16	Carrot Creek Forestry	2.70	68.6
1940	July 25	July 27	Twin Lakes (Kimball)	3.46	87.9
*1940	Sept 4	Sept 6	Kananaskis	4.00	101.6
1940	Sept 13	Sept 14	High River	2.61	66.3
1940	Sept 21	Sept 22	Medicine Hat	4.83	122.7

YEAR	DATE				LOCATION	IN	MM
1941	May	18	May	19	Buffalo Head Prairie	2.60	66.0
1941	June	17	June	20	Edmonton Airport	3.57	90.7
1941	June	23	June	25	Mayberne Forestry	3.48	88.4
1941	June	28	June	29	Beaver Mines	2.50	63.5
1941	July	4	July	4	Vegreville	2.08	52.8
1941	Aug	2	Aug	3	Sedgewick	2.57	65.3
1941	Aug	23	Aug	25	Pekisko	3.49	88.6
*1942	May	9	May	12	Pekisko	6.36	161.5
1942	May	13	May	14	Waterton Park	2.62	66.5
1942	May	24	May	28	Mayberne Forestry	2.57	65.3
1942	June	3	June	5	Lundbreck	4.01	101.9
1942	June	9	June	11	Mayberne Forestry	2.50	63.5
1942	June	14	June	18	Sion	3.75	95.2
*1942	June	24	June	28	Mossleigh	6.30	160.0
1942	July	7	July	8	Hughenden	3.27	83.1
1942	July	10	July	12	Hardisty	2.68	68.1
1942	July	16	July	18	Ranfurly	3.68	93.5
1942	July	22	July	26	Macleod	2.54	64.5
1942	July	29	July	31	High River	3.54	89.9
1942	Aug	11	Aug	12	Lloydminister	2.74	69.6
1942	Aug	24	Aug	26	Lovett Lookout Forestry	2.50	63.5
1943	Apr	26	Apr	29	Hillspring (Caldwell)	2.95	74.9
1943	May	9	May	11	Kananaskis	2.55	64.8
1943	June	1	June	3	Red Rock	3.43	87.1
1943	June	22	June	23	Meanook	2.76	70.1
1943	Aug	12	Aug	13	Slave Lake	2.16	54.9
1943	Aug	21	Aug	22	Carrot Creek Forestry	3.12	79.2
1944	May	9	May	10	Sion	2.30	58.4
1944	May	21	May	25	Carrot Creek Forestry	4.46	113.3
1944	June	1	June	3	Entrance	3.20	81.3
*1944	June	12	June	16	Thorsby	7.30	185.4
1944	June	25	June	27	Belly River	3.00	76.2
1944	July	5	July	6	Brazeau Tower	3.70	94.0
1944	July	13	July	13	Fort McMurray	2.03	51.6
1944	July	28	July	31	Bowden	5.94	150.9
1944	Aug	7	Aug	7	Blue Creek	4.78	121.4
1944	Aug	12	Aug	13	Belly River	2.25	57.1
1944	Aug	24	Aug	24	Brooks	2.16	54.9
1944	Sept	16	Sept	17	Acadia Valley	2.23	56.6
1945	Apr	11	Apr	12	Waterton Lakes (Pass Cr)	2.60	66.0
1945	May	16	May	19	Pekisko	3.44	87.4
1945	June	1	June	6	Waterton Park H.Q.	4.86	123.4
1945	June	25	June	28	Pekisko	4.02	102.1
1945	July	28	July	31	Mayberne Forestry	4.85	123.2
1945	Aug	3	Aug	5	Lloydminister	2.76	70.1
1945	Aug	25	Aug	26	Calgary A	3.19	81.0

YEAR	DATE				LOCATION OF HEAVIEST RAINFALL	IN	MM
1945	Sept	19	Sept	21	Lovett Lookout Forestry	3.22	81.8
1946	May	27	May	29	Rocky Mtn. House	2.76	70.1
1946	June	5	June	7	Macleod	4.14	105.2
1946	June	14	June	15	Brazeau Tower	3.36	85.3
1946	July	6	July	7	Calmar	2.08	52.8
1946	July	9	July	11	Beaver Mines	2.73	69.3
1946	July	11	July	12	Fort McMurray	2.42	61.5
1946	July	12	July	14	Buck Mountain	3.84	97.5
1946	July	21	July	22	Embarras A	3.80	96.5
1946	Aug	6	Aug	7	Jenner	3.28	83.3
1946	Aug	16	Aug	17	Vermilion A	2.97	75.4
1946	Aug	23	Aug	27	Banff	2.79	70.9
1946	Sept	4	Sept	8	Hanna	2.66	67.6
1947	May	8	May	10	High River	2.14	54.4
1947	June	2	June	3	Macleod	3.08	78.2
1947	June	8	June	11	Macleod	3.02	76.7
1947	June	25	June	27	Lyndon	2.73	69.3
1947	July	14	July	15	Elmworth	2.16	54.9
1947	July	23	July	25	Lovett Lookout Forestry	3.09	78.5
1947	July	28	July	29	Lovett Lookout Forestry	3.85	97.8
*1947	Aug	22	Aug	23	Rockyford (Ryecroft)	4.96	126.0
*1947	Sept	16	Sept	19	Beaver Mines	5.50	139.7
1948	May	7	May	9	Hillspring (Caldwell)	3.76	95.5
1948	May	22	May	23	Coleman	2.14	54.4
1948	May	26	May	27	Waterton Lakes	3.26	82.8
1948	June	9	June	12	Beaver Mines	3.76	95.5
1948	June	14	June	18	Waterton Lakes	4.80	121.9
1948	June	20	June	22	Grande Prairie	2.54	64.5
1948	July	5	July	6	Saskatoon Mtn.	3.03	77.0
1948	July	7	July	8	Carrot Creek Forestry	2.50	63.5
1948	July	11	July	13	Thorsby	3.77	95.8
1948	July	21	July	23	Mayberne Forestry	2.64	67.1
1948	July	27	July	28	Lyndon	4.39	111.5
1948	Aug	4	Aug	8	Entrance	6.06	153.9
1949	May	16	May	17	Caldwell	3.34	84.8
1949	May	20	May	22	Macleod	2.52	64.0
1949	June	14	June	16	Kananaskis	2.46	62.5
1949	June	29	June	30	Drumheller	2.50	63.5
1949	July	15	July	15	Goose Mtn. Forestry	4.97	126.2
1949	July	19	July	19	Brazeau Tower	2.30	58.4
1949	July	21	July	21	Springdale	2.41	61.2
1949	July	24	July	24	Stettler	3.05	77.5
1949	Aug	6	Aug	9	Goose Mtn. Forestry	3.67	93.2
1949	Aug	19	Aug	21	Lovett Lookout Forestry	2.86	72.6
1949	Sept	15	Sept	17	Goose Mtn. Forestry	2.19	55.6
1950	June	5	June	5	Hardisty	2.00	50.8

YEAR	DATE		LOCATION OF HEAVIEST RAINFALL	IN	MM
1950	June 14	June 14	Kananaskis	2.75	69.8
1950	June 21	June 23	Hughenden	2.99	75.9
1950	July 10	July 12	Oyen	3.32	84.3
1950	July 29	July 30	Calgary A	2.67	67.8
1950	Aug 6	Aug 7	Oyen	2.26	57.4
*1951	Apr 29	May 2	Beaver Mines	7.10	180.3
1951	May 12	May 14	Cardston	3.26	82.8
1951	June 3	June 7	Kananaskis	5.99	152.1
1951	June 23	June 24	Waterton Lakes	5.00	127.0
1951	July 4	July 5	Saskatoon Mtn.	5.42	137.7
1951	July 18	July 19	Ryley	2.56	65.0
1951	July 26	July 28	Campsie	2.41	61.2
1951	Aug 4	Aug 8	Heart Lake Forestry	3.80	96.5
1951	Aug 25	Sept 1	Waterton Lakes	6.06	153.9
1952	May 13	May 15	Pekisko	2.64	67.1
1952	June 10	June 13	Alder Flats	3.42	86.9
1952	June 15	June 16	Buffalo Head Prairie	2.18	55.4
1952	June 20	June 22	Sion	4.96	126.0
1952	June 29	June 30	Buffalo Head Prairie	2.94	74.7
1952	July 4	July 5	Elk Point	2.26	57.4
1952	July 17	July 22	Magrath	5.65	143.5
1952	Aug 6	Aug 6	Brooks	2.03	51.6
1953	Apr 5	Apr 13	Waterton Lakes (Pass Cr.)	7.05	179.1
1953	May 8	May 9	Puskwaskau	2.46	62.5
1953	May 24	May 26	Waterton Park	4.90	124.5
*1953	June 1	June 4	Taber	5.08	129.0
1953	June 7	June 9	Claresholm A	4.65	118.1
*1953	July 30	Aug 1	Sion	6.62	168.1
1953	Aug 8	Aug 9	Coronation	2.90	73.7
1953	Aug 24	Aug 26	Carrot Creek Forestry	3.78	96.0
1954	Apr 21	Apr 28	Waterton Lakes	5.60	142.2
1954	May 10	May 12	Red Deer	3.05	77.5
1954	May 20	May 21	Whitecourt (Forestry)	2.10	53.3
1954	May 25	May 26	Whitecourt (Forestry)	2.75	69.8
1954	June 1	June 1	Manyberries	2.06	52.3
1954	June 4	June 7	Conklin Forestry	3.83	97.3
1954	June 14	June 18	Goose Mtn. Forestry	4.51	114.6
1954	June 26	June 28	Vulcan	2.56	65.0
*1954	July 4	July 5	Saskatoon Mtn.	5.49	139.4
1954	July 26	July 27	Ponoka	2.90	73.7
1954	Aug 1	Aug 5	Red Deer	4.55	115.6
1954	Aug 8	Aug 10	Mound	6.25	158.7
1954	Aug 13	Aug 15	Drumheller	2.36	59.9
1954	Aug 22	Aug 25	Lovett Lookout Forestry	4.57	116.1
1954	Aug 30	Aug 31	Meanook	3.73	94.7
1954	Sept 15	Sept 17	Waterton Lakes	3.40	86.4

YEAR	DATE				LOCATION OF HEAVIEST RAINFALL	IN	MM
1954	Sept	27	Sept	28	Waterton Lakes	2.10	53.3
1955	Apr	25	Apr	28	Moon Lake	2.40	61.0
1955	May	8	May	10	Pincher Creek	3.67	93.2
1955	May	13	May	16	Waterton Lakes	4.75	120.6
1955	May	29	May	31	Snuff Mtn.	3.17	80.5
1955	June	29	June	30	Heart Lake Forestry	3.86	98.0
1955	July	1	July	2	Camrose (2)	2.58	65.5
1955	July	5	July	7	Whitecourt (Forestry)	3.77	95.8
1955	July	17	July	18	Embarras A	2.07	52.6
*1955	July	24	July	26	Chipman	5.32	135.1
1955	Sept	15	Sept	16	Athabasca	2.44	62.0
1955	Sept	19	Sept	20	Stoney Mountain Forestry	2.86	72.6
1956	June	4	June	6	Bald Mountain	4.80	121.9
1956	June	9	June	11	Goose Mountain Forestry	4.17	105.9
1956	June	15	June	16	Vulcan	2.90	73.7
1956	June	28	June	29	Olds	2.76	70.1
1956	July	1	July	3	Carway	3.07	78.0
1956	July	6	July	6	Goose Mountain Forestry	2.01	51.1
1956	July	25	July	27	Bald Mountain	3.64	92.5
1956	Aug	1	Aug	2	Brooks	3.25	82.5
*1956	Aug	3	Aug	5	Sweathouse	4.63	117.6
1956	Aug	24	Aug	24	Trochu	2.72	69.1
1956	Aug	27	Aug	28	Naylor Hills Forestry	2.06	52.3
1956	Sept	20	Sept	21	Heart Lake Forestry	2.99	75.9
1957	May	13	May	14	Waterton Lake Belly River	2.53	64.3
1957	May	19	May	21	Waterton Lake	2.49	63.2
1957	June	10	June	11	Goose Mtn. Forestry	3.86	98.0
1957	June	20	June	21	Fort MacLeod	3.38	85.9
1957	June	27	June	28	Clear Hills	3.55	90.2
1957	July	13	July	16	Sweathouse	2.96	75.2
1957	July	29	July	27	Watt Mtn.	3.42	86.9
1957	July	30	Aug	1	Salt Prairie Forestry	5.49	139.4
*1957	Aug	8	Aug	10	Campsie	8.65	219.7
1957	Aug	23	Aug	24	Goose Mtn. Forestry	3.21	81.5
1957	Sept	16	Sept	18	Waterton Lakes	2.65	67.3
1958	Apr	22	Apr	22	Lundbreck	2.15	54.6
1958	May	12	May	12	Compeer	2.01	51.1
1958	June	7	June	11	Waterton Park	3.65	92.7
*1958	June	26	June	30	Yellowhead Tower	5.74	145.8
1958	July	4	July	6	Pekisko	2.71	68.8
1958	Aug	3	Aug	4	May Tower	3.90	99.1
1958	Sept	12	Sept	14	Fort Saskatchewan	4.77	121.2
1959	Apr	22	Apr	23	Waterton Park	2.40	61.0
1959	May	17	May	18	Waterton Park H.Q.	2.95	74.9
1959	June	9	June	10	Shunda Rs	3.42	86.9
1959	June	25	June	27	Stravel Exp. St. 2	4.85	123.2

YEAR	DATE		LOCATION OF HEAVIEST RAINFALL	IN	MM
1959	July 3	July 4	Conklin Forestry	2.69	68.3
1959	July 27	July 28	Clearwater Rs	3.77	95.8
1959	Aug 15	Aug 18	Evanburg	5.45	138.4
1959	Aug 25	Aug 27	Nose Mtn. Forestry	4.84	122.9
1959	Sept 25	Sept 27	Stoney Mtn.	3.66	93.0
1960	Apr 21	Apr 24	Highwood Rs	4.10	104.1
1960	May 12	May 14	Pelican Mtn.	2.92	74.2
1960	May 20	May 22	Beaverlodge	3.59	91.2
1960	June 6	June 8	Buffalo Tower	3.28	83.3
1960	June 16	June 16	Vegreville 2	2.72	69.1
1960	June 19	June 21	Athabaska 2	4.75	120.6
1960	June 23	June 27	Stoney Mtn. Forestry	3.71	94.2
1960	July 1	July 2	Naco	2.76	70.1
1960	July 14	July 14	Tony Creek Tower	3.74	95.0
*1960	July 22	July 24	Stoney Mtn.	7.19	182.6
1960	Aug 1	Aug 2	Castle Rs	2.99	75.9
1960	Aug 4	Aug 5	Calmar	3.29	83.6
1960	Aug 13	Aug 13	Hinton	2.13	54.1
1960	Aug 21	Aug 22	Muskeg Mtn. Tower	3.44	87.4
1960	Aug 29	Aug 31	Buffalo Tower	2.30	58.4
*1960	Sept 4	Sept 6	Pelican Mtn.	5.10	129.5
1960	Sept 18	Sept 19	Grave Flats Lookout	2.42	61.5
1961	May 4	May 6	Waterton Lake	2.62	66.5
1961	May 27	May 27	Three Hills	2.34	59.4
1961	June 6	June 7	Whitemud	2.17	55.1
1961	June 12	June 13	Flattop Tower	3.58	90.9
1961	June 17	June 18	Fort MacLeod Exp. St.	2.55	64.8
1961	June 20	June 21	Cowpar Lake Tower	2.41	61.2
1961	June 26	June 27	Marten Mtn.	4.60	116.8
*1961	June 29	June 30	Flattop	5.03	127.8
1961	July 7	July 8	Marten Mountain	4.20	106.7
1961	July 14	July 16	Chungo Lookout	4.06	103.1
1961	July 23	July 25	Edmonton International	3.39	86.1
1961	July 30	July 30	Chungo Lookout	3.25	82.5
1961	Aug 5	Aug 6	Keane Tower	2.72	69.1
1961	Aug 15	Aug 16	Chungo Lookout	3.02	76.7
1961	Sept 18	Sept 20	Caldwell	2.44	62.0
1961	Sept 27	Sept 28	Nose Mtn. Forestry	2.30	58.4
1962	May 3	May 4	Deer Mtn. Tower	2.25	57.1
1962	May 13	May 15	Waterton Lakes	2.40	61.0
*1962	June 3	June 6	Cowpar Lake Tower	5.40	137.2
1962	June 11	June 14	Buffalo Tower	4.08	103.6
1962	June 26	June 27	Keg River Tower	3.69	93.7
1962	July 1	July 2	Heart Lake Forestry	2.38	60.5
*1962	July 12	July 16	Castor	6.42	163.1
1962	July 19	July 19	Swan Dive	2.66	67.6
1962	July 24	July 25	Cowley Olin Creek	2.51	63.8

YEAR	DATE				LOCATION OF HEAVIEST RAINFALL	IN	MM
1962	Aug	2	Aug	5	Carrot Creek Forestry	3.69	93.7
1962	Aug	25	Aug	28	Grave Flats Lookout	4.18	106.2
1962	Sept	6	Sept	6	Elbow Rs	2.38	60.5
1962	Sept	10	Sept	12	Tony Creek Tower	3.16	80.3
1963	June	7	June	9	Waterton Lakes Red Rock	3.69	93.7
*1963	June	21	June	22	Taber	4.98	126.5
*1963	June	28	June	30	Hailstone Butte Lookout	7.42	188.5
1963	July	7	July	8	Brownfield	2.90	73.7
1963	July	13	July	15	Alder Flats	4.02	102.1
*1963	July	21	July	23	Bison Tower	4.83	122.7
1963	July	24	July	25	Mockingbird Lookout	3.18	80.8
1963	July	27	July	28	Zama Tower	2.30	58.4
1963	Aug	14	Aug	16	Mirror Landing Rs	3.66	93.0
1963	Aug	20	Aug	21	Zama Tower	2.66	67.6
1963	Sept	9	Sept	10	Algar Tower	2.03	51.6
1963	Sept	13	Sept	15	Duchess	3.11	79.0
1964	Apr	4	Apr	6	Waterton Lakes Belly River	4.00	101.6
1964	Apr	22	Apr	22	Waterton Lakes Belly River	2.60	66.0
*1964	May	1	May	7	Mtn. View Birdseye	7.00	177.8
1964	May	12	May	13	Deadwood	2.16	54.9
1964	May	20	May	21	Peace River	3.09	78.5
1964	June	7	June	8	Waterton Lakes RR	9.90	251.5
1964	June	11	June	12	Bald Mtn. Lookout	2.59	65.8
1964	June	14	June	20	Ghost Rs.	4.92	125.0
*1964	June	27	June	28	White Mtn. Lookout	5.64	143.3
1964	July	2	July	3	Crossfield	2.93	74.4
1964	July	9	July	10	Iron River	4.11	104.4
1964	July	14	July	16	O Chiese Lookout	4.46	113.3
1964	July	21	July	21	Talbot Lake Lookout	2.58	65.5
*1964	July	29	Aug	2	White Mtn. Lookout	5.97	151.6
1964	Aug	4	Aug	4	Buffalo Lookout	2.52	64.0
1964	Aug	28	Aug	30	O Chiese Lookout	2.85	72.4
1964	Sept	1	Sept	2	Hughenden	2.83	71.9
1964	Sept	23	Sept	24	Grave Flats Lookout	2.70	68.6
1965	Apr	18	Apr	20	Waterton Park	2.29	58.2
1965	May	16	May	16	Warwick	2.03	51.6
1965	May	29	May	31	Lovett Lookout	3.21	81.5
1965	June	12	June	12	Paradise Valley	3.28	83.3
1965	June	15	June	18	Herronton East	4.64	117.9
*1965	June	25	June	27	Pimple Lookout	6.21	157.7
*1965	July	7	July	9	Kakwa Lookout	4.94	125.5
1965	July	17	July	18	Salt Prairie Lookout	4.40	111.8
1965	July	21	July	22	Whitefish Lookout	2.95	74.9
1965	July	27	July	28	Deer Mtn. Lookout	3.13	79.5
1965	Aug	3	Aug	4	Rainier	4.07	103.4
1965	Aug	8	Aug	8	Berland Lookout	2.94	74.7

YEAR	DATE				LOCATION OF HEAVIEST RAINFALL	IN	MM
*1965	Aug	12	Aug	13	Goose Mnt. Lookout	4.10	104.1
1965	Aug	22	Aug	23	Beaverlodge	2.71	68.8
1965	Aug	25	Aug	26	Madden	3.50	88.9
1965	Aug	27	Aug	30	Lloydminister Sefton Pa	3.93	99.8
1965	Sept	1	Sept	2	Clearwater Rs.	2.16	54.9
1966	Apr	24	Apr	26	Crossfield	2.58	65.5
1966	May	21	May	22	Algar Lookout	2.93	74.4
1966	May	29	May	31	Forget Me Not	4.72	119.9
1966	June	3	June	4	Waterton Lakes	5.13	130.3
1966	June	22	June	24	Whitla	2.98	75.7
*1966	July	1	July	4	Arrowwood	4.85	123.2
1966	July	13	July	14	Fort McLeod North	2.43	61.7
1966	July	19	July	20	Watt Mtn. Lookout	2.97	75.4
1966	July	23	July	25	Kiska Lookout	2.40	61.0
*1966	Aug	3	Aug	6	Blackstone Lookout	4.73	120.1
1966	Aug	18	Aug	19	Waterton Lakes	3.47	88.1
*1966	Aug	27	Aug	28	Ansell	4.26	108.2
1966	Aug	29	Aug	30	Viking	3.00	76.2
1967	Apr	17	Apr	20	Waterton Lakes	4.30	109.2
1967	Apr	27	Apr	29	Waterton Park H.Q.	4.55	115.6
1967	May	29	May	30	Sheep Rs	3.49	88.6
1967	July	8	July	10	Lac La Biche A	4.05	102.9
*1967	July	13	July	14	Wadlin Lookout	4.47	113.5
1967	July	20	July	21	Forestburg	3.13	79.5
1967	July	23	July	24	Watt Mtn. Lookout	2.57	65.3
1967	July	28	July	28	Heart Lake Lookout	2.04	51.8
1967	Aug	4	Aug	6	Primrose Lookout	4.14	105.2
1967	Aug	23	Aug	24	High Level Rs	2.06	52.3
1968	May	6	May	7	Whiskey Gap	2.06	52.3
1968	June	6	June	8	Medicine Hat A	2.97	75.4
*1968	June	10	June	13	White Mtn. Lookout	4.47	113.5
1968	June	28	June	29	Simonette Lookout	2.81	71.4
1968	July	19	July	21	Bowden	4.13	104.9
1968	July	28	July	29	Primrose Lookout	2.56	65.0
1968	Aug	3	Aug	6	Kakwa Lookout	3.44	87.4
1968	Aug	14	Aug	15	Mountain View	2.72	69.1
1968	Sept	19	Sept	21	Whiskey Gap	5.07	128.8
1969	Apr	28	Apr	29	Clearwater Rs	2.33	59.2
1969	June	5	June	6	Pincher Creek Springdale	2.61	66.3
*1969	June	19	June	29	Pekisko	9.00	228.6
1969	July	3	July	6	Baseline Lookout	4.95	125.7
1969	July	25	July	25	Lloydminister	2.37	60.2
1969	July	26	July	29	Whitecourt	4.20	106.7
*1969	Aug	3	Aug	6	Grave Flats Lookout	6.95	176.5
1969	Aug	16	Aug	16	Stoney Mtn. Lookout	2.79	70.9
*1969	Sept	2	Sept	5	House Mtn. Lookout	5.20	132.1

YEAR	DATE				LOCATION OF HEAVIEST RAINFALL	IN	MM
1969	Sept	12	Sept	14	South Wapiti Lookout	3.27	83.1
1969	Sept	20	Sept	21	Drumheller Institution	2.62	66.5
1970	Apr	13	Apr	15	Castle Rs.	2.86	72.6
1970	Apr	26	Apr	27	Castle Rs	3.48	88.4
1970	May	16	May	17	Stoney Mtn. Lookout	2.53	64.3
1970	May	26	May	27	Calmar	2.28	57.9
*1970	June	12	June	14	Caldwell	4.67	118.6
*1970	June	27	July	1	Pelican Mtn. Lookout	8.91	226.3
1970	July	9	July	11	Whitecourt	3.85	97.8
1970	July	16	July	17	Highway	4.76	120.9
1970	July	24	July	25	Jean Lookout	3.58	90.9
1970	July	26	July	29	Lloydminister Sefton Pa	2.67	67.8
1970	Aug	13	Aug	14	Primrose Lookout	2.88	73.2
1970	Sept	1	Sept	2	Stoney Mtn. Lookout	3.33	84.6
1970	Sept	22	Sept	23	Thickwood Lookout	2.60	66.0
1971	May	19	May	21	Castle Rs.	2.67	67.8
1971	May	27	May	28	St. Lina	2.49	63.2
1971	June	3	June	7	Foremose Ext	4.18	106.2
1971	June	7	June	10	Nose Mtn. Lookout	3.47	88.1
*1971	June	13	June	17	House Mtn. Lookout	6.36	161.5
1971	June	24	June	27	Buckton Lookout	5.38	136.7
*1971	July	1	July	7	House Mtn. Lookout	5.38	136.7
1971	July	8	July	11	Whitecourt Lookout	5.49	139.4
1971	July	23	July	24	Alder Flats Lookout	3.23	82.0
1971	Aug	3	Aug	3	Carrot Creek Lookout	2.65	67.3
1971	Aug	5	Aug	7	Goose Mtn. Lookout	2.46	62.5
1971	Aug	14	Aug	15	Hotchkiss Lookout	3.09	78.5
1971	Aug	30	Aug	31	Livingstone Lookout	2.29	58.2
1971	Sept	1	Sept	2	Watt Mtn. Lookout	3.05	77.5
1971	Sept	23	Sept	26	Nose Mtn. Lookout	4.40	111.8
1972	Apr	16	Apr	16	Claresholm Trout Creek	2.40	61.0
1972	May	24	May	25	Mountain View	2.94	74.7
1972	June	8	June	12	Sunnyslope	7.50	190.5
*1972	June	10	June	12	Nose Mtn. Lookout	8.05	204.5
1972	June	16	June	17	Pelican Mtn. Lookout	4.03	102.4
*1972	June	23	June	25	Aurora Lookout	6.02	152.9
1972	July	7	July	10	White Mtn. Lookout	3.72	94.5
1972	July	23	July	26	Tom Hill Lookout	3.23	82.0
1972	Aug	10	Aug	11	McLennan Rs	2.95	74.9
1972	Aug	19	Aug	20	Millarville	3.19	81.0
1972	Aug	21	Aug	22	Chain Lakes Rs	3.16	80.3
1972	Sept	5	Sept	6	Elbow Rs	2.07	52.6
1972	Sept	9	Sept	9	Alix	2.02	51.3
1973	May	19	May	20	Panny Lookout	2.82	71.6
1973	May	24	May	27	Berland Lookout	4.80	121.9
1973	May	31	June	1	Chipewyan Lookout	3.23	82.0

YEAR	DATE				LOCATION OF HEAVIEST RAINFALL	IN	MM
1973	June	8	June	11	Saddle Hills Lookout	2.78	70.6
*1973	June	14	June	17	Sedalia	8.60	218.4
1973	June	23	June	25	Pimple Lookout	4.18	106.2
1973	June	30	July	1	Edberg	3.20	81.3
1973	July	6	July	7	Johnston Lake Lookout	3.05	77.5
1973	July	11	July	12	Fort McMurray A	2.79	70.9
1973	July	15	July	16	Panny Lookout	3.40	86.4
1973	July	24	July	26	Economy Lookout	3.50	88.9
1973	July	27	July	27	Atmore	2.08	52.8
1973	Aug	1	Aug	2	Fort Assinibone	3.60	91.4
1973	Aug	4	Aug	7	Cowpar Lookout	6.53	165.9
1973	Aug	15	Aug	18	Codesa Lookout	4.85	123.2
1973	Aug	23	Aug	24	Sand River Lookout	2.45	62.2
1973	Aug	30	Aug	31	Pekisko	2.47	62.7
1973	Sept	11	Sept	12	Cowpar Lookout	3.12	79.2
1974	Apr	26	Apr	27	Herronton	5.30	134.6
1974	May	14	May	18	Forget Me Not Lookout	4.94	125.5
1974	June	3	June	4	Winfield	2.32	58.9
1974	June	25	June	26	Wetaskiwin	3.66	93.0
1974	July	11	July	14	Calling Lake Rs	4.43	112.5
1974	July	30	July	30	Worsley Rs	2.06	52.3
1974	Aug	10	Aug	13	Chain Lakes Rs	3.86	98.0
1975	Apr	7	Apr	9	Mountain View Birdseye	3.75	95.2
1975	Apr	27	Apr	28	Horshoe Lake	3.00	76.2
1975	May	4	May	8	Caldwell	4.92	125.0
1975	May	22	May	23	Yates Lookout	2.85	72.4
1975	June	18	June	21	Caldwell	4.71	119.6
1975	June	25	June	27	Marten Mtn. Lookout	5.03	127.8
1975	July	2	July	3	Alder Flats Lookout	3.25	82.5
1975	July	12	July	13	Tar Island	2.95	74.9
1975	July	15	July	17	Marten Mtn. Lookout	5.10	129.5
1975	July	29	July	30	Pincher Creek	3.56	90.4
1975	Aug	7	Aug	10	Tofield North	5.54	140.7
1975	Aug	14	Aug	16	Forget Me Not Lookout	4.34	110.2
*1975	Aug	22	Aug	24	Wadlin Lookout	6.37	161.8
1975	Aug	28	Aug	30	Meridian Lookout	5.43	137.9
1976	May	30	May	31	Wadlin	2.53	64.3
1976	June	12	June	13	Fabyan	2.73	69.3
1976	June	19	June	20	Winered	3.14	79.8
1976	June	22	June	23	Elk Point	3.58	90.9
1976	July	31	Aug	1	Edmonton Municiple A	2.41	61.2
1976	Aug	3	Aug	5	Cowley Olin Creek	5.45	138.4
1976	Aug	6	Aug	7	Elmworth CDA	3.00	76.2
1976	Aug	8	Aug	9	Rimbey	4.10	104.1
1976	Aug	15	Aug	17	Dakota	4.13	104.9

YEAR	DATE				LOCATION OF HEAVIEST RAINFALL	IN	MM
1976	Aug	25	Aug	26	Fort McMurray A	4.23	107.4
1977	May	3	May	3	Obed Lookout	4.33	110.0
1977	May	27	May	29	Kiska Lookout	3.43	87.1
1977	July	1	July	3	Birch Mtn. Lookout	4.21	106.9
1977	July	4	July	7	Tony Lookout	3.00	76.2
1977	July	28	July	30	Lacombe	2.30	58.4
1978	May	29	May	30	Sand River	2.62	66.5
1978	June	14	June	15	Eagle Lookout	5.09	129.3
1978	July	11	July	12	Brazeau Lookout	3.69	93.7
1978	July	27	July	28	Pass Creek Lookout	2.60	66.0
1978	Aug	16	Aug	17	Penhold A	3.39	86.1
1978	Sept	8	Sept	10	Birch Mountain Lookout	3.36	85.3
1978	Sept	10	Sept	12	Medicine Lodge	4.61	117.1

8.2 GRAPHS OF SPATIAL AND SEASONAL DISTRIBUTION OF RAINSTORMS

This appendix contains graphs associated with Section 2 Figures 56 to 61 comprise a sequence of six maps, every ten years beginning with 1921, of the spatial distribution of stations collecting precipitation data in Alberta. Figures 62 to 67 show the number of occurrence of rainstorms for each month from April to September with depths 50 mm and more in 100 years, while Figures 68 to 73 are for depths 100 mm and more, and Figures 74 to 79 for 150 mm and more. Figures 80 to 84 depict the spatial distribution of the storm-station density in ten-year periods beginning with 1921.

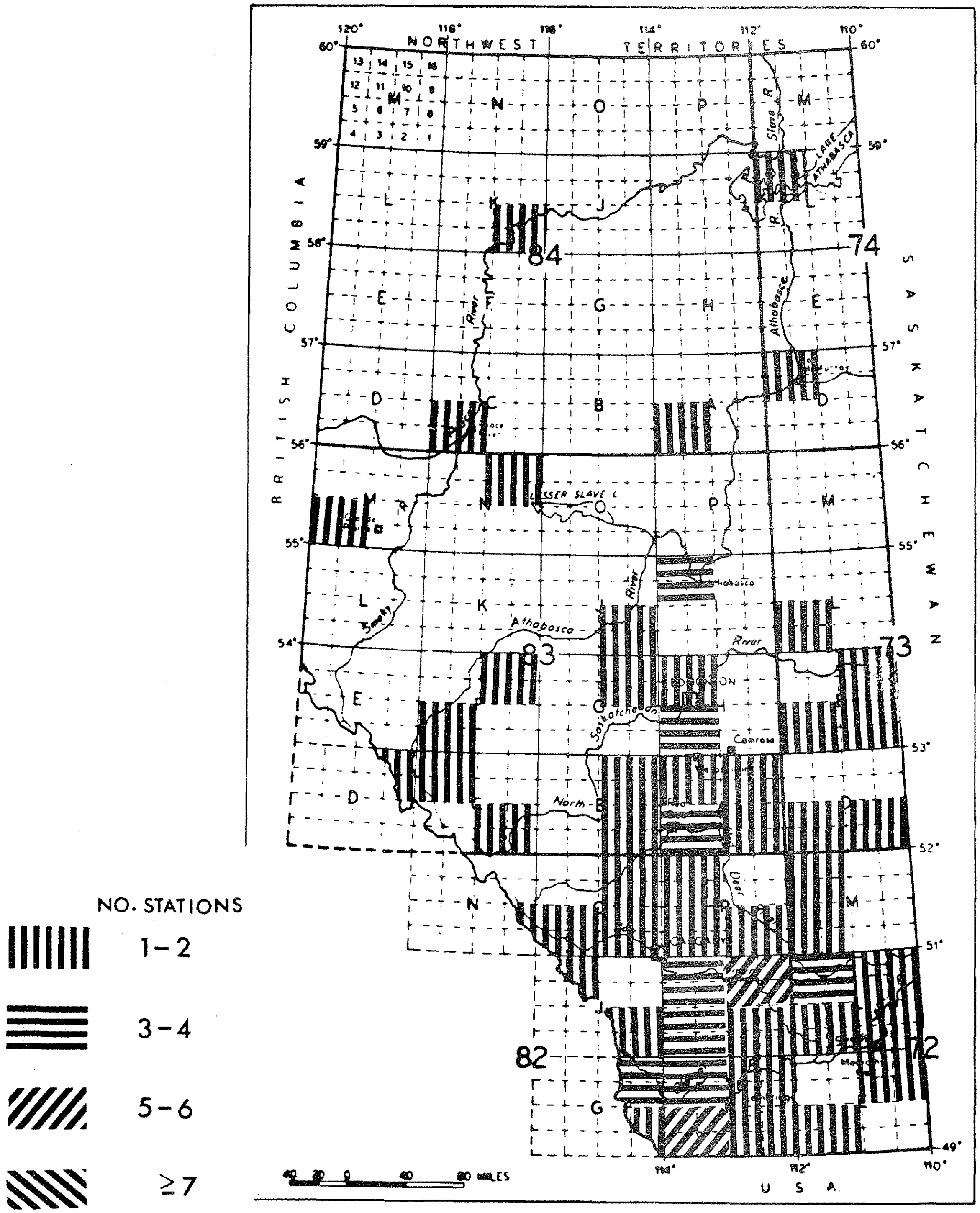

Figure 56 Spatial distribution of stations collecting precipitation data in 1921 in Alberta.

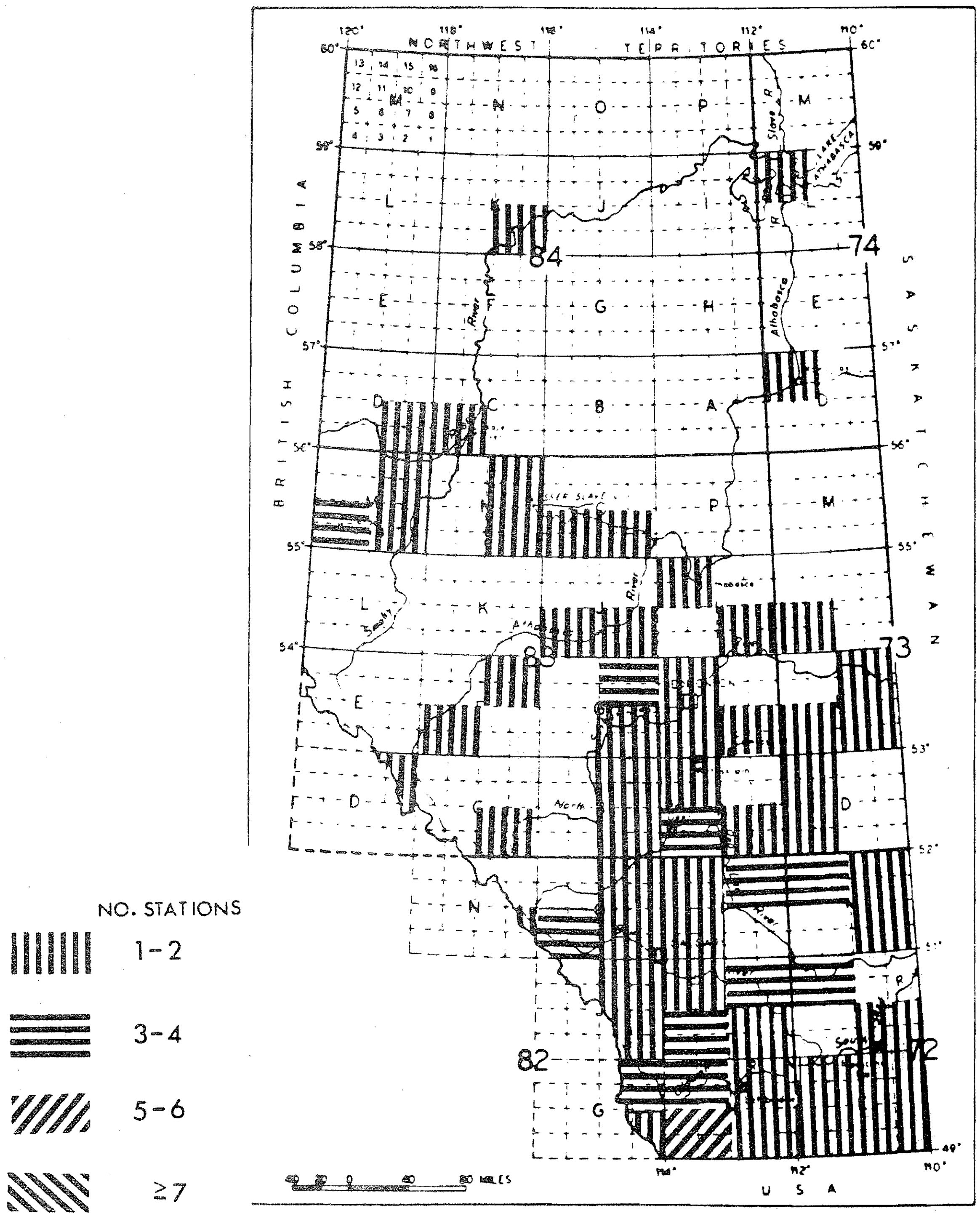

Figure 57 Spatial distribution of stations collecting precipitation data in 1931 in Alberta.

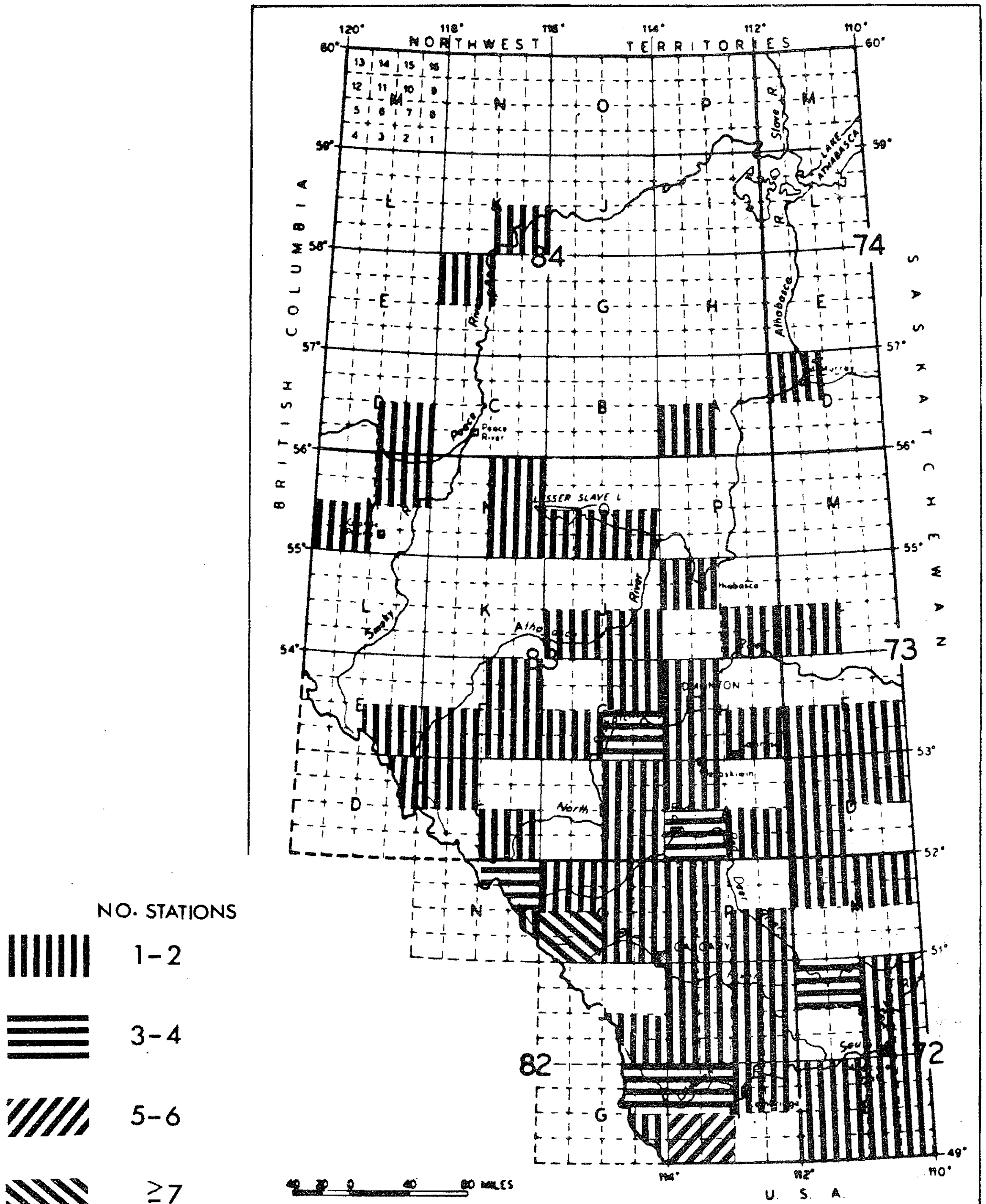

Figure 58 Spatial distribution of stations collecting precipitation data in 1941 in Alberta.

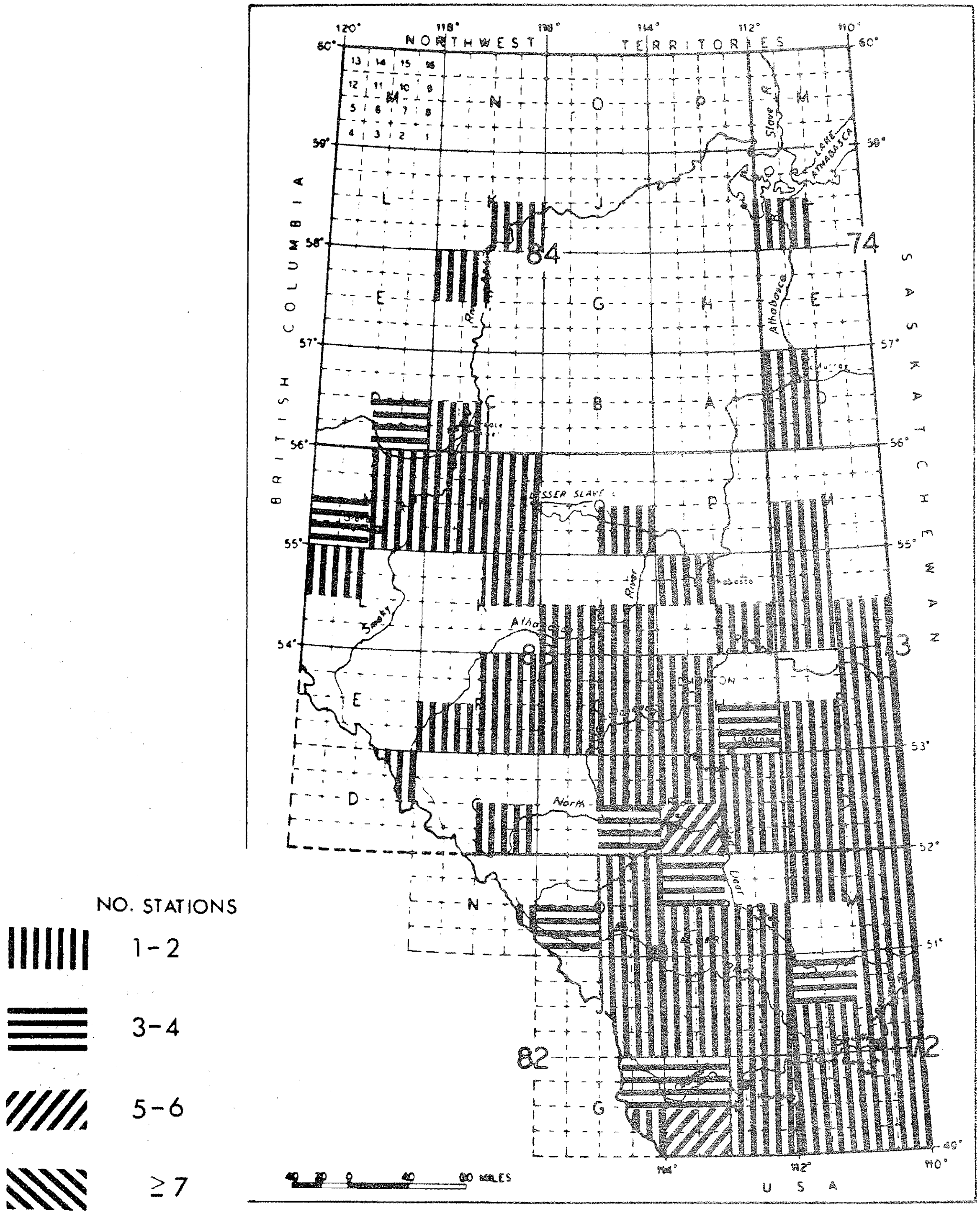

Figure 59 Spatial distribution of stations collecting precipitation data in 1951 in Alberta.

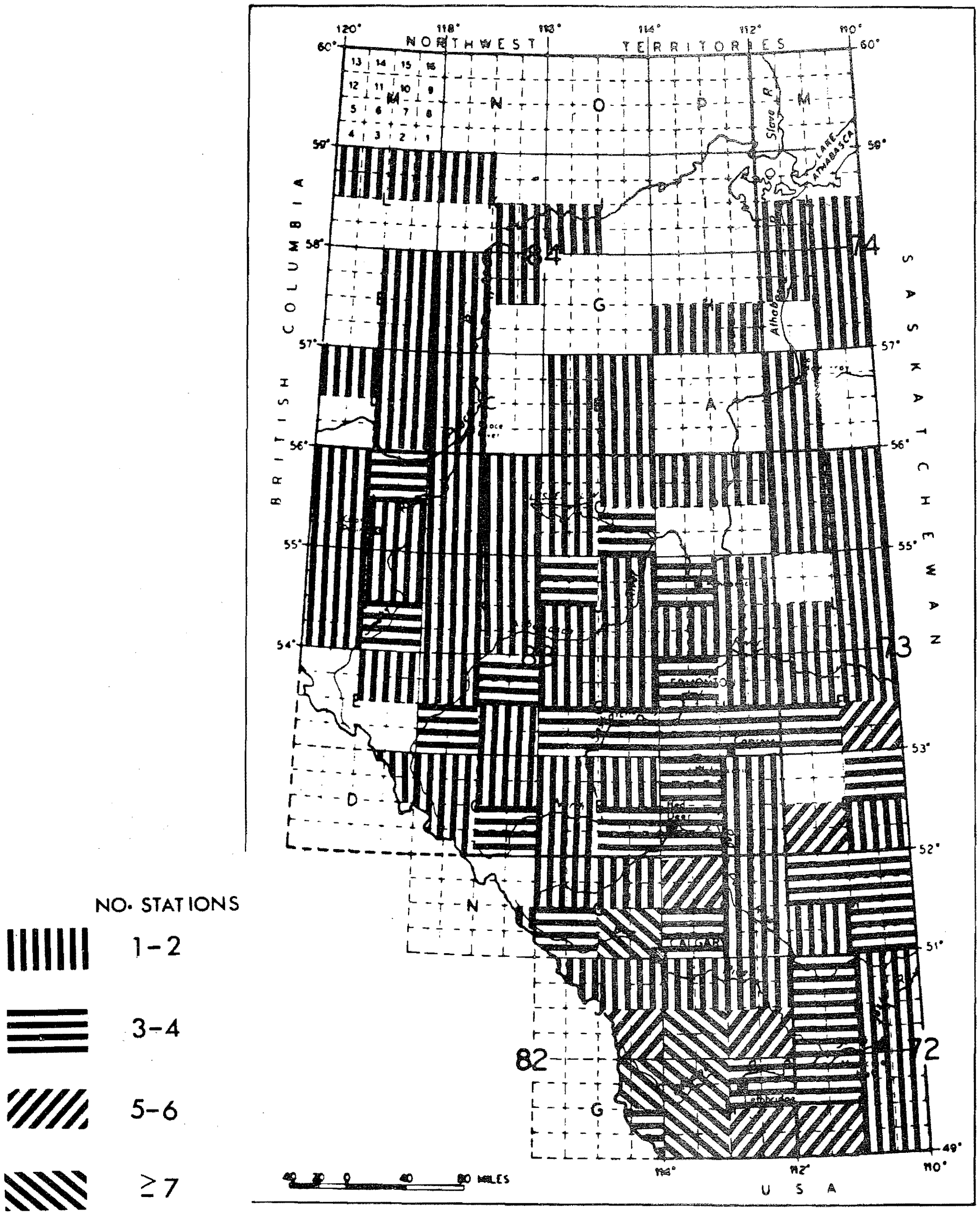

Figure 60 Spatial distribution of stations collecting precipitation data in 1961 in Alberta.

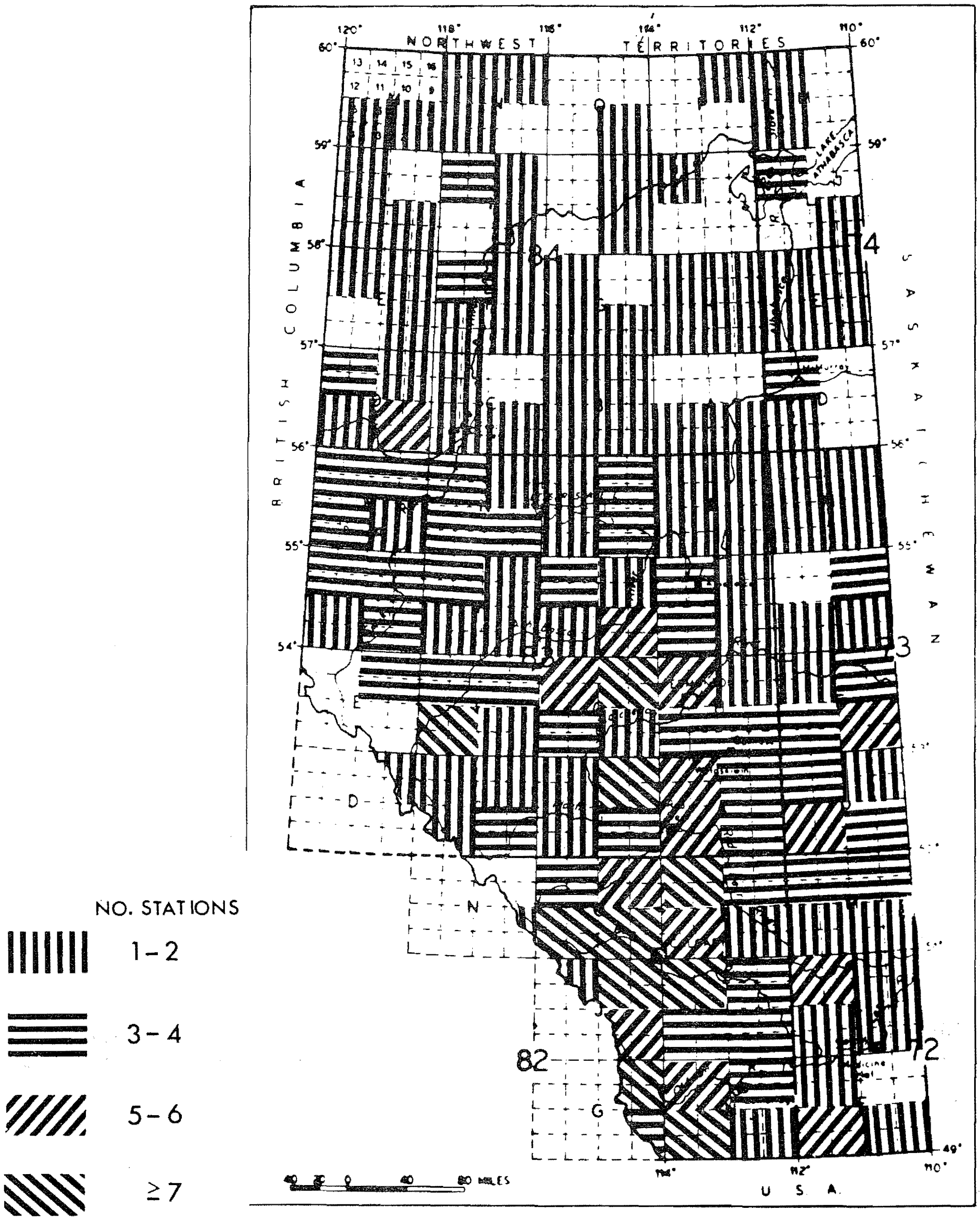

Figure 61 Spatial distribution of stations collecting precipitation data in 1971 in Alberta.

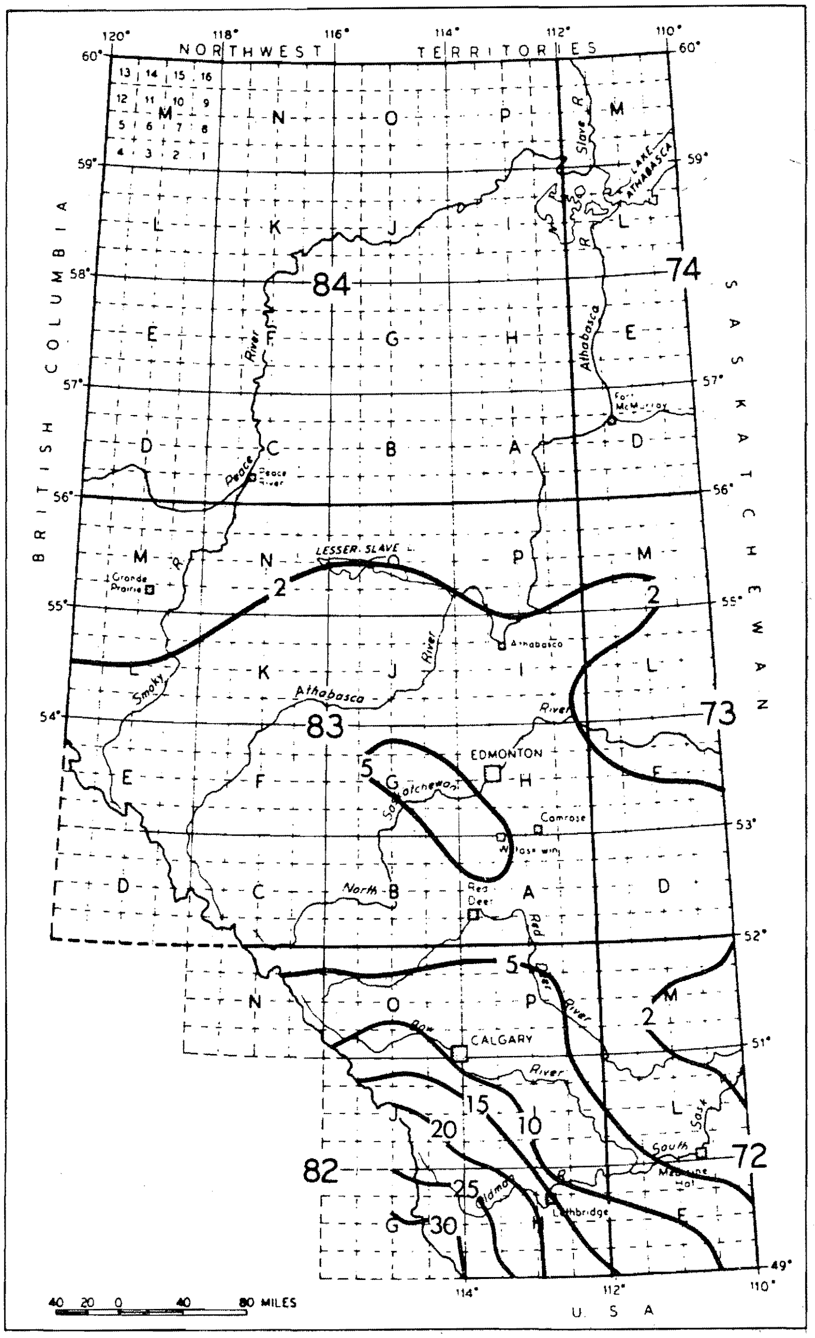

Figure 62 Number of occurrences of rainstorms in April with depths 50 mm and more in 100 years.

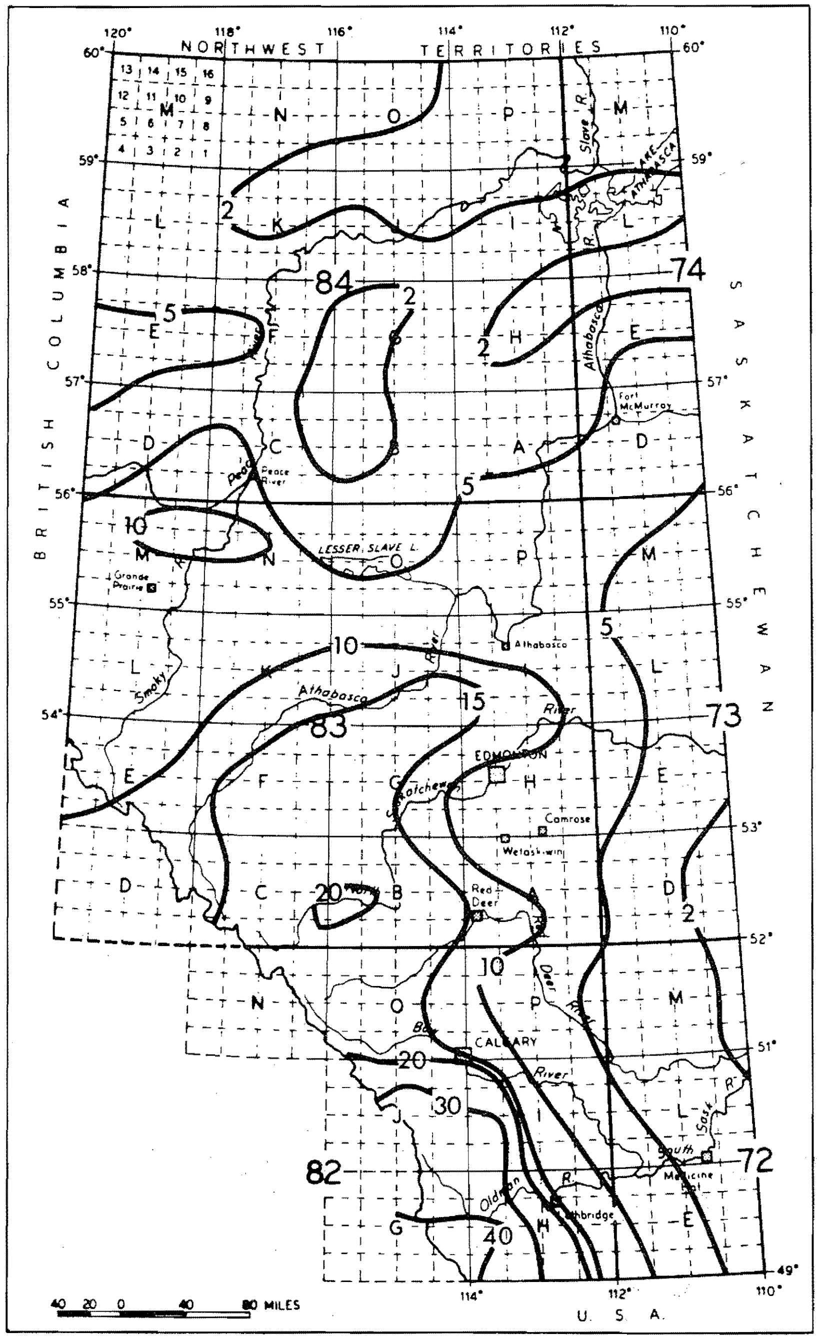

Figure 63 Number of occurrences of rainstorms in May with depths 50 mm and more in 100 years.

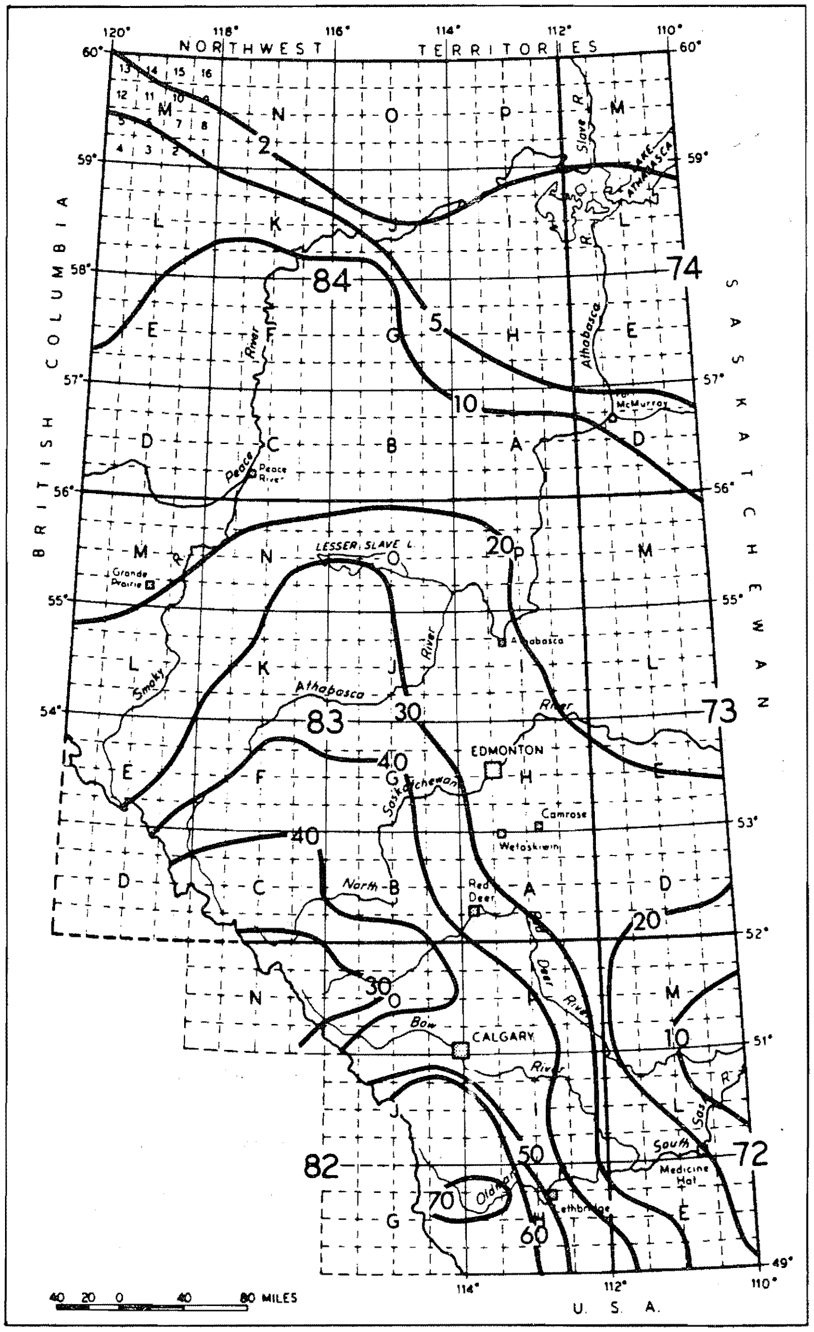

Figure 64 Number of occurrences of rainstorms in June with depths 50 mm or more in 100 years.

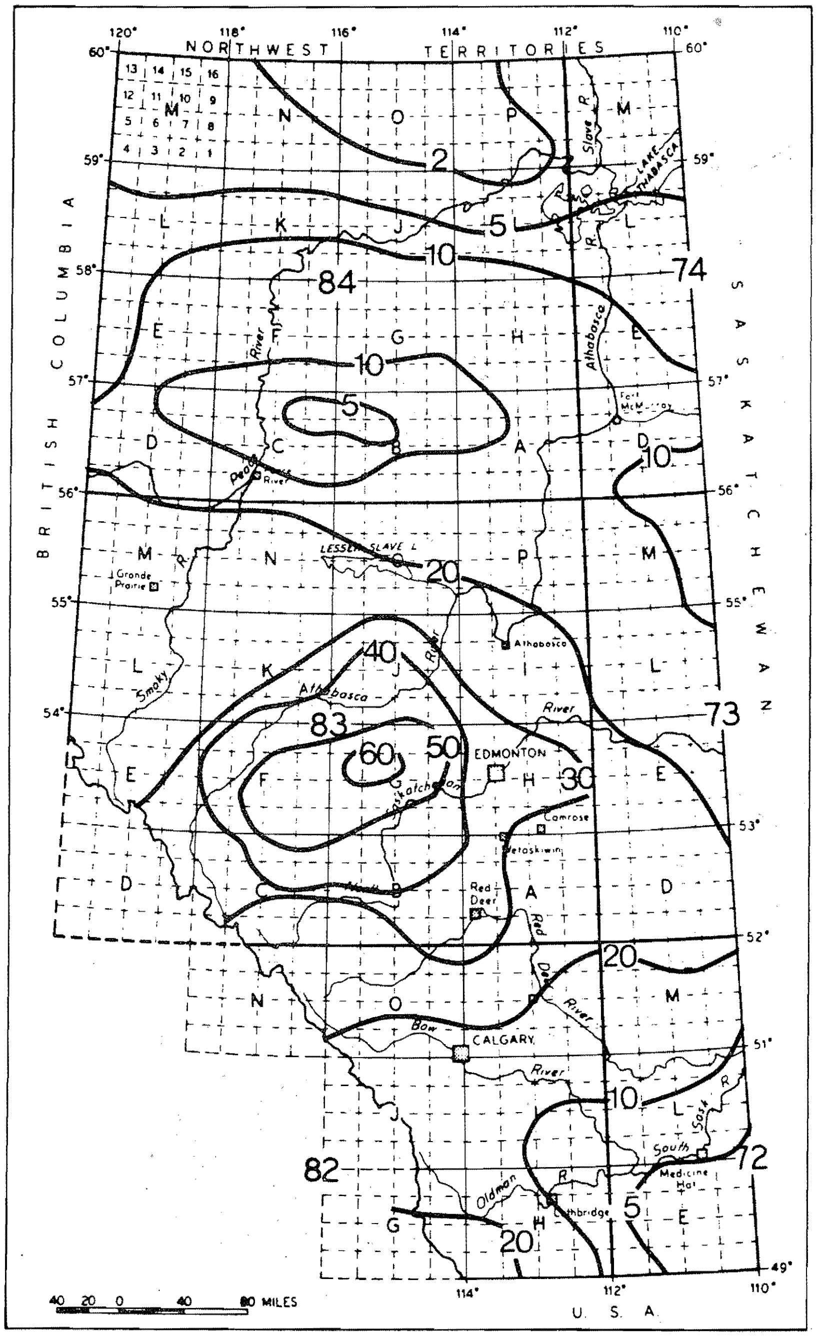

Figure 65 Number of occurrences of rainstorms in July with depths 50 mm and more in 100 years.

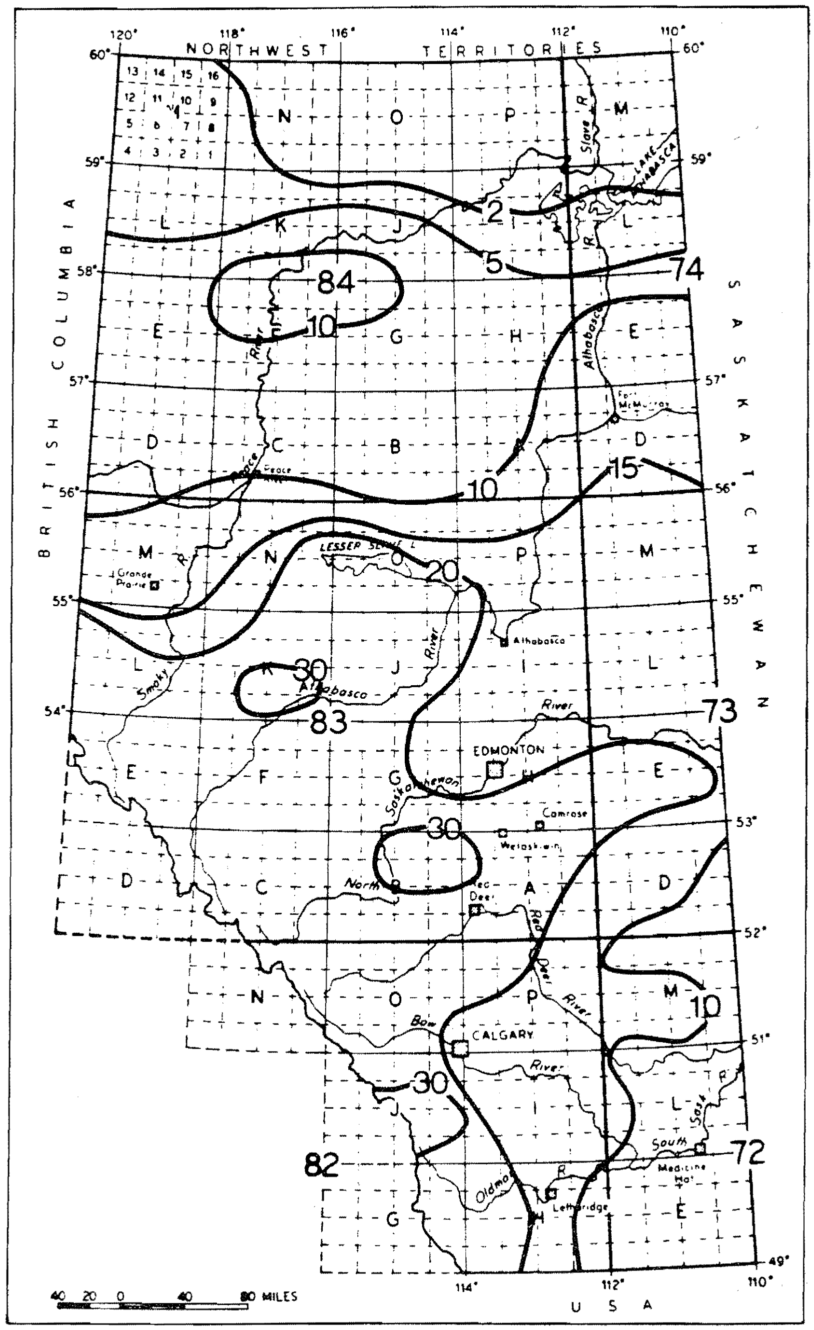

Figure 66 Number of occurrences of rainstorms in August with depths 50 mm and more in 100 years.

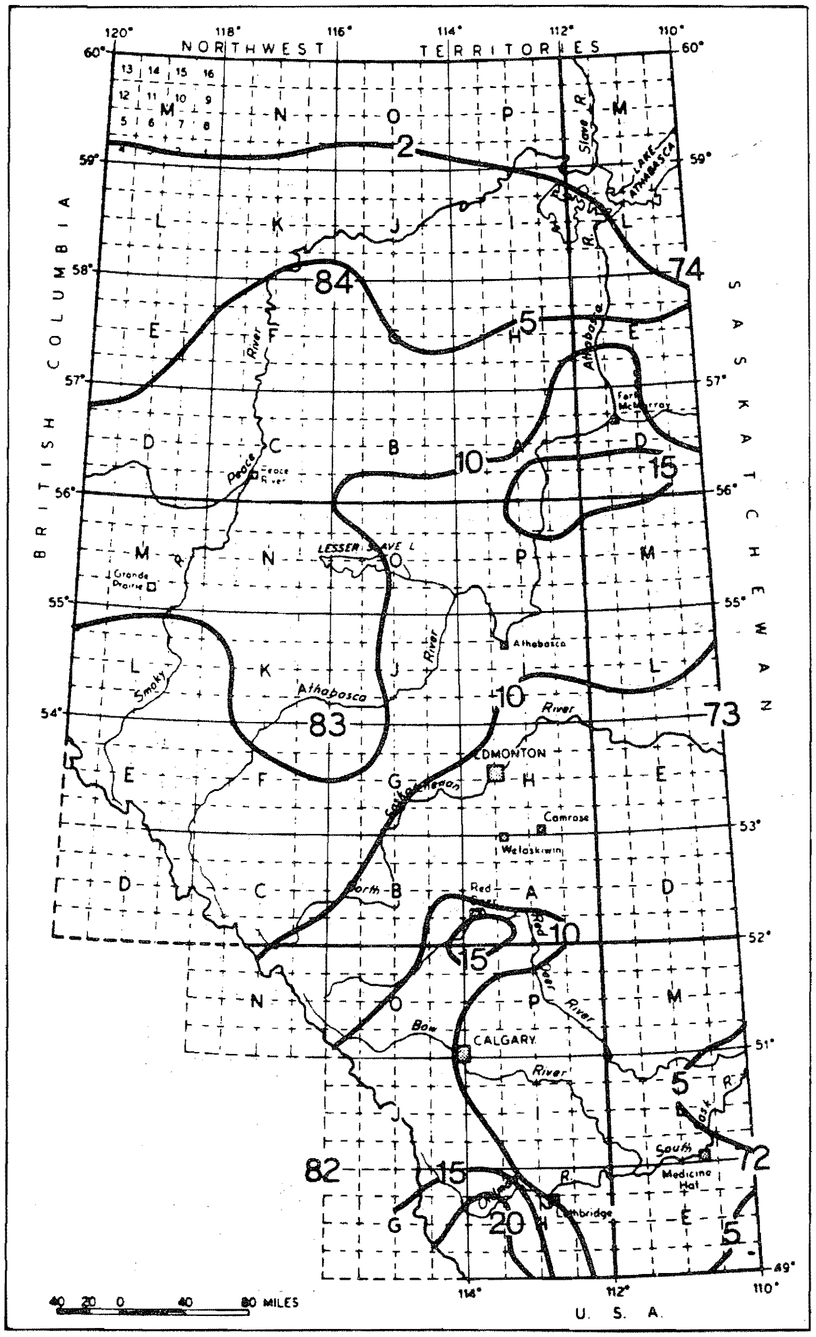

Figure 67 Number of occurrences of rainstorms in September with depths 50 mm and more in 100 years.

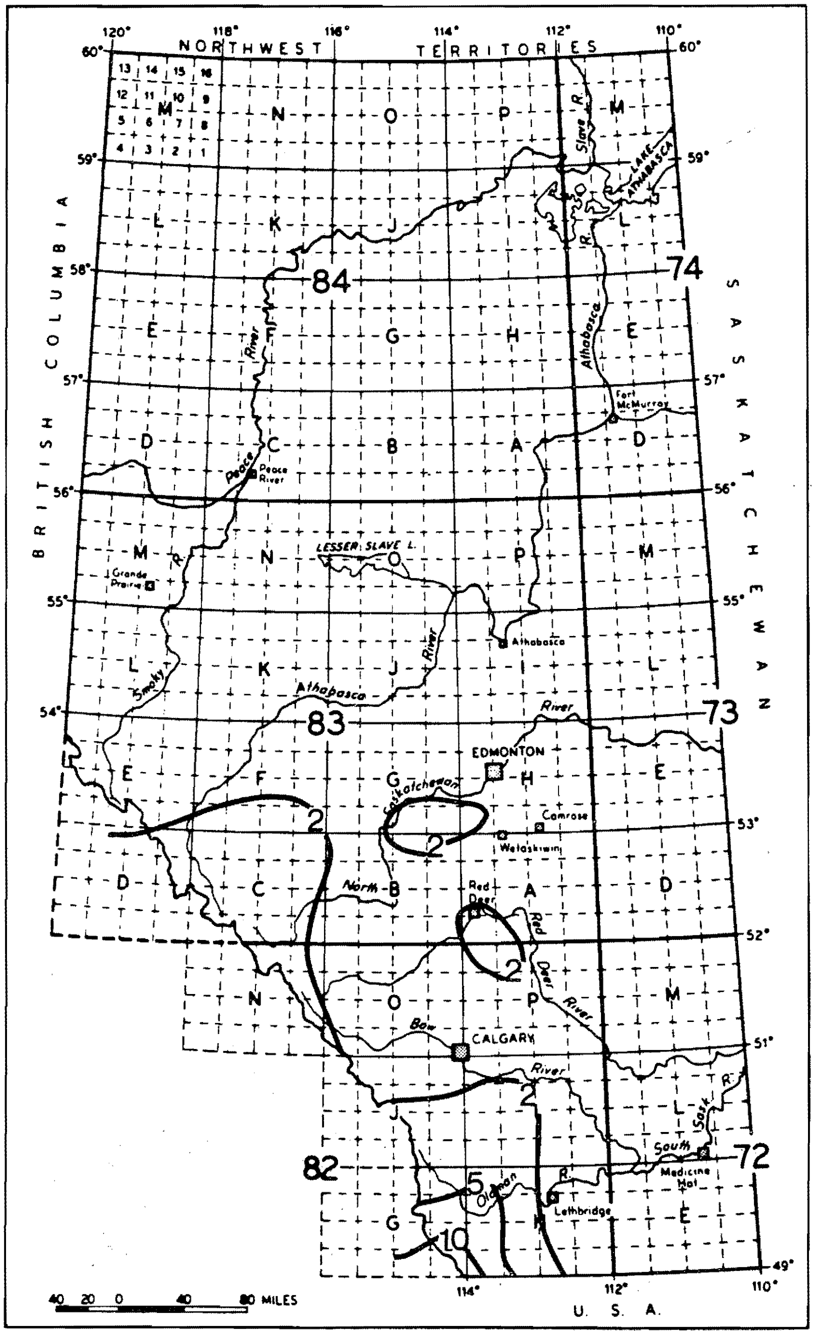

Figure 68 Number of occurrences of rainstorms in April with depths 100 mm and more in 100 years.

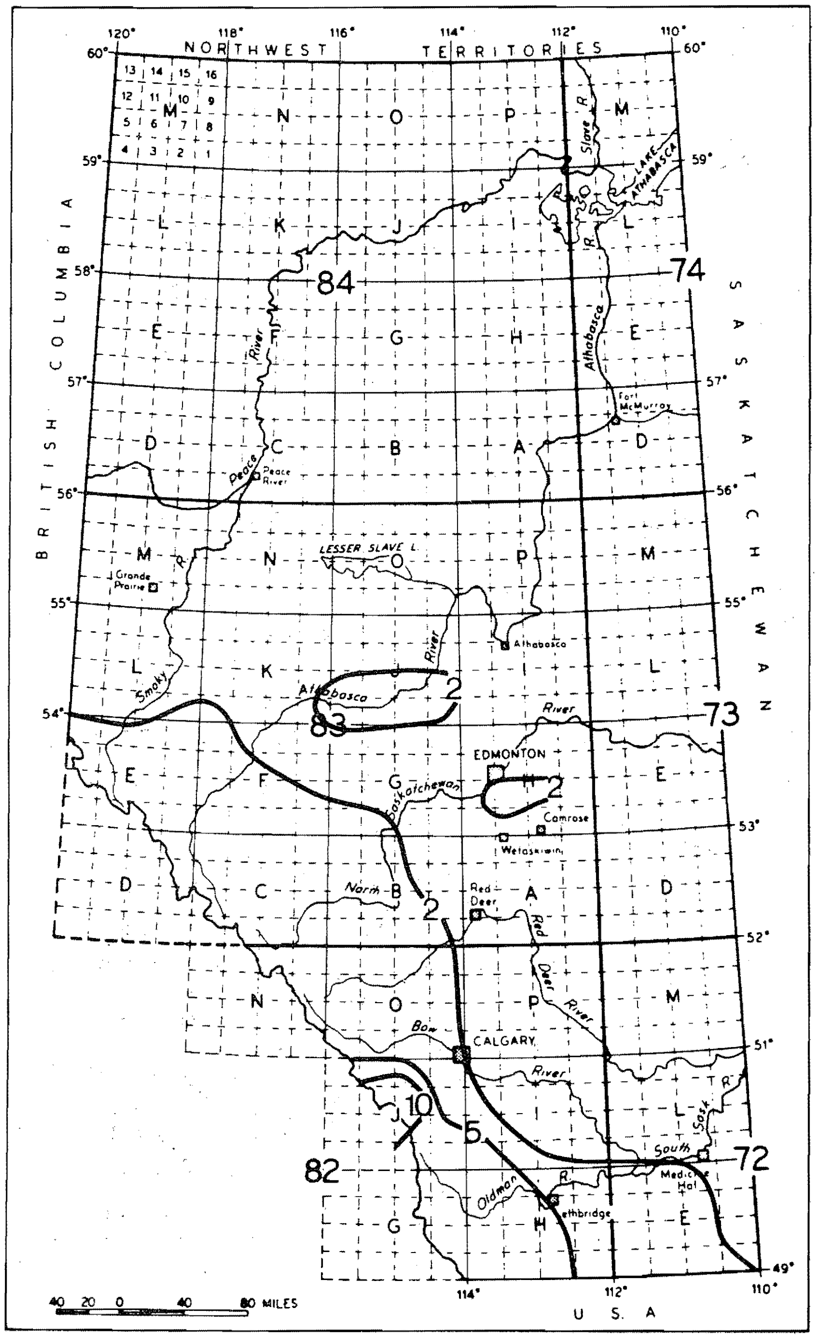

Figure 69 Number of occurrences of rainstorms in May with depths 100 mm and more in 100 years.

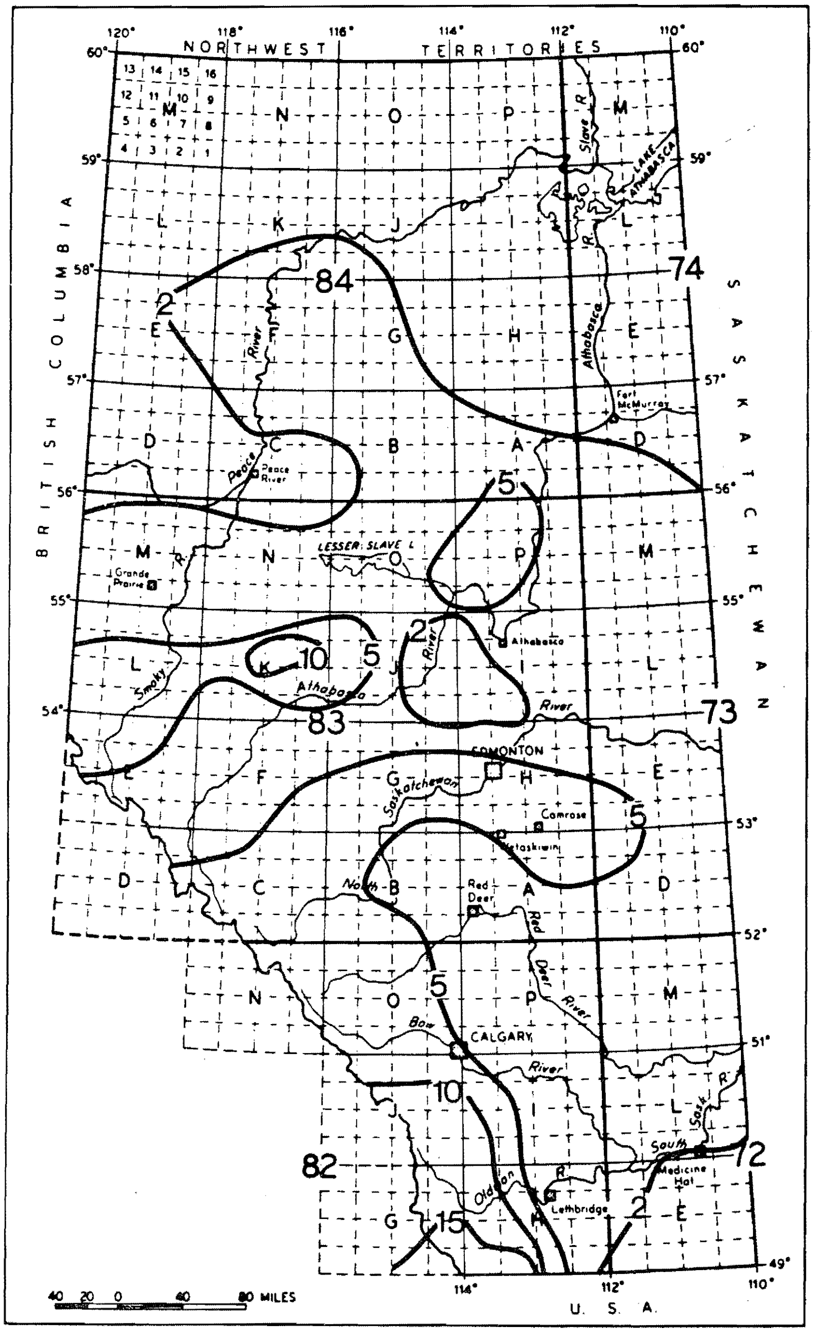

Figure 70 Number of occurrences of rainstorms in June with depths 100 mm and more in 100 years.

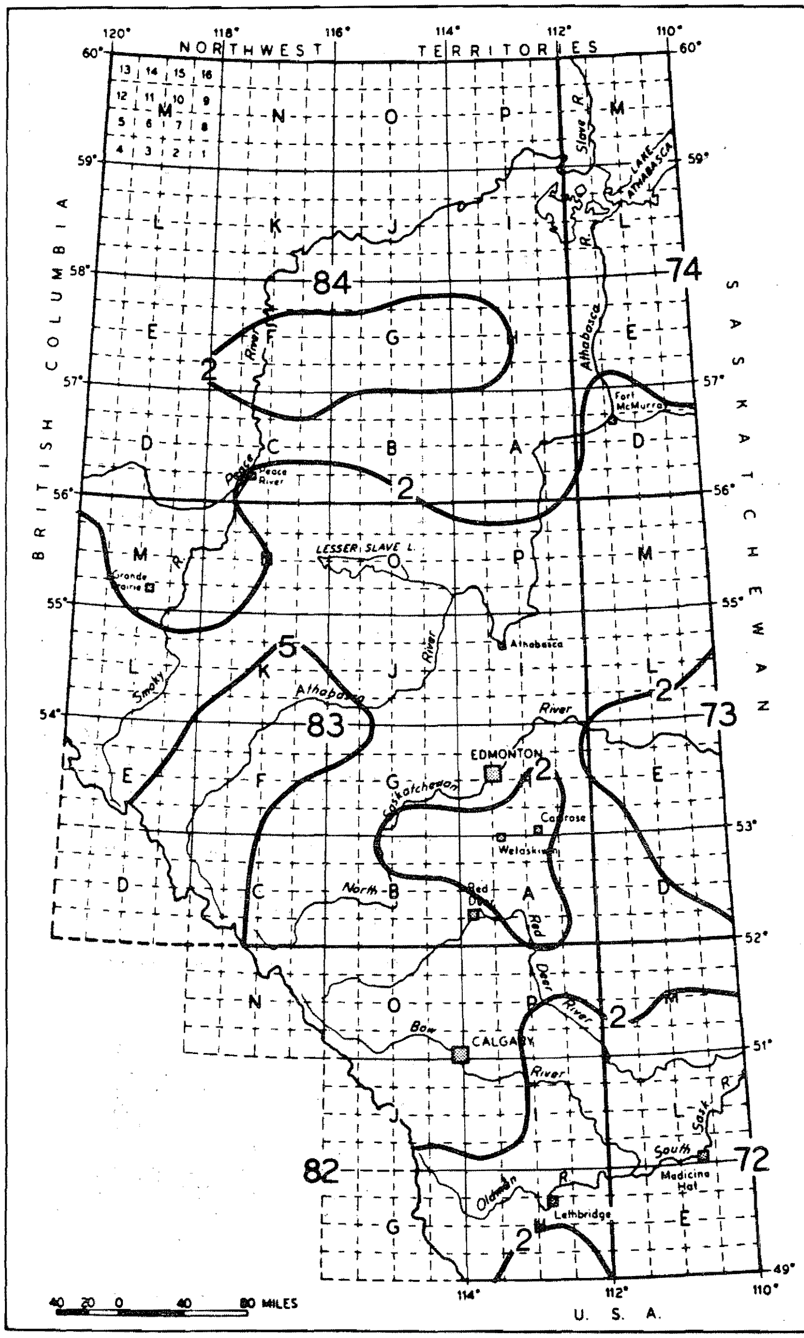

Figure 71 Number of occurrences of rainstorms in July with depths 100 mm and more in 100 years.

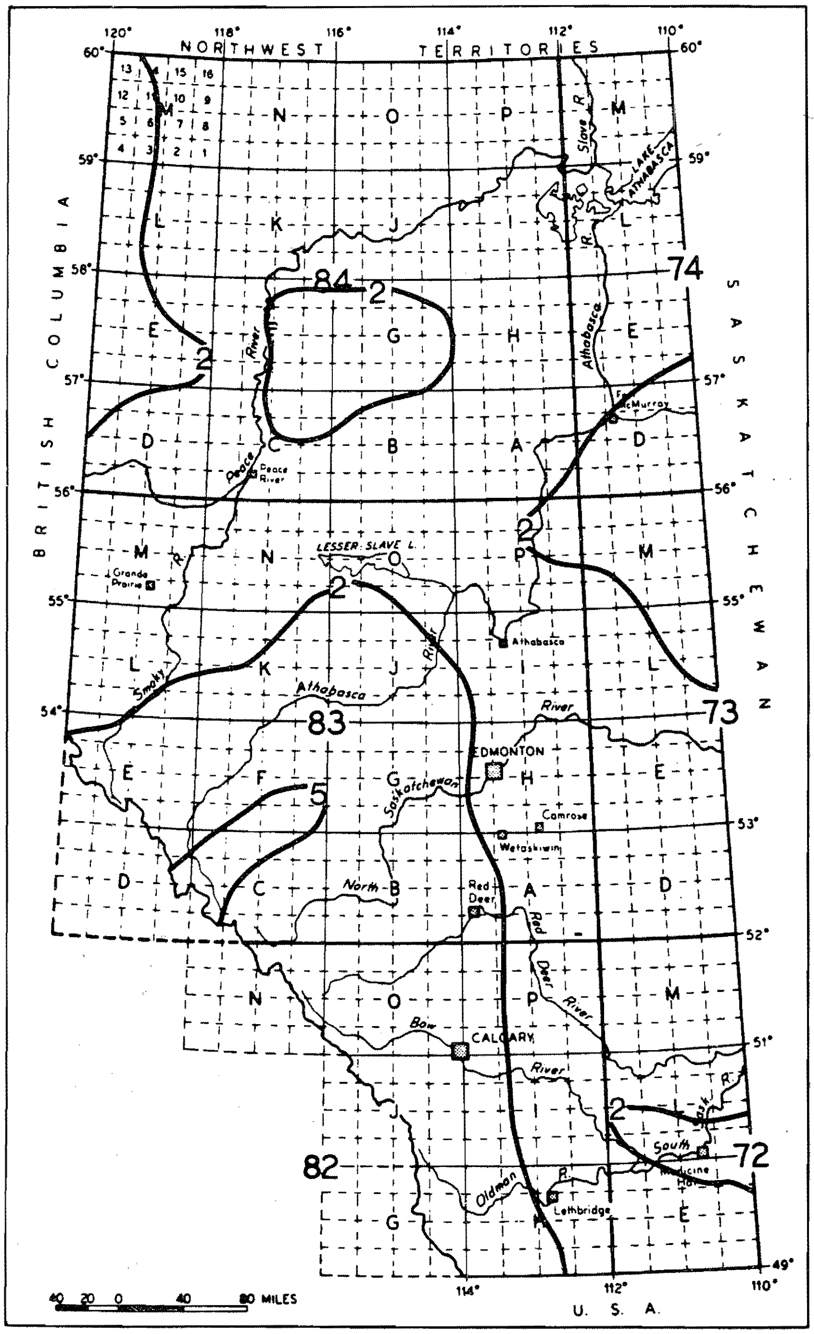

Figure 72. Number of occurrences of rainstorms in August with depths 100 mm and more in 100 years.

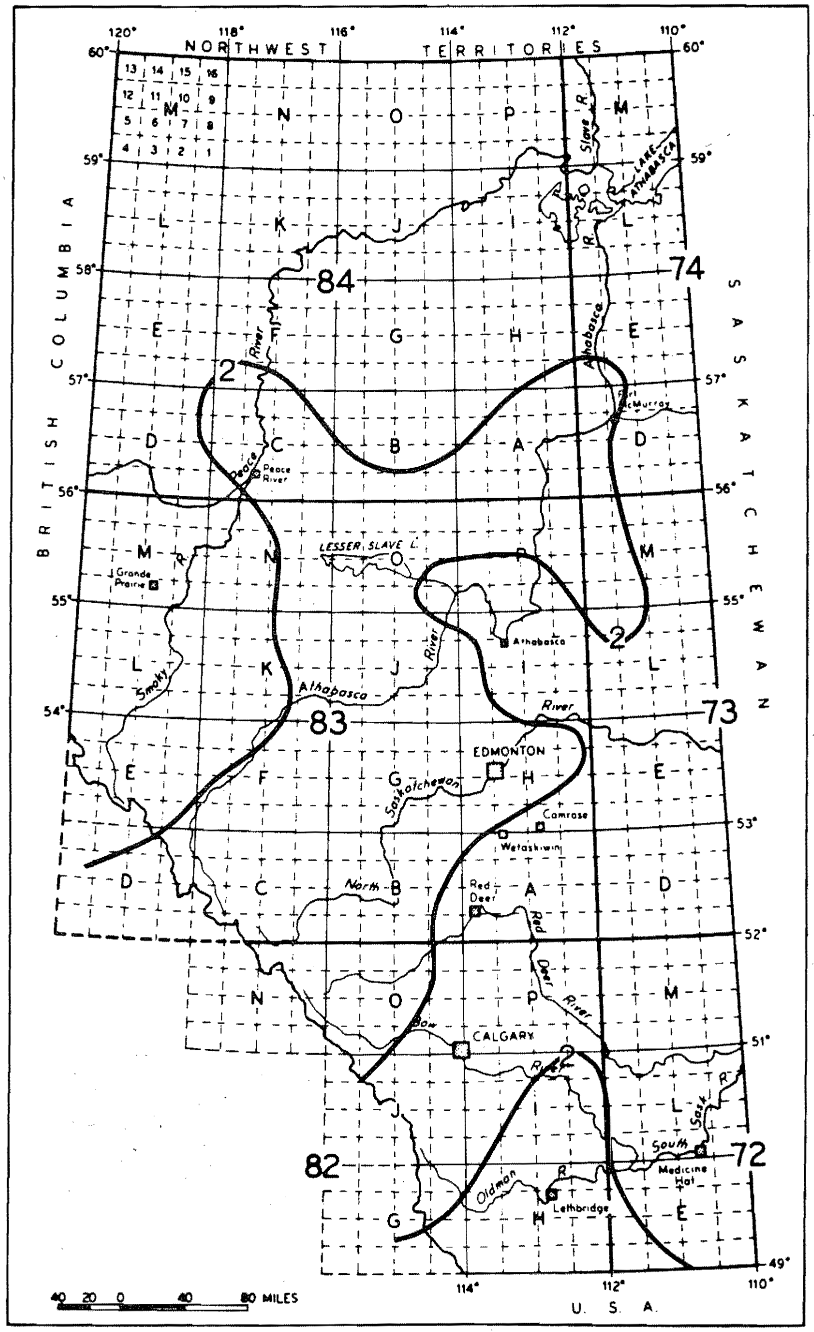

Figure 73 Number of occurrences of rainstorms in September with depths 100 mm and more in 100 years.

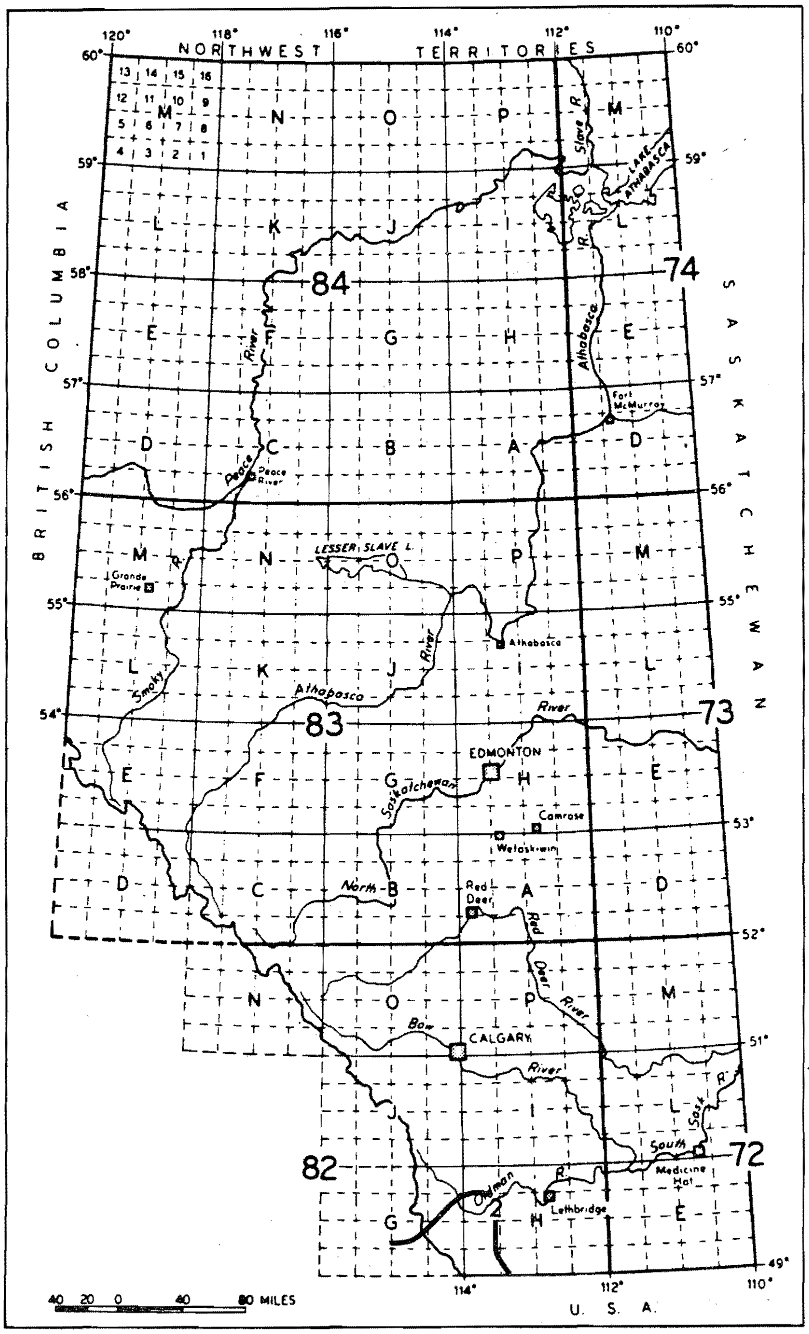

Figure 74 Number of occurrences of rainstorms in April with depths 150 mm and more in 100 years.

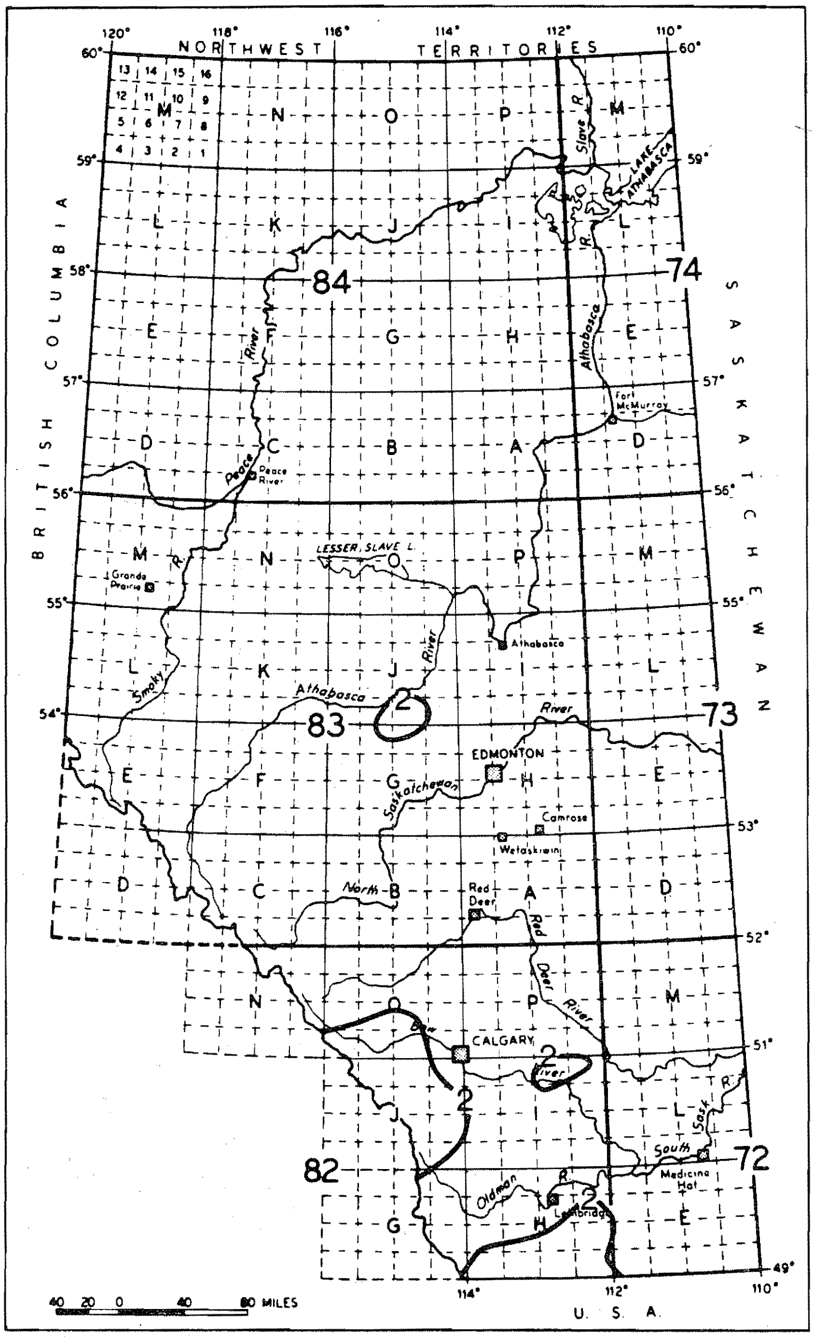

Figure 75 Number of occurrences of rainstorms in May with depths 150 mm and more in 100 years.

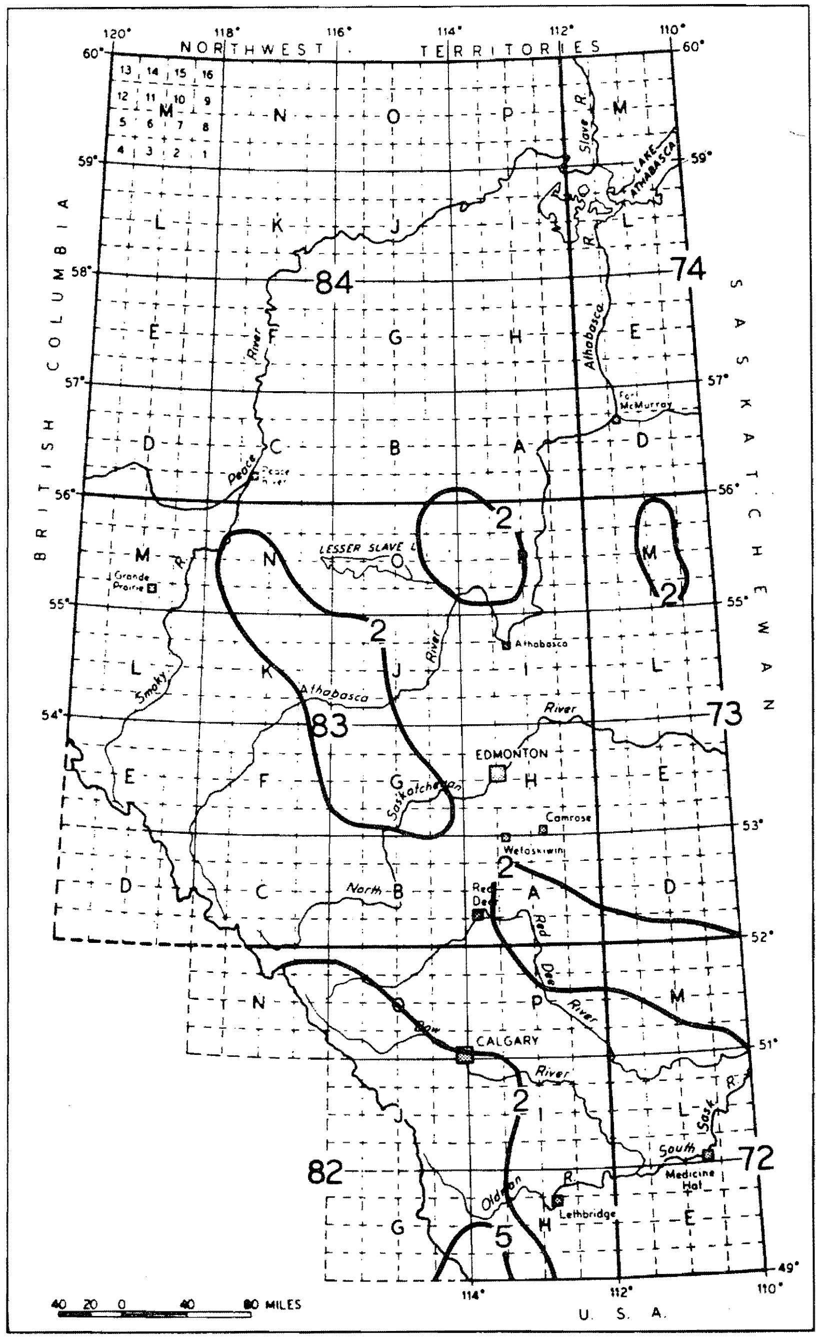

Figure 76 Number of occurrences of rainstorms in June with depths 150 mm and more in 100 years.

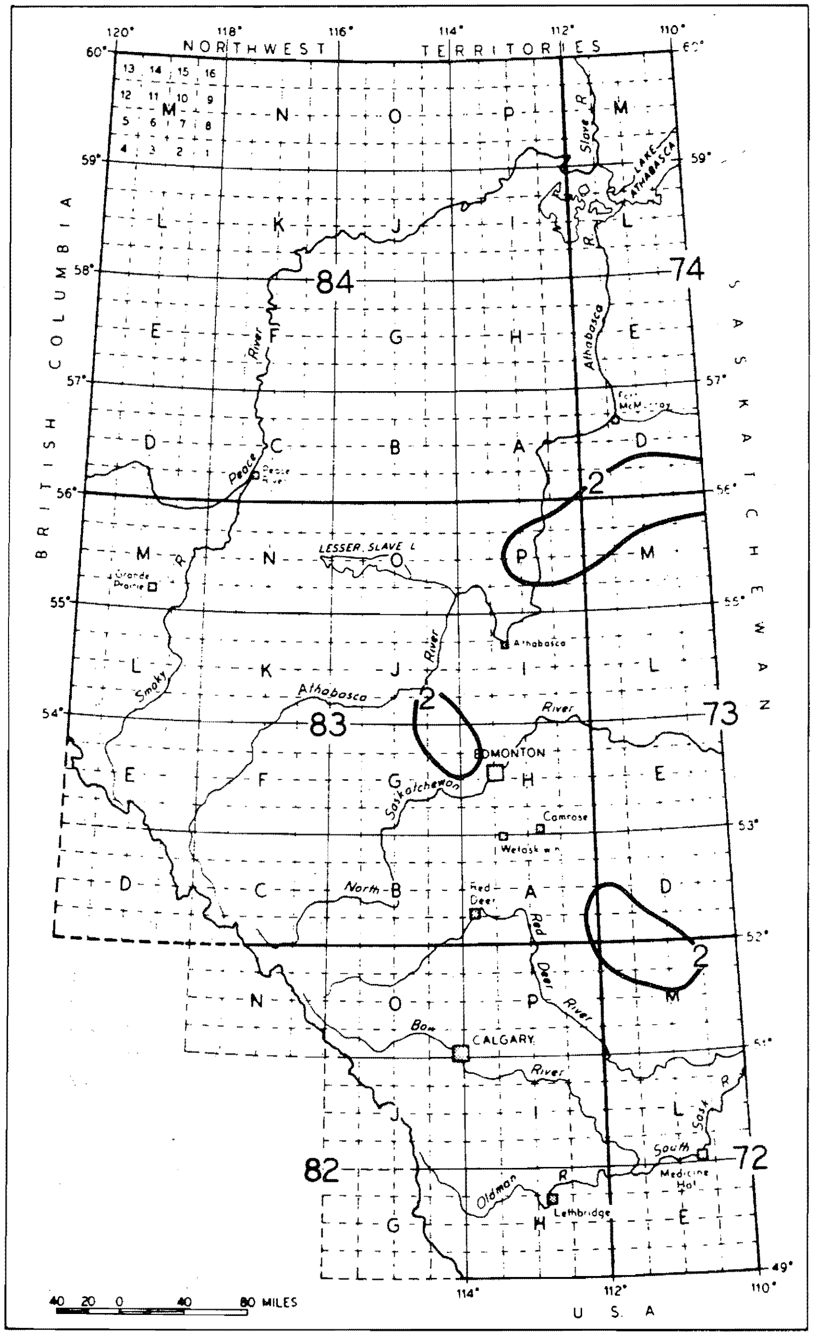

Figure 77 Number of occurrences of rainstorms in July with depths 150 mm and more in 100 years.

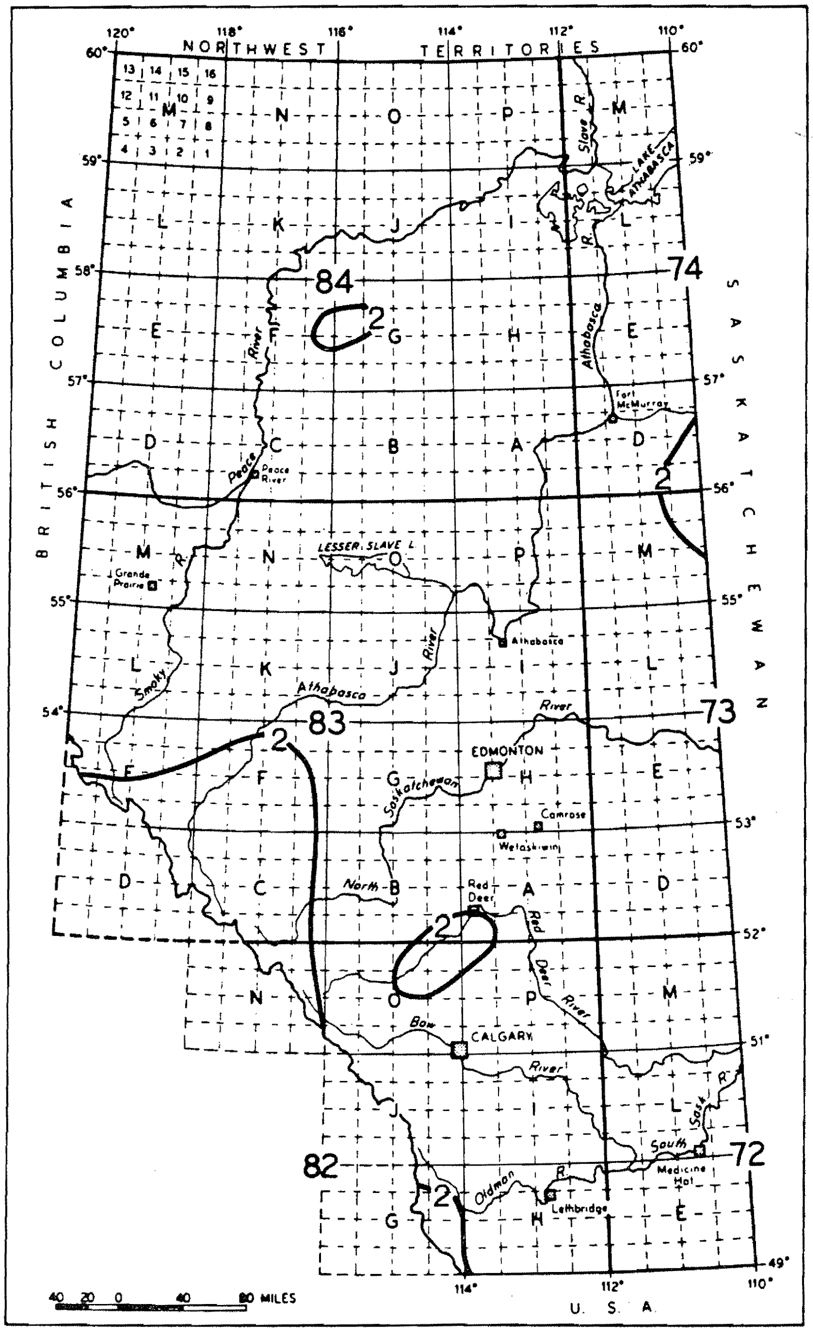

Figure 78 Number of occurrences of rainstorms in August with depths 150 mm and more in 100 years.

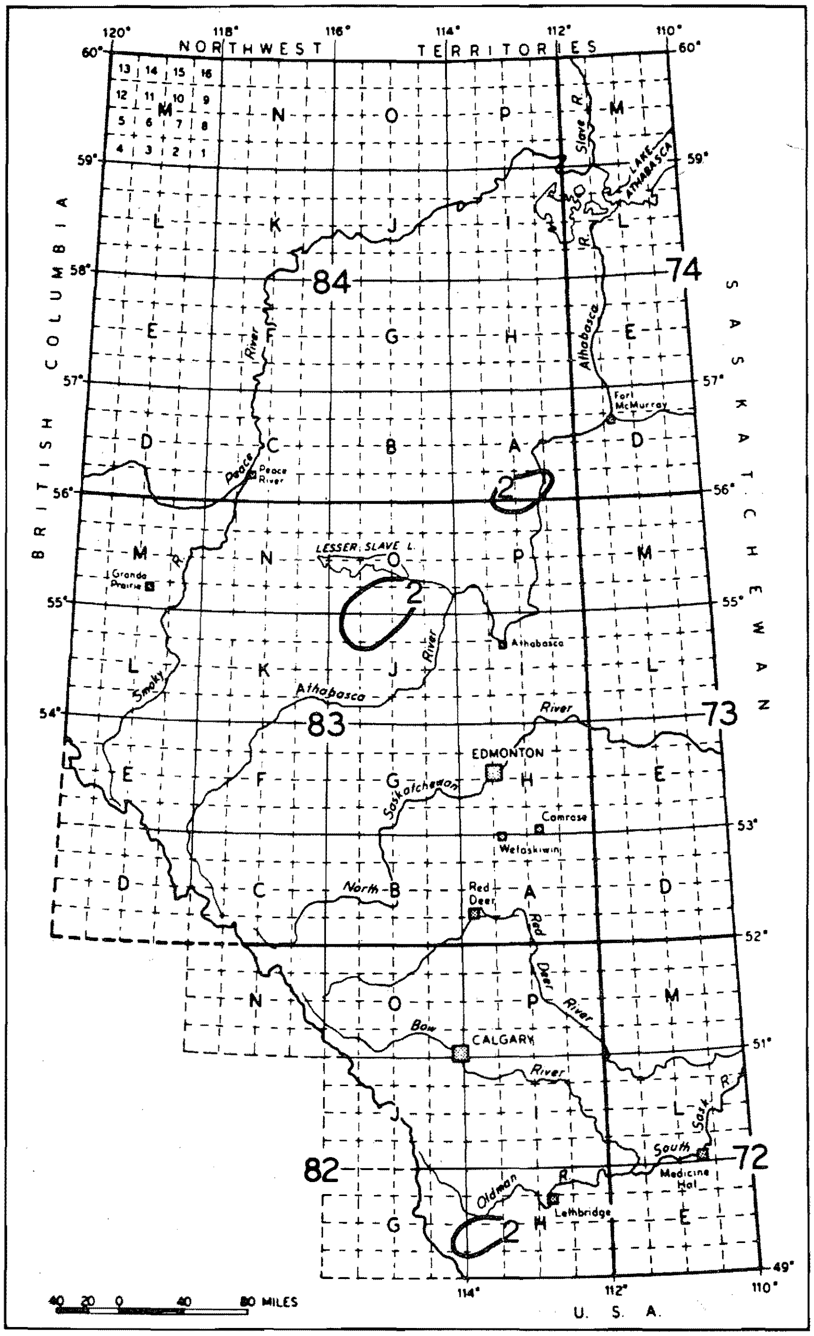

Figure 79 Number of occurrences of rainstorms in September with depths 150 mm and more in 100 years.

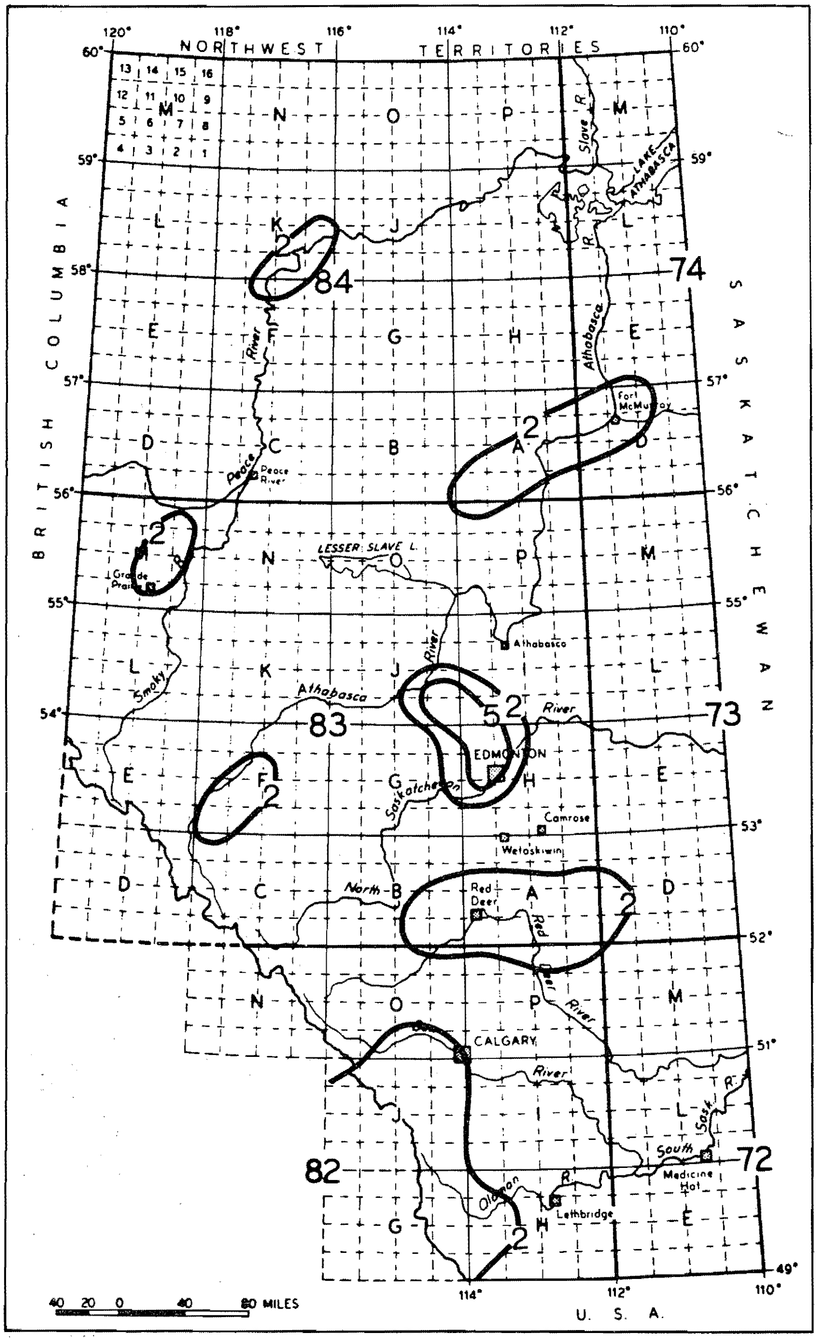

Figure 80 Spatial distribution storm-station density ratio from 1921 to 1930.

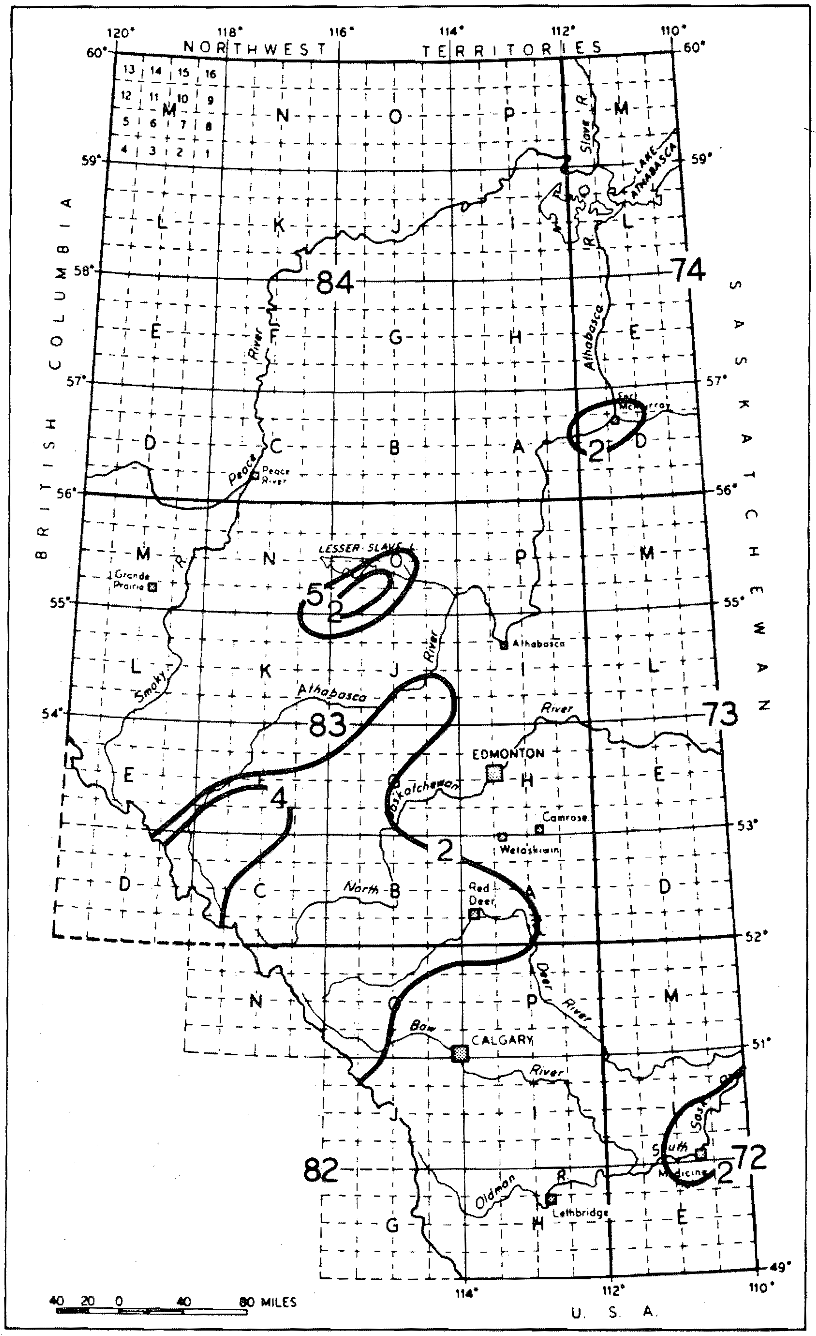

Figure 81 Spatial distribution storm-station density ratio from 1931 to 1940.

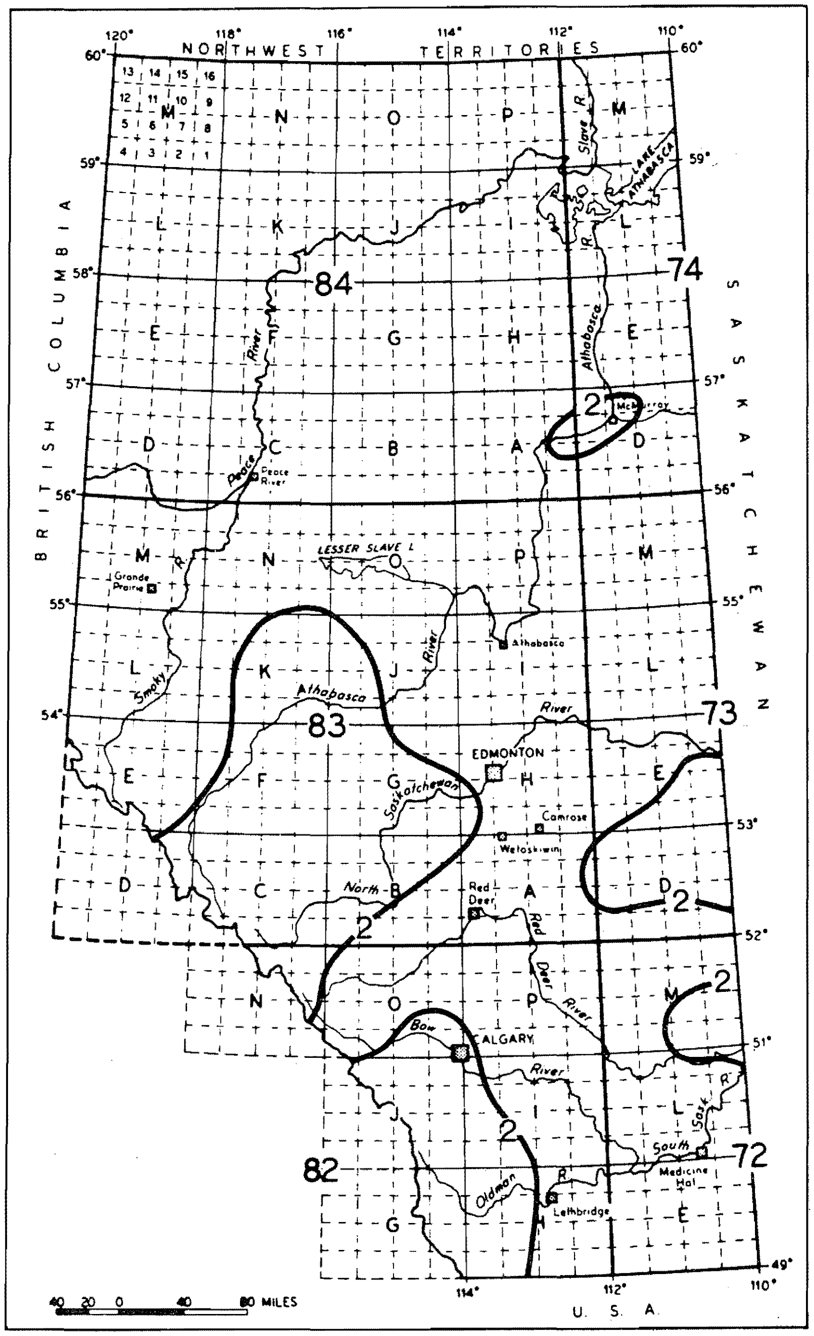

Figure 82 Spatial distribution storm-station density ratio from 1941 to 1950.

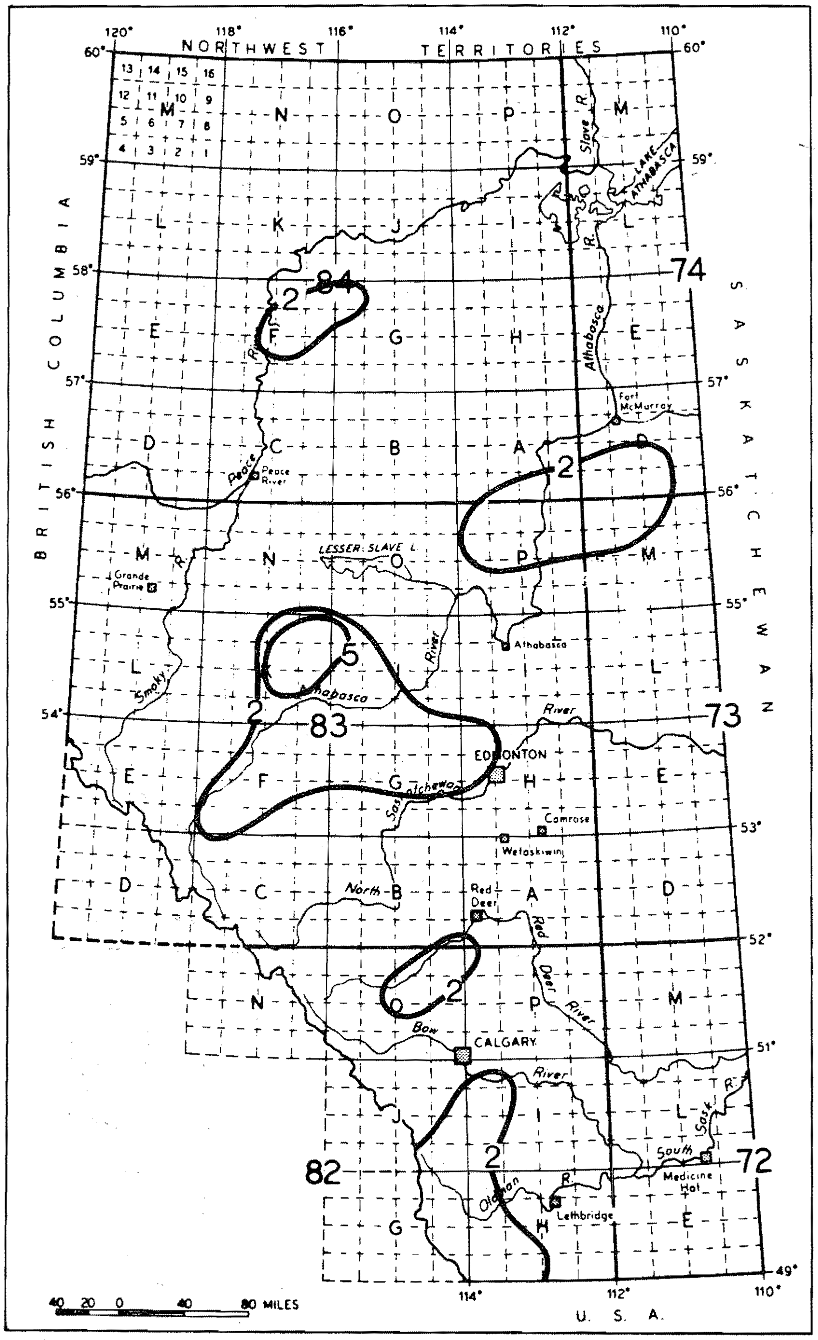

Figure 83 Spatial distribution storm-station density ratio from 1951 to 1960.

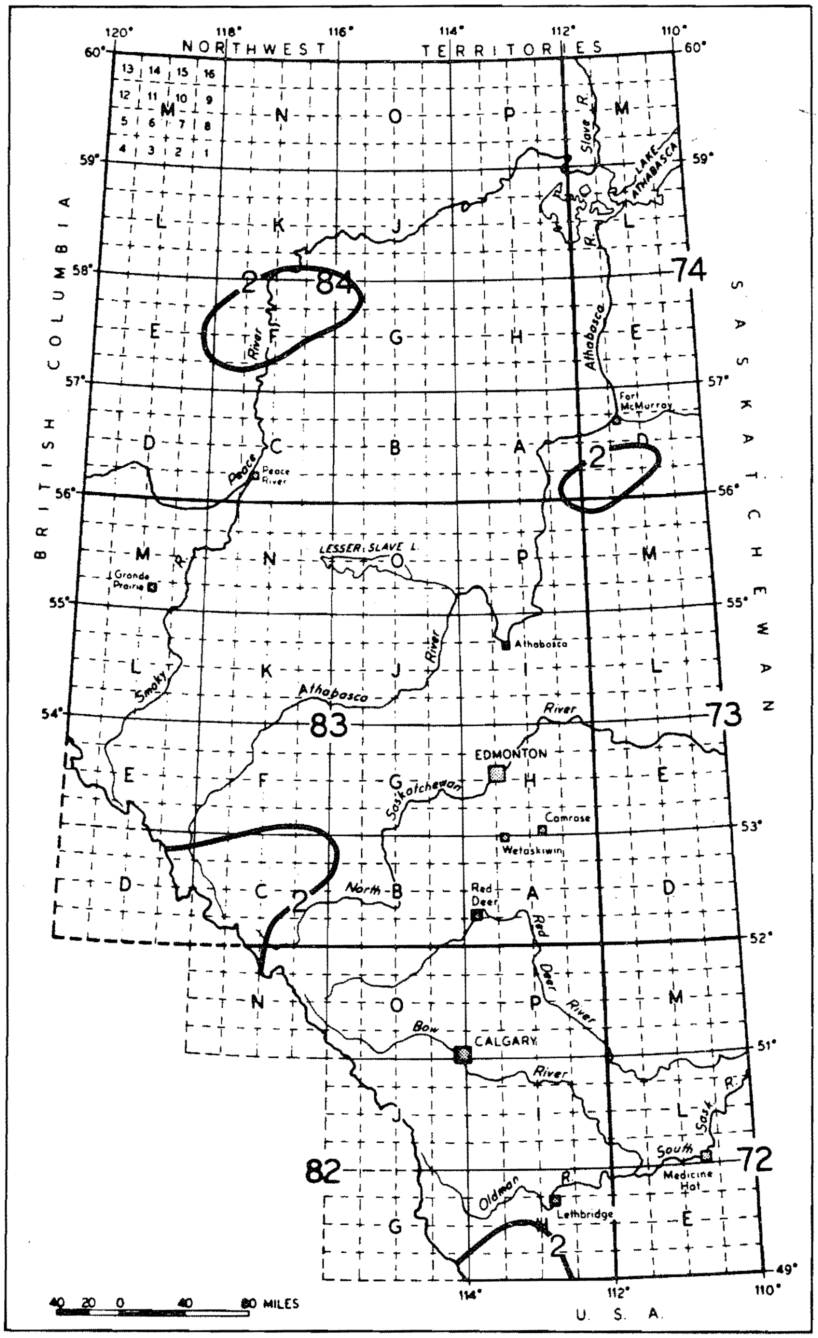

Figure 84 Spatial distribution storm-station density ratio from 1961 to 1970.

8.3 DEW POINT AND MAXIMIZED DEPTH-AREA-DURATION CURVES

This appendix contains tables and figures used in estimating the PMP by the physical approach. Tables 5 and 6 show precipitable water amount in a saturated pseudoadiabatic atmosphere. Table 5 presents values of precipitable water (mm) between the 1 000 mb surface and various pressure levels up to 300 mb in a saturated pseudoadiabatic atmosphere as a function of the 1 000 mb dew point temperature. Table 6 lists similar values for layers between the 1 000 mb surface, assumed to be at zero elevation, and various heights up to 8 km.

Figures 85 to 100 give the maximum recorded persisting 12-hour 1 000 mb dew point temperatures for 15 first-order weather stations in Alberta. The stations are given in alphabetical order. Figures 101 to 106 give the monthly spatial variation of the maximum recorded persisting 12-hour 1 000 mb dew point temperatures from April to September. Figures 107 to 142 give the maximized DAD curves for 6-, 12-, 48-, 72-, and 96-hour PMP for each of the six basins. Figures 143 to 173 give the envelope of the DAD curves of the estimated PMP for the six basins for each month (April to September).

Table 5 Precipitable water (mm) between 1 000 mb surface and indicated pressure (mb) in a saturated pseudo-adiabatic atmosphere as a function of the 1 000 mb dew point (°C).

°C

mb	2	4	6	8	10	12	13	14	15	16	17	18	19	20	21	22	23	24
990	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2
980	1	1	1	1	1	2	2	2	2	2	2	2	3	3	3	3	3	4
970	1	1	2	2	2	3	3	3	3	3	4	4	4	4	5	5	5	5
960	2	2	2	3	3	3	4	4	4	4	5	5	5	6	6	6	7	7
950	2	2	3	3	4	4	4	5	5	6	6	6	7	7	8	8	9	9
940	2	3	3	4	4	5	5	6	6	7	7	7	8	9	9	10	10	11
930	3	3	4	4	5	6	6	7	7	8	8	9	9	10	11	11	12	13
920	3	4	4	5	6	7	7	8	8	9	9	10	10	11	12	13	14	14
910	3	4	5	5	6	7	8	9	9	10	10	11	12	13	13	14	15	16
900	4	4	5	6	7	8	9	9	10	11	11	12	13	14	15	16	17	18
890	4	5	6	7	8	9	9	10	11	12	12	13	14	15	16	17	18	20
880	4	5	6	7	8	9	10	11	12	12	13	14	15	16	17	19	20	21
870	5	6	7	8	9	10	11	12	13	13	14	15	16	18	19	20	21	23
860	5	6	7	8	9	11	12	12	13	14	15	16	18	19	20	21	23	24
850	5	6	7	9	10	11	12	13	14	15	16	18	19	20	21	23	24	26
840	6	7	8	9	10	12	13	14	15	16	17	19	20	21	23	24	26	28
830	6	7	8	9	11	13	14	15	16	17	18	19	21	22	24	26	27	29
820	6	7	8	10	11	13	14	15	17	18	19	20	22	24	25	27	29	31
810	6	8	9	10	12	14	15	16	17	19	20	21	23	25	26	28	30	32
800	7	8	9	11	12	15	16	17	18	19	21	22	24	26	28	29	32	34
780	7	8	10	11	13	16	17	18	19	21	23	24	26	28	30	32	34	37
760	7	9	10	12	14	17	18	19	21	22	24	26	28	30	32	34	37	39
740	8	9	11	13	15	18	19	20	22	24	26	28	30	32	34	37	39	42
720	8	10	11	13	16	18	20	22	23	25	27	29	31	34	36	39	42	45
700	8	10	12	14	16	19	21	23	24	26	28	31	33	35	38	41	44	47
680	9	10	12	15	17	20	22	24	25	27	30	32	34	37	40	43	46	49
660	9	11	13	15	18	21	23	24	26	29	31	33	36	39	42	45	48	52
640	9	11	13	15	18	21	23	25	27	29	32	35	37	40	43	46	50	54
620	9	11	13	16	19	22	24	26	28	30	33	36	38	42	45	48	52	56
600	9	11	13	16	19	23	25	27	29	31	34	37	40	43	46	50	54	58
580	10	11	14	16	19	23	25	27	30	32	36	38	41	44	48	51	55	60
560	10	12	14	17	20	23	26	28	30	33	36	39	42	45	49	53	57	61
540	10	12	14	17	20	24	26	28	31	33	36	39	43	46	50	54	58	63
520	10	12	14	17	20	24	26	29	31	34	37	40	43	47	51	55	60	64
500	10	12	14	17	20	24	27	29	32	34	37	41	44	48	52	56	61	66
400	10	12	15	18	21	25	28	30	33	36	39	43	47	51	55	60	65	71
300	10	12	15	18	21	25	28	30	33	36	40	44	48	52	57	62	67	71

Table 6 Precipitable water (mm) between 1 000 mb surface and indicated height (m) above that surface in a saturated pseudo-adiabatic atmosphere as a function of the 1 000 mb dew point (°C).

	°C															
(m)	2	4	6	8	10	12	14	15	16	17	18	19	20	21	22	23
200	1	1	1	2	2	2	2	2	3	3	3	3	3	4	4	4
400	2	2	3	3	4	4	5	5	5	5	6	6	6	7	7	8
600	3	3	4	5	5	6	7	7	7	8	8	9	10	10	11	11
800	4	4	5	6	7	8	9	9	10	10	11	12	13	13	14	15
1000	4	5	6	7	8	9	10	11	12	13	13	14	15	16	17	18
1200	5	6	7	8	9	11	12	13	14	15	16	17	18	19	20	21
1400	6	7	8	9	10	12	14	15	16	17	18	19	20	22	23	24
1600	6	7	9	10	11	13	15	16	17	19	20	21	23	24	25	27
1800	7	8	9	11	12	14	17	18	19	20	22	23	25	26	28	30
2000	7	9	10	11	13	16	18	19	21	22	24	25	27	29	31	33
2200	8	9	10	12	14	16	19	20	22	24	25	27	29	31	33	35
2400	8	9	11	13	15	17	20	22	23	25	27	29	31	33	35	37
2600	8	10	11	13	16	18	21	23	24	26	28	30	32	35	37	40
2800	9	10	12	14	16	19	22	24	26	27	30	32	34	36	39	42
3000	9	10	12	14	17	20	23	25	27	29	31	33	35	38	41	44
3200	9	11	13	15	17	20	24	26	28	30	32	34	37	40	42	45
3400	9	11	13	15	18	21	24	26	29	31	33	36	38	41	44	47
3600	9	11	13	15	18	22	25	27	29	32	34	37	39	42	45	49
3800	10	11	13	16	19	22	26	28	30	32	35	38	41	44	47	50
4000	10	11	14	16	19	22	26	28	31	33	36	39	42	45	48	52
4200	10	12	14	16	19	23	27	29	31	34	37	40	43	46	49	53
4400	10	12	14	16	20	23	27	29	32	34	37	40	44	47	51	54
4600	10	12	14	17	20	24	28	30	32	35	38	41	44	48	52	56
4800	10	12	14	17	20	24	28	30	33	36	39	42	45	49	53	57
5000	10	12	14	17	20	24	28	31	33	36	39	42	46	50	54	58
5200	10	12	14	17	20	24	29	31	34	37	40	43	47	50	54	59
5400	10	12	14	17	20	24	29	31	34	37	40	44	47	51	55	60
5600	10	12	14	17	21	24	29	32	35	38	41	44	48	52	56	60
5800	10	12	14	17	21	25	29	32	35	38	41	45	48	52	57	61
6000	10	12	15	17	21	25	30	32	35	38	42	45	49	53	57	62
7000	10	12	15	18	21	25	30	33	36	39	43	46	51	55	60	65
8000	10	12	15	18	21	26	30	33	36	40	43	47	52	56	61	67

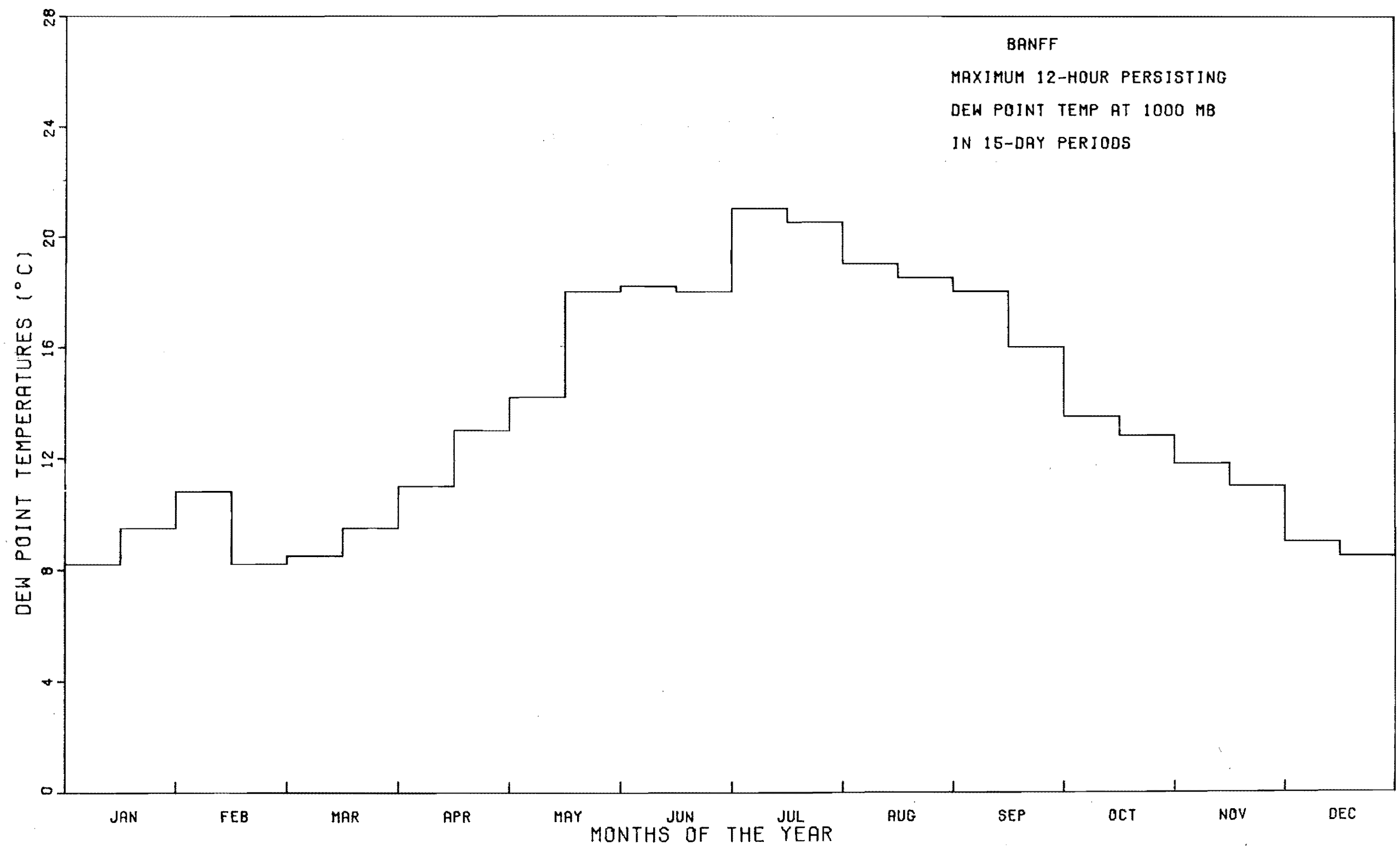

Figure 85 Maximum recorded persisting 12-hour 1000 mb dew point temperatures for Banff.

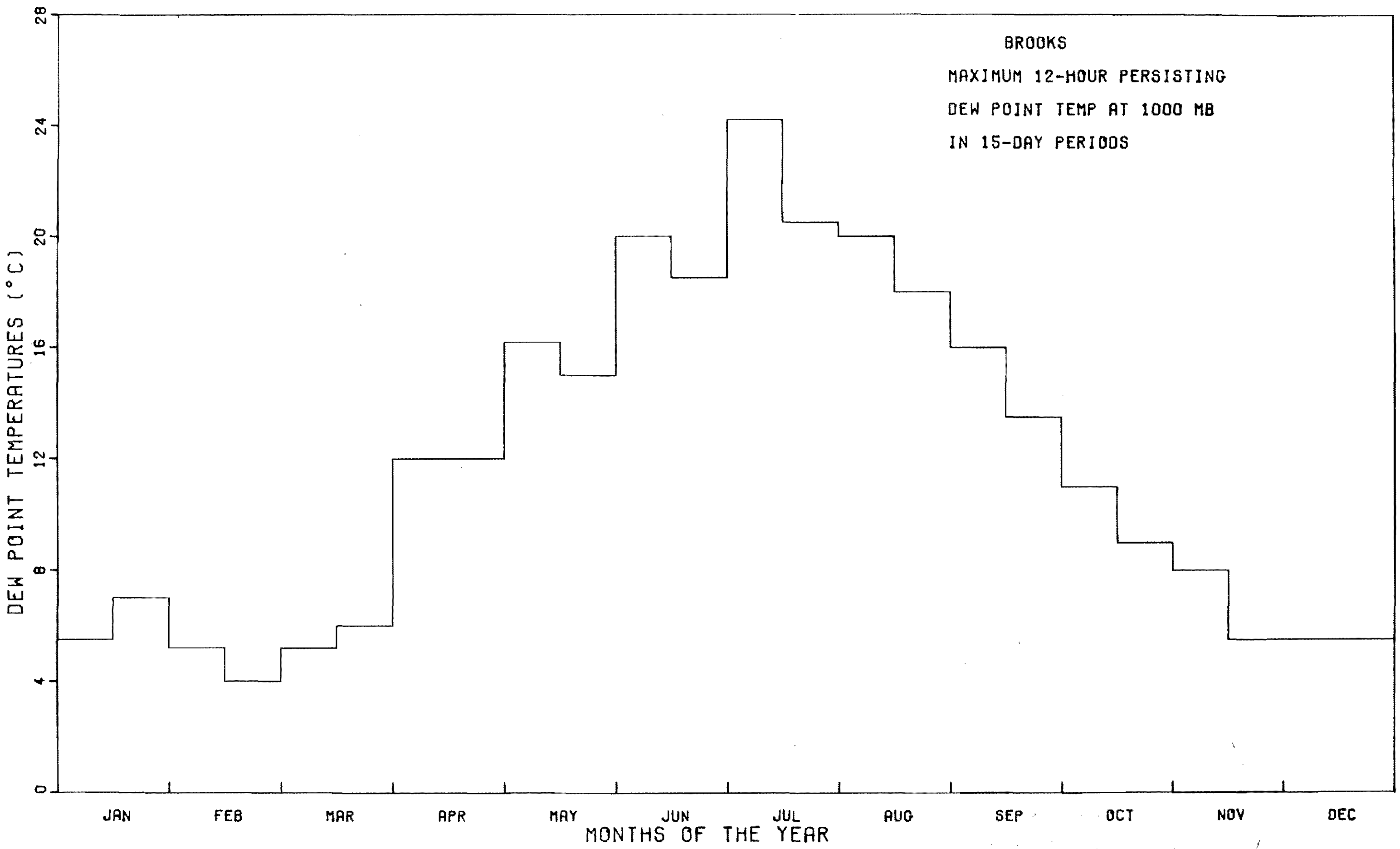

Figure 86 Maximum recorded persisting 12-hour 1 000 mb dew point temperatures for Brooks.

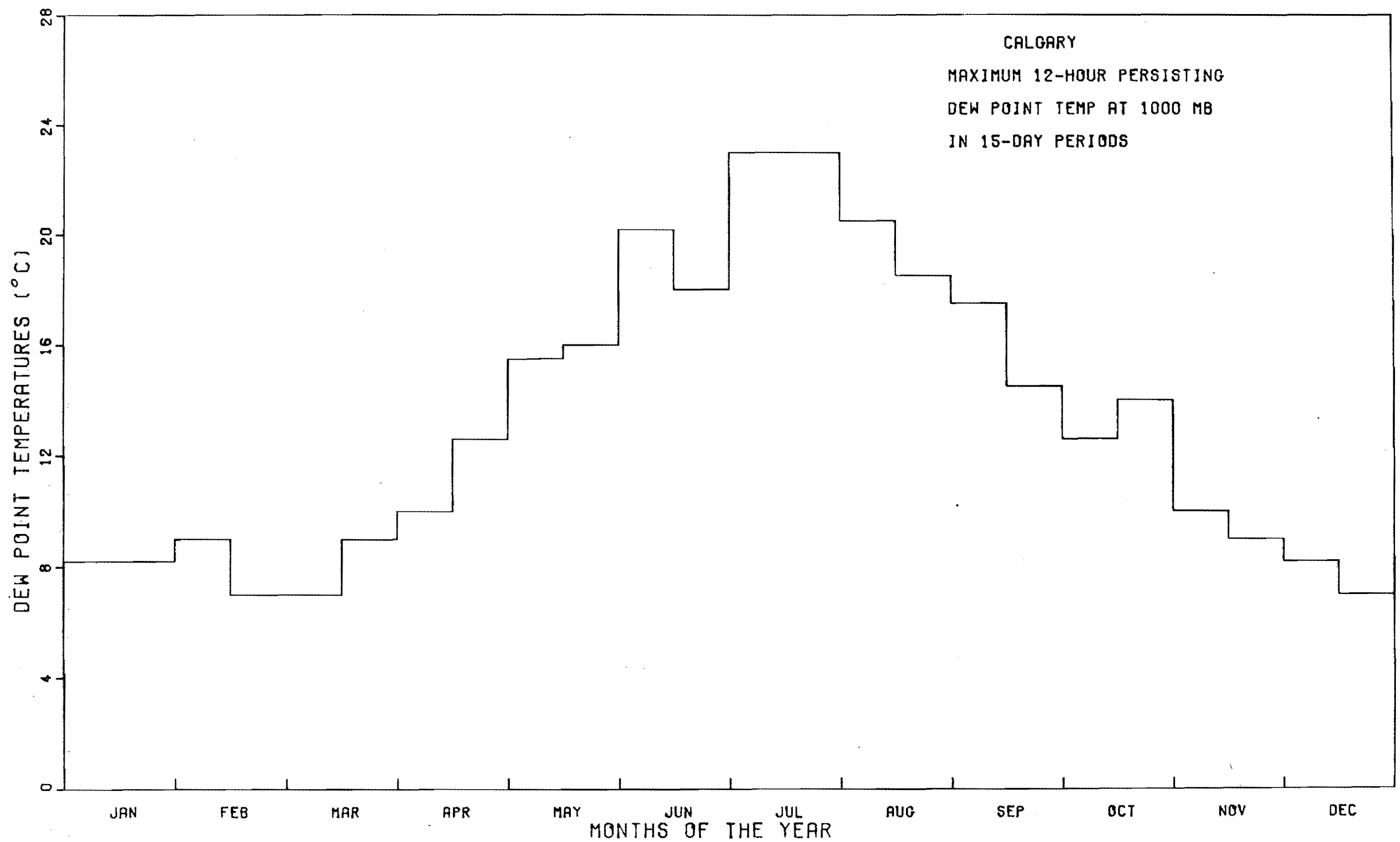

Figure 87 Maximum recorded persisting 12-hour 1 000 mb dew point temperatures for Calgary.

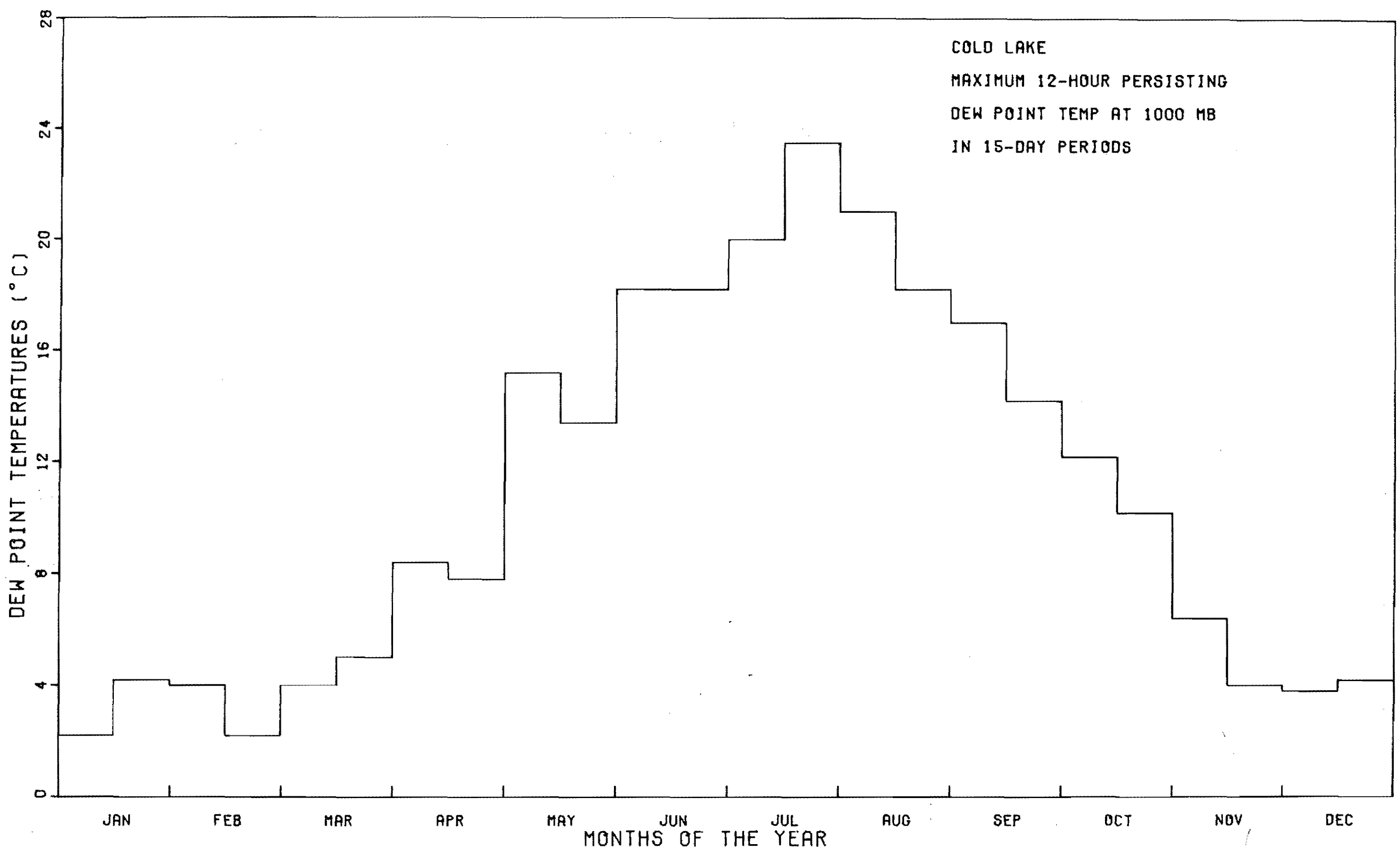

Figure 88 Maximum recorded persisting 12-hour 1 000 mb dew point temperatures for Cold Lake.

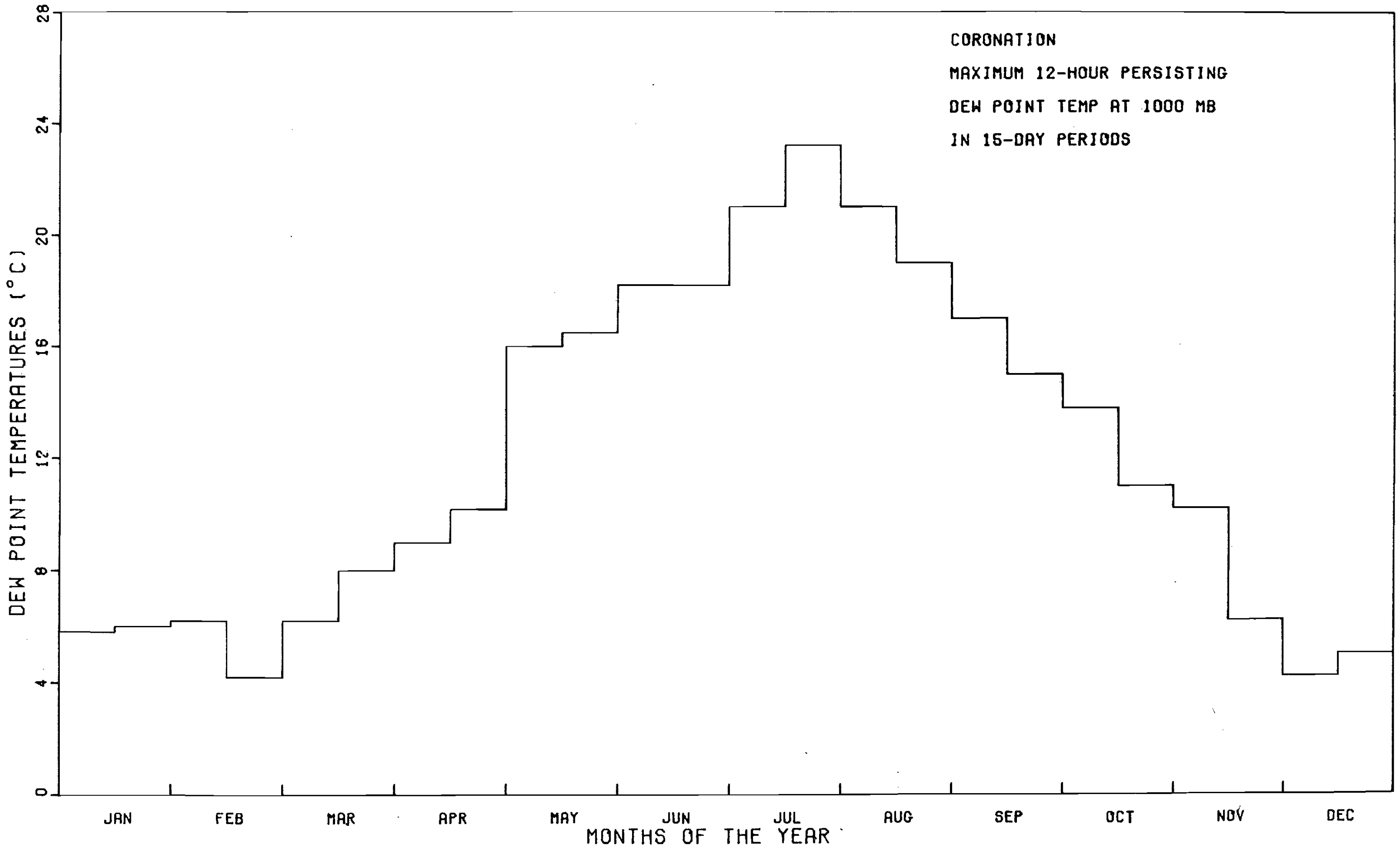

Figure 89 Maximum recorded persisting 12-hour 1 000 mb dew point temperatures for Coronation.

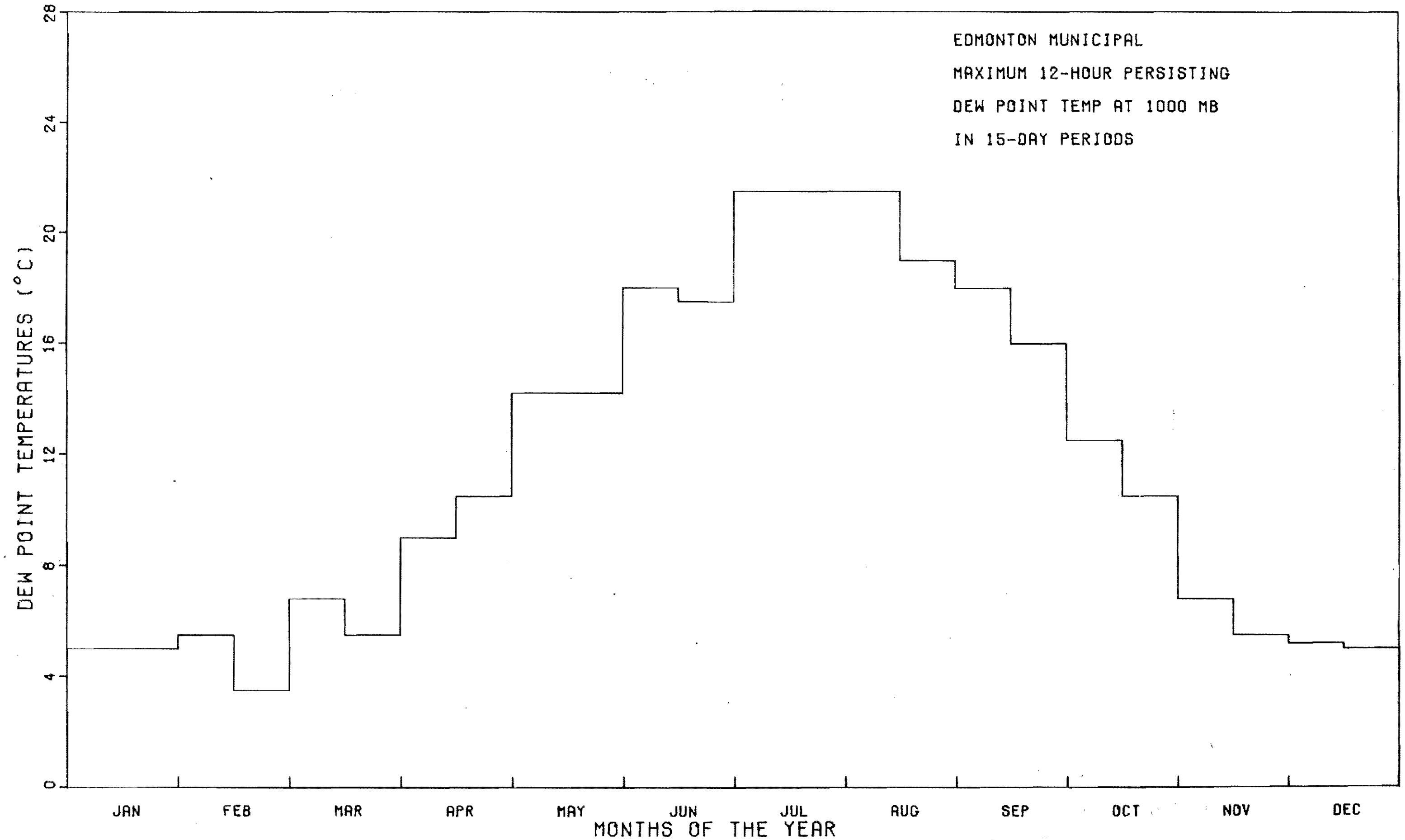

Figure 90 Maximum recorded persisting 12-hour 1 000 mb dew point temperatures for Edmonton Municipal.

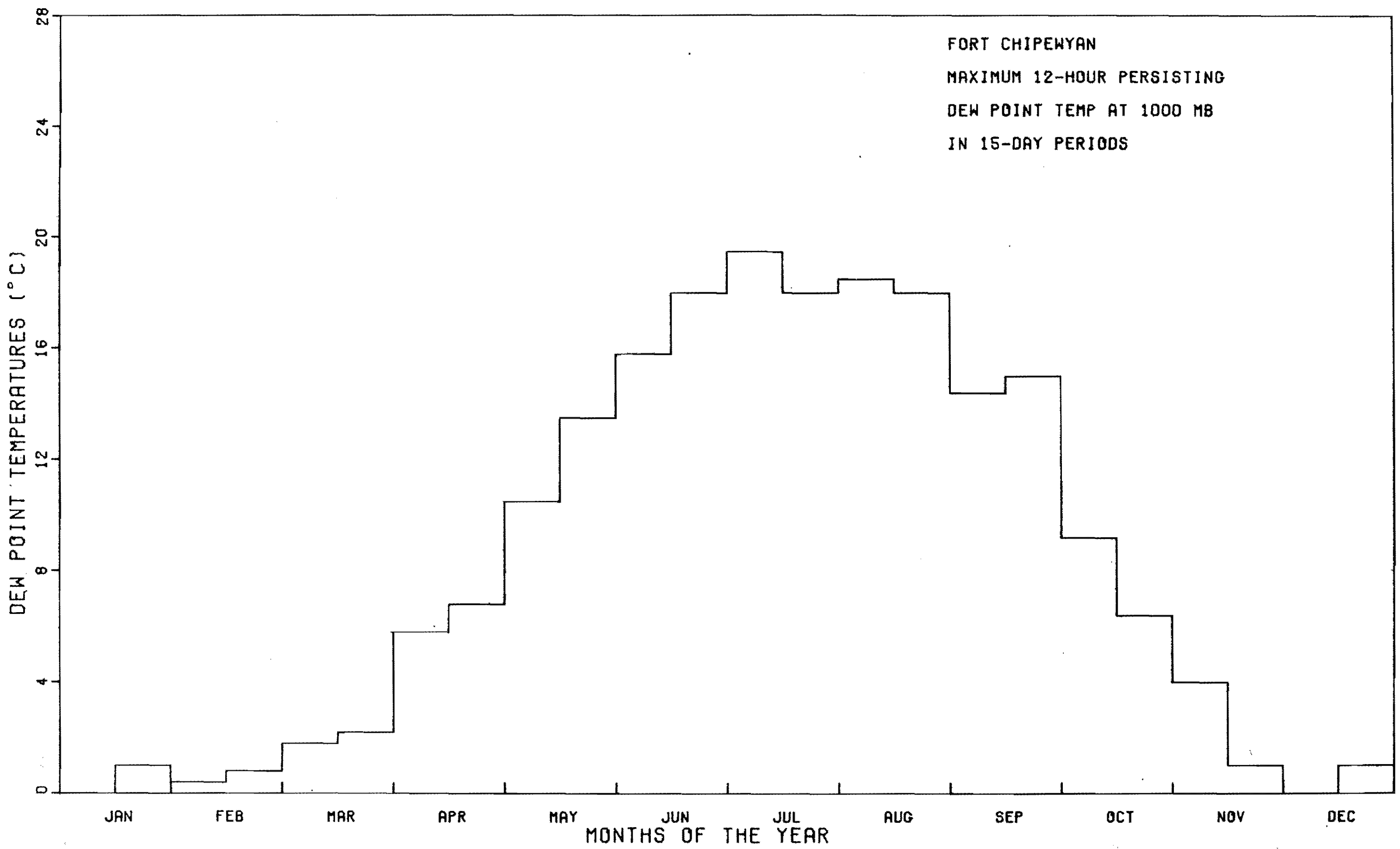

Figure 91 Maximum recorded persisting 12-hour 1 000 mb dew point temperatures for Fort Chipewyan.

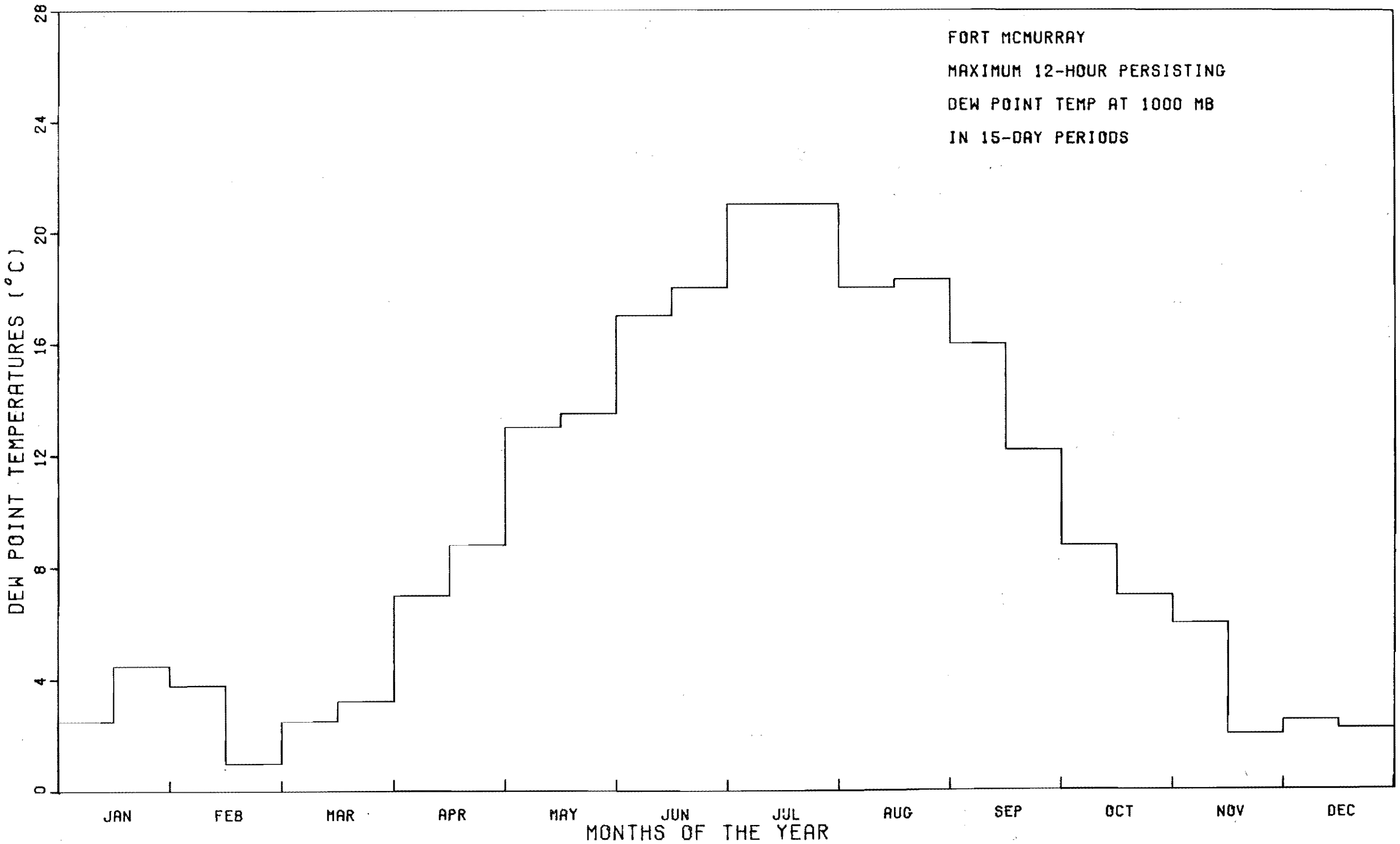

Figure 92 Maximum recorded persisting 12-hour 1 000 mb dew point temperatures for Fort McMurray.

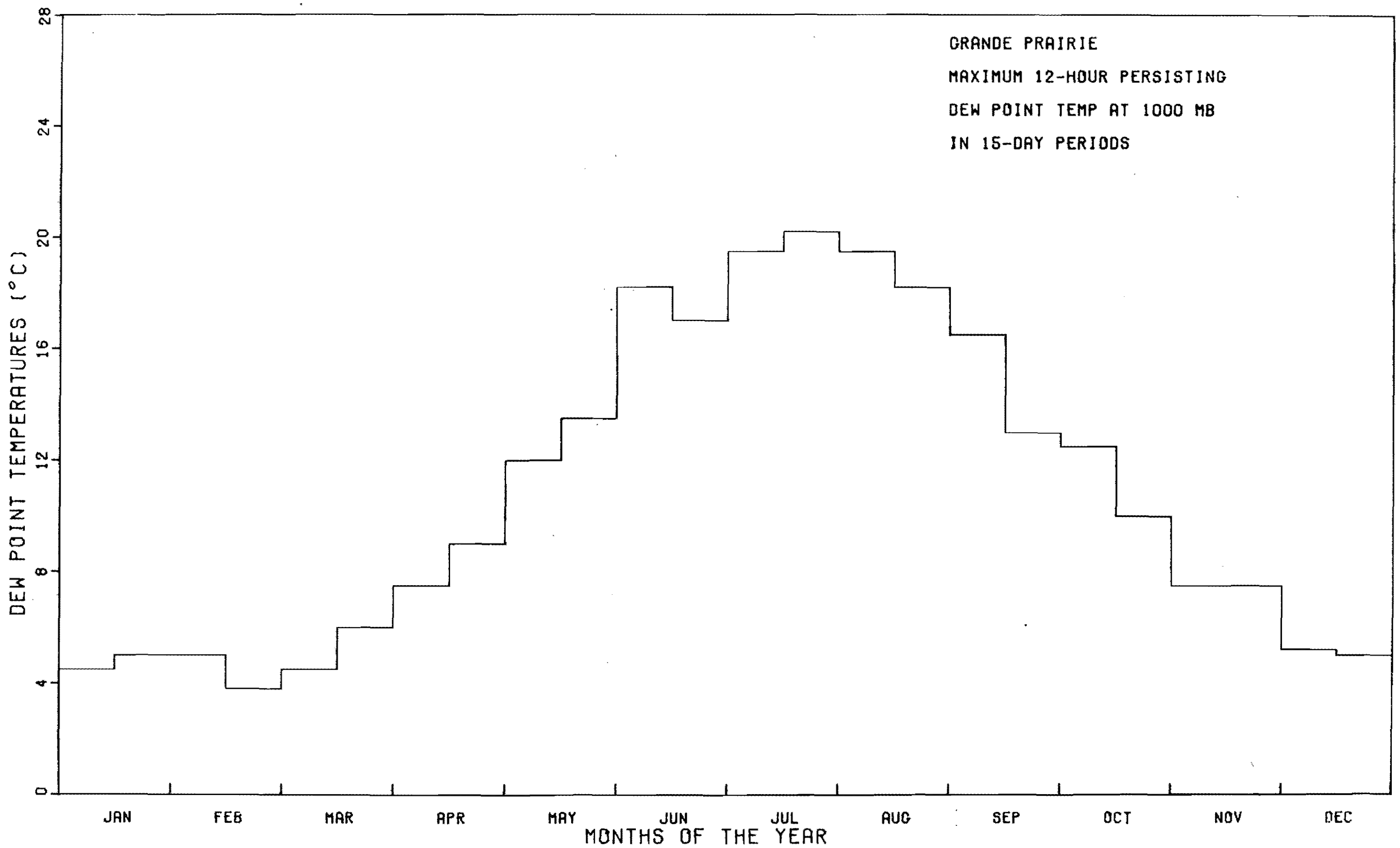

Figure 93 Maximum recorded persisting 12-hour 1 000 mb dew point temperatures for Grande Prairie.

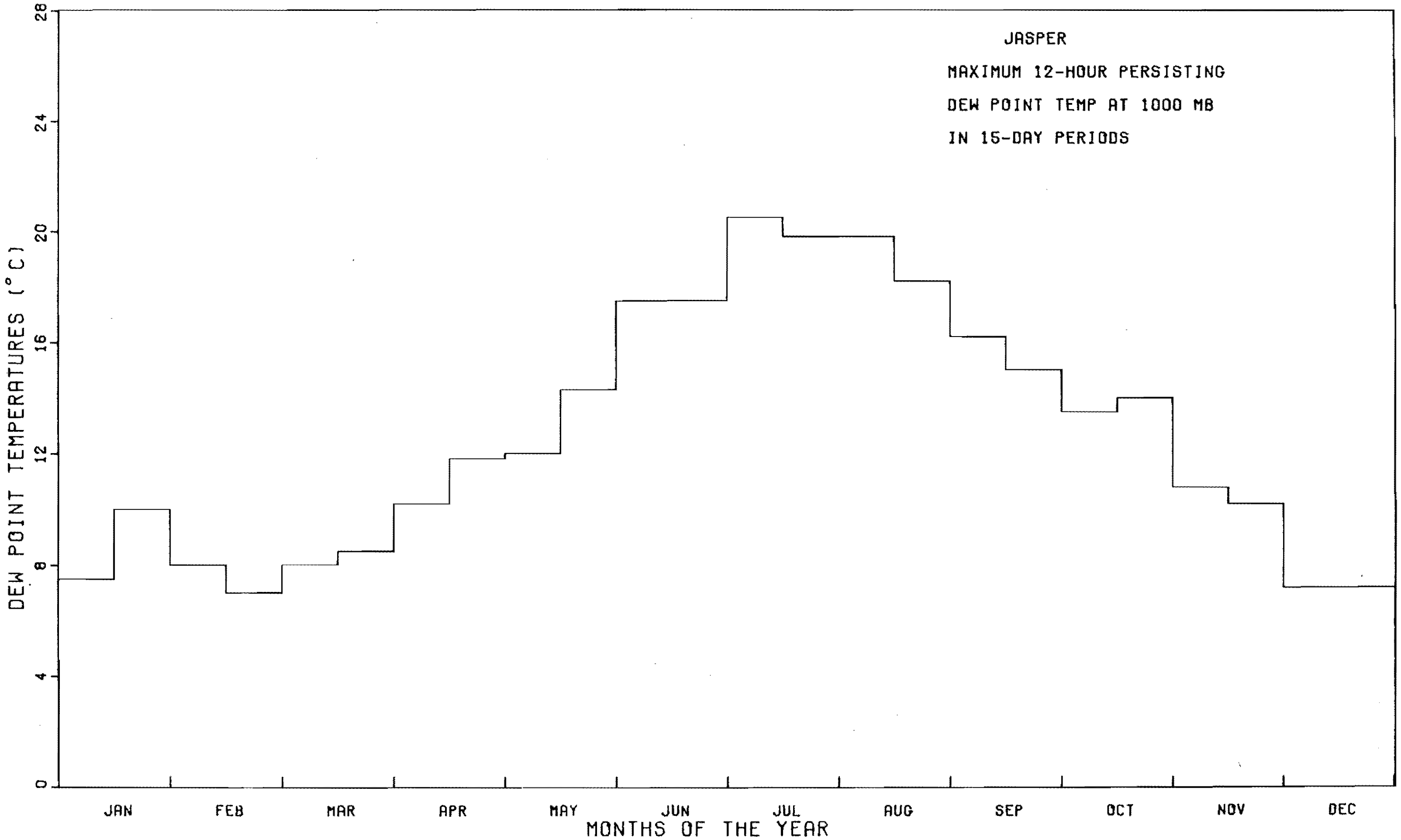

Figure 94 Maximum recorded persisting 12-hour 1 000 mb dew point temperatures for Jasper.

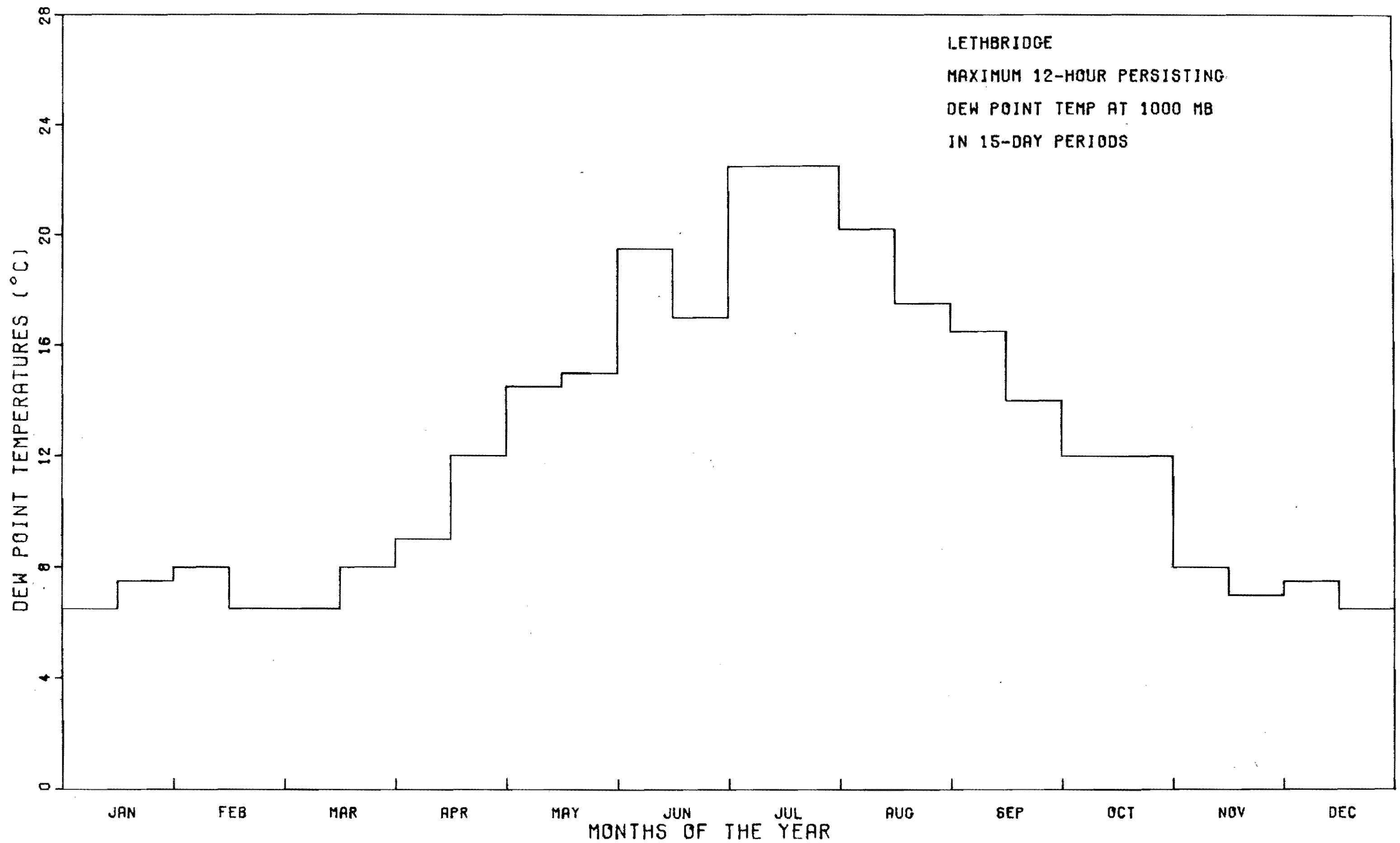

Figure 95 Maximum recorded persisting 12-hour 1 000 mb dew point temperatures for Lethbridge.

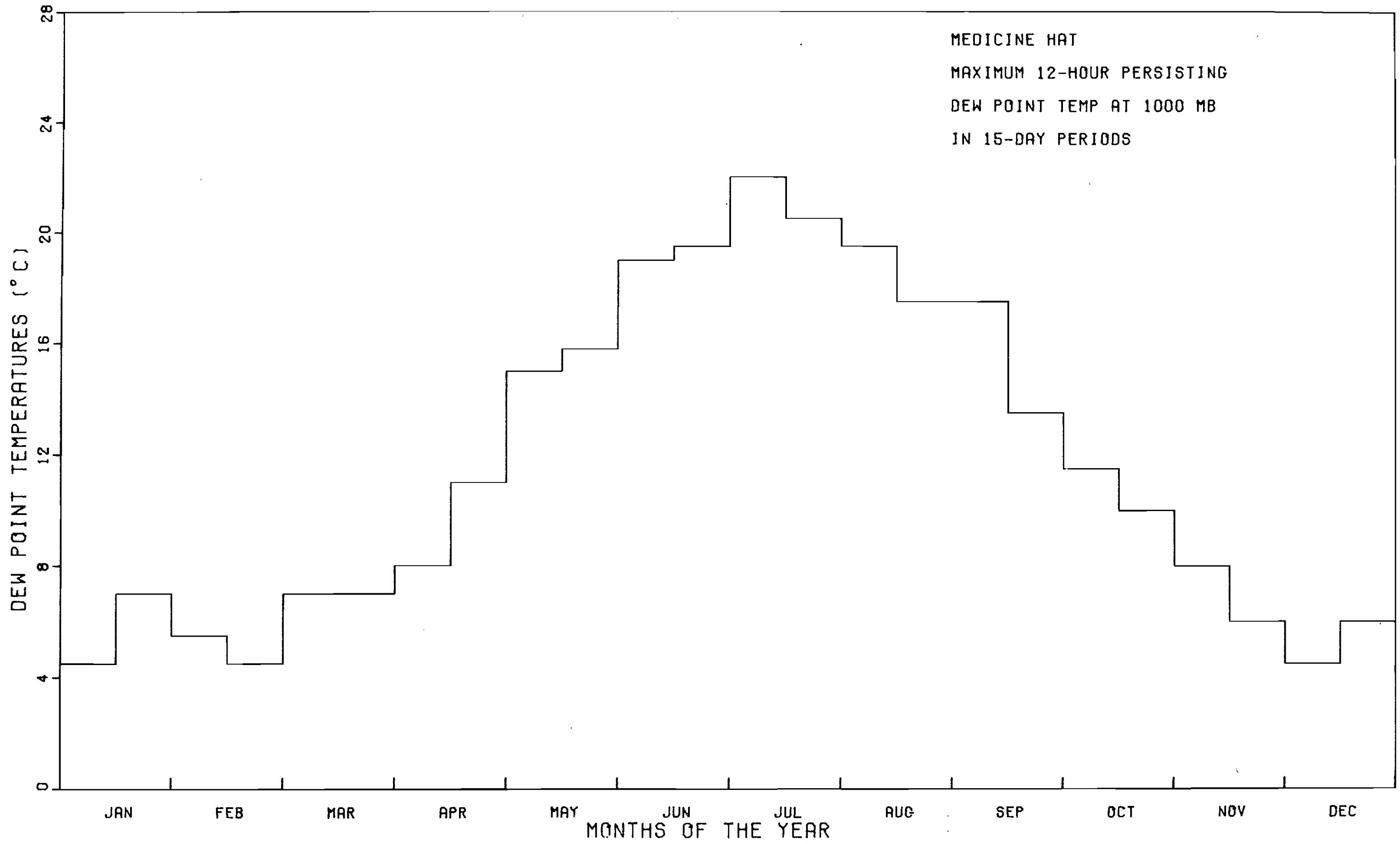

Figure 96 Maximum recorded persisting 12-hour 1 000 mb dew point temperatures for Medicine Hat.

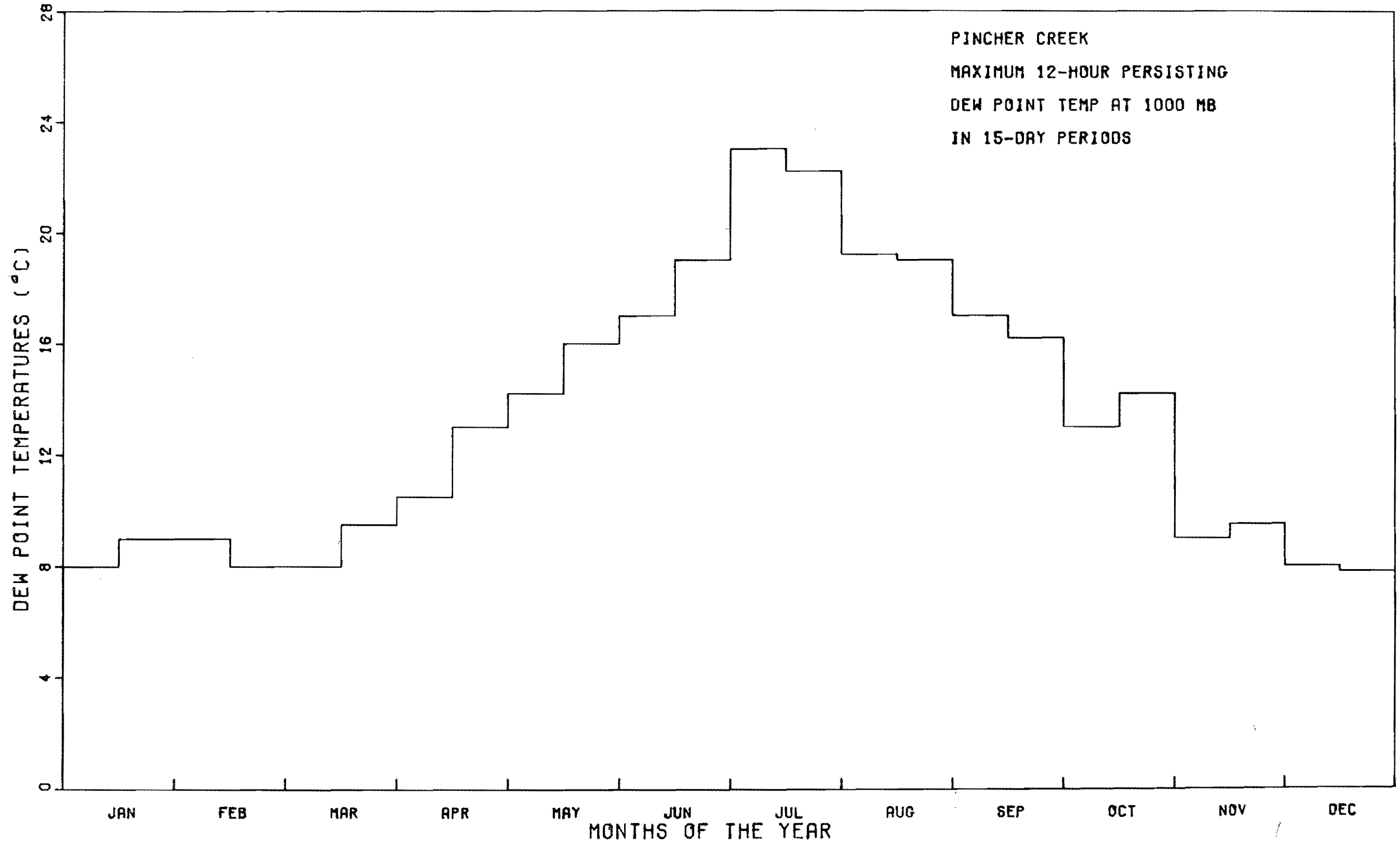

Figure 97 Maximum recorded persisting 12-hour 1 000 mb dew point temperatures for Pincher Creek.

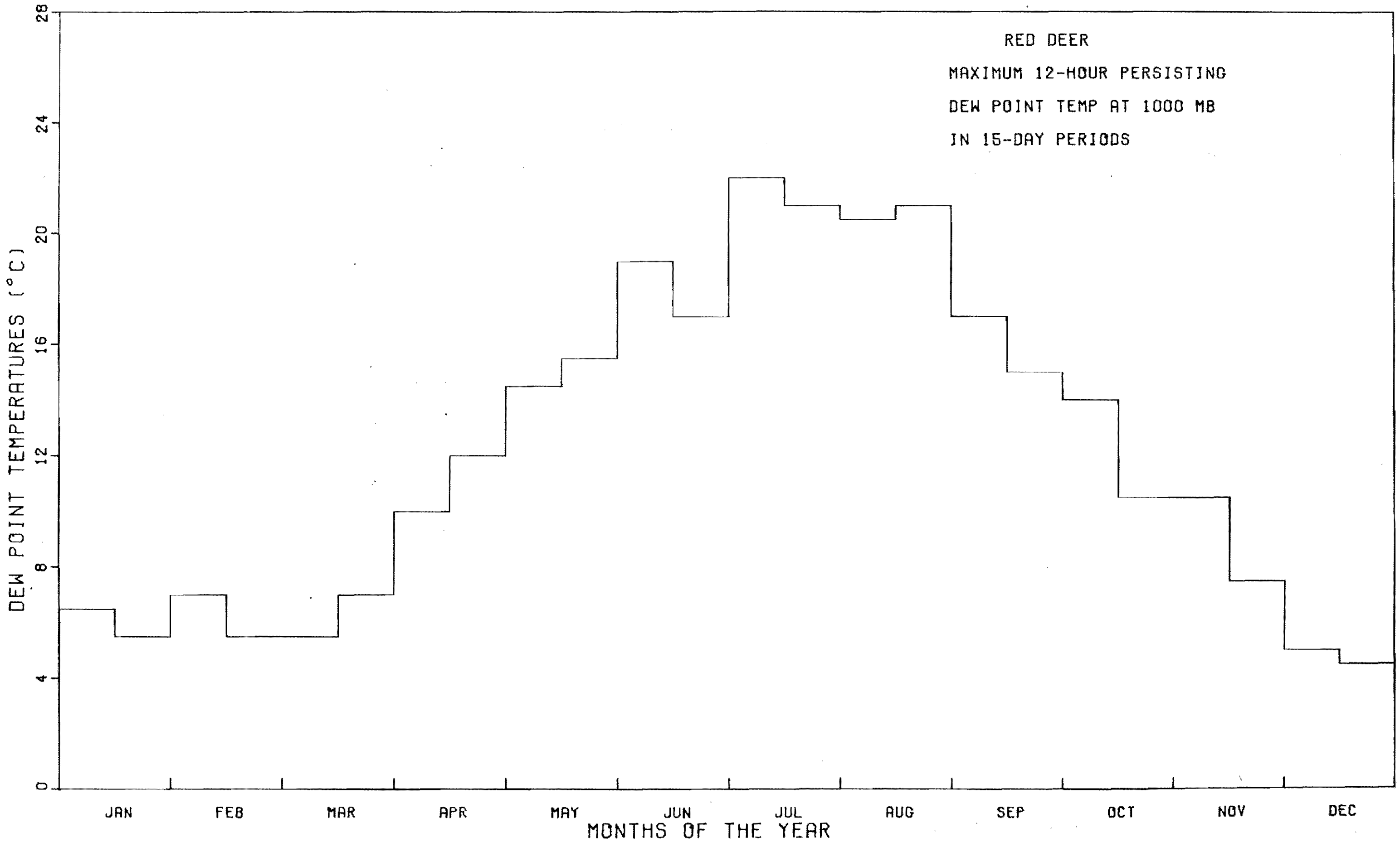

Figure 98 Maximum recorded persisting 12-hour 1 000 mb dew point temperatures for Red Deer.

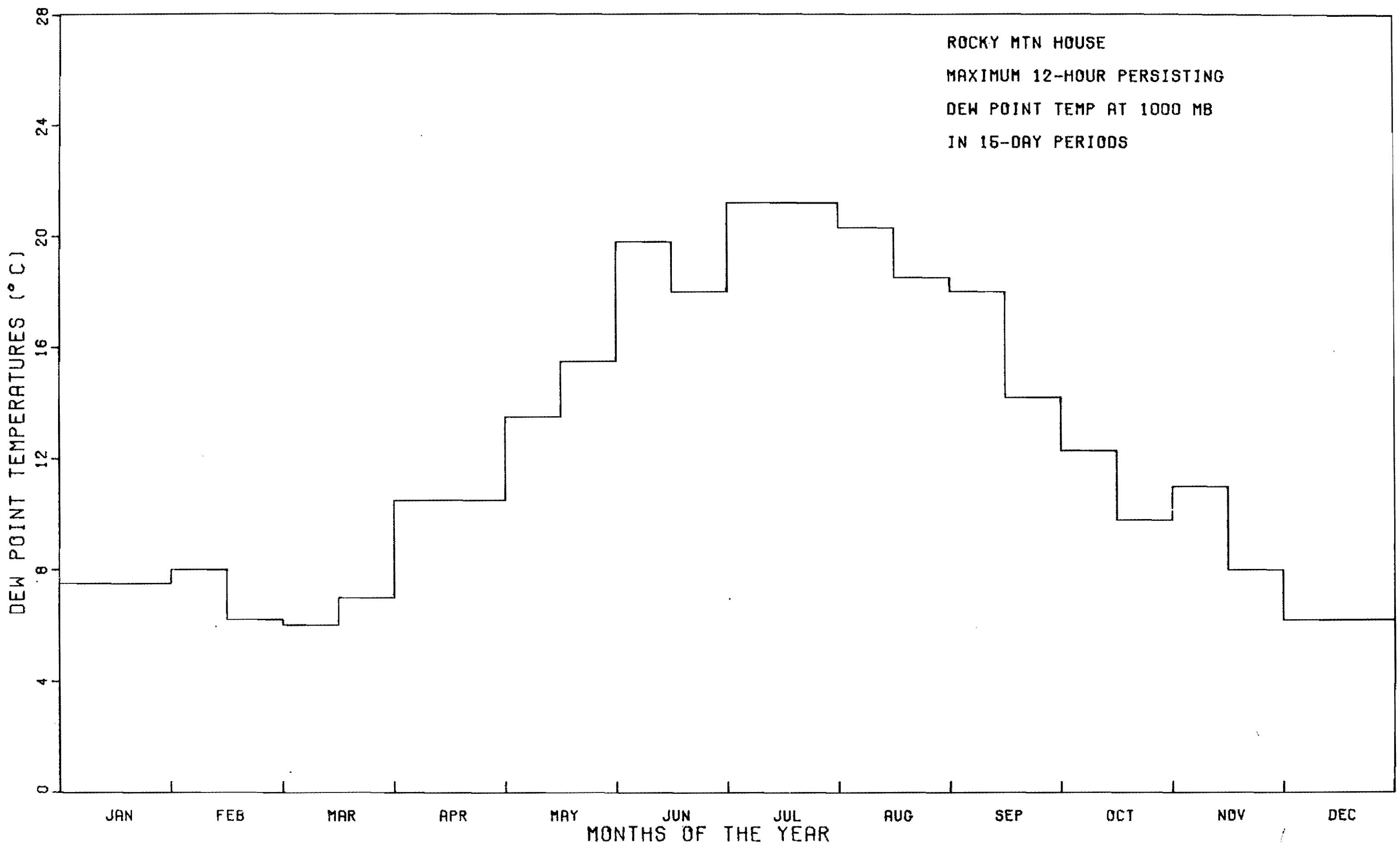

Figure 99 Maximum recorded persisting 12-hour 1 000 mb dew point temperatures for Rocky Mountain House.

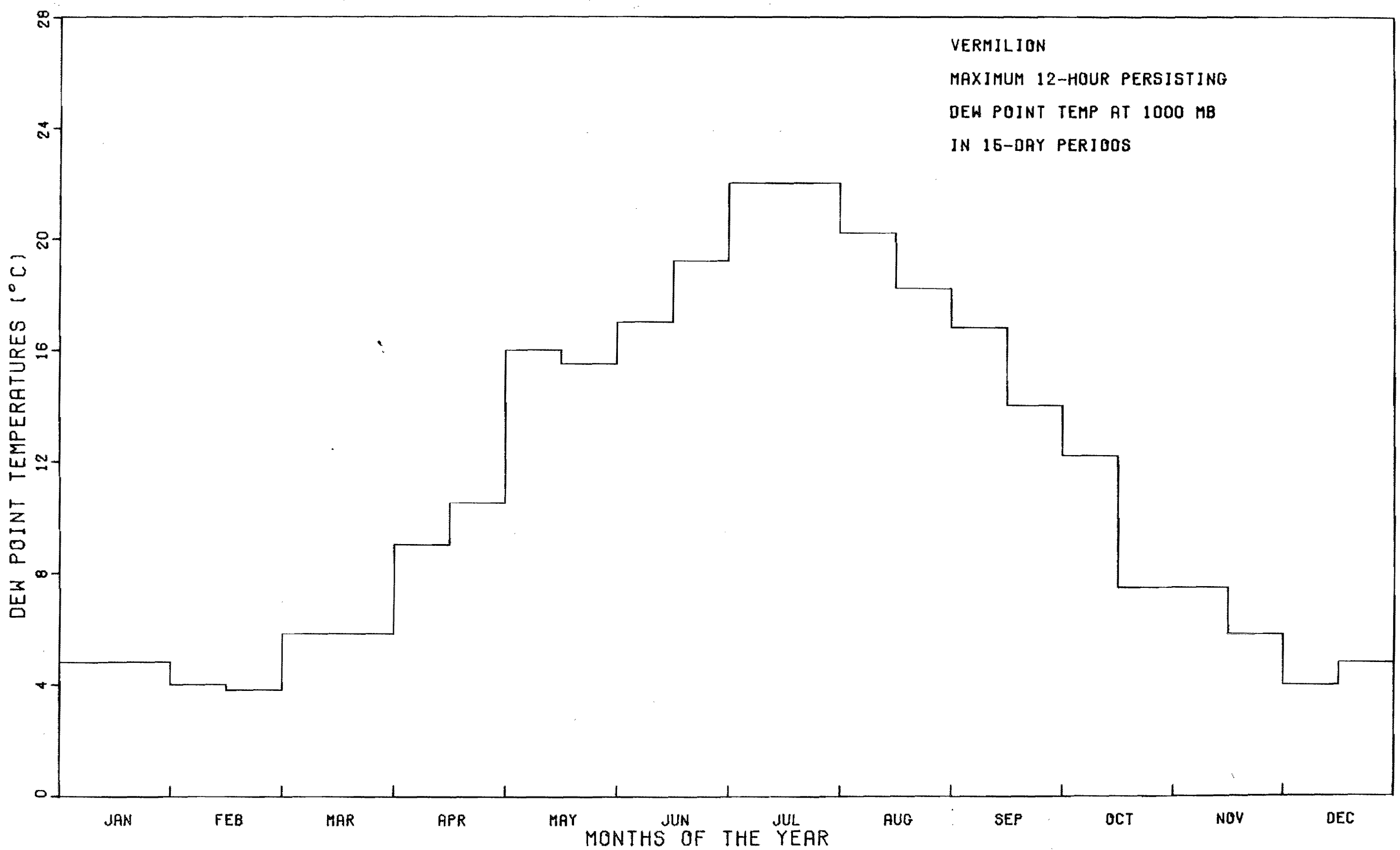

Figure 100 Maximum recorded persisting 12-hour 1 000 mb dew point temperatures for Vermilion.

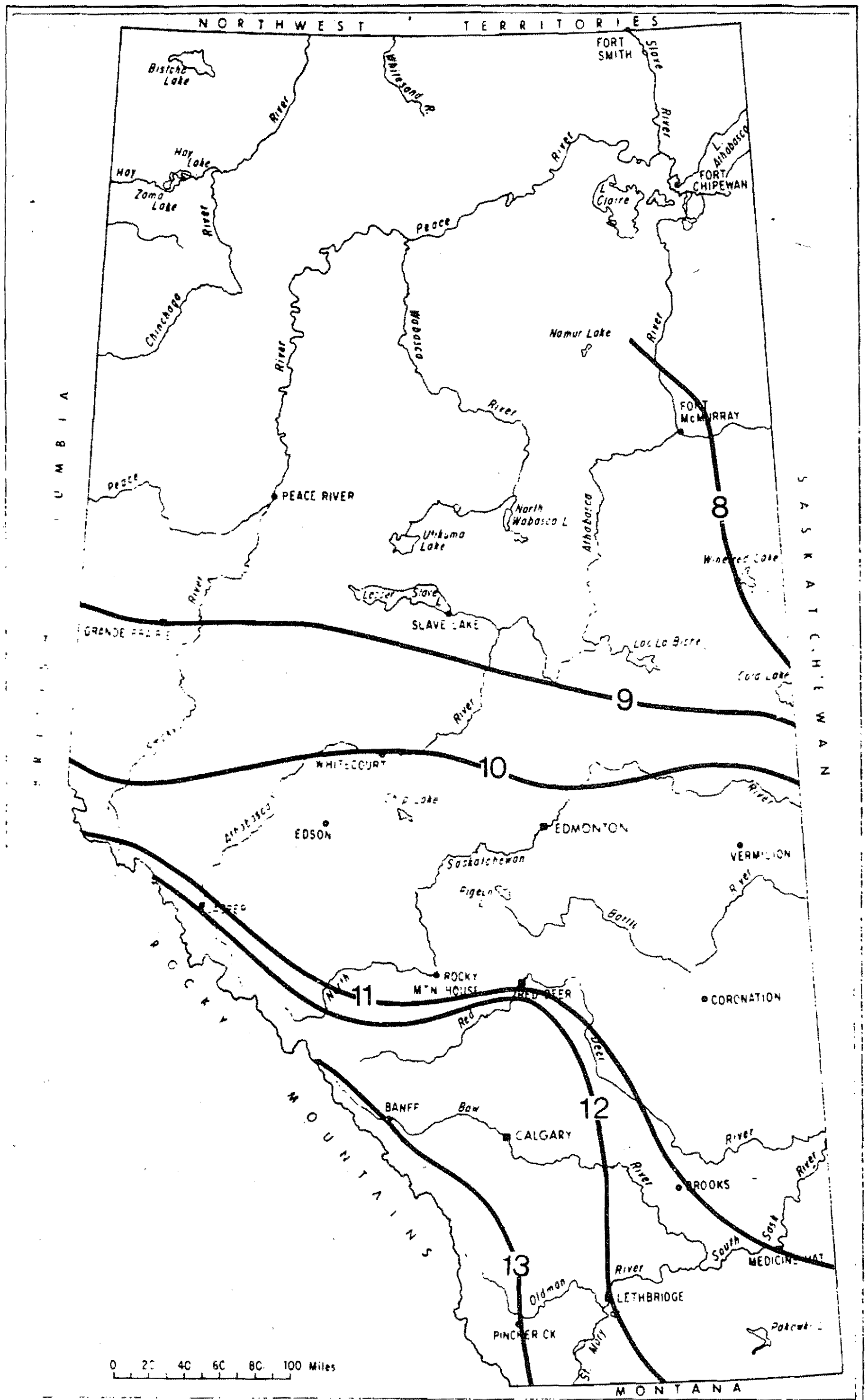

Figure 101 Spatial variation of the maximum persisting 12-hour 1 000 mb dew point temperatures for April (°C).

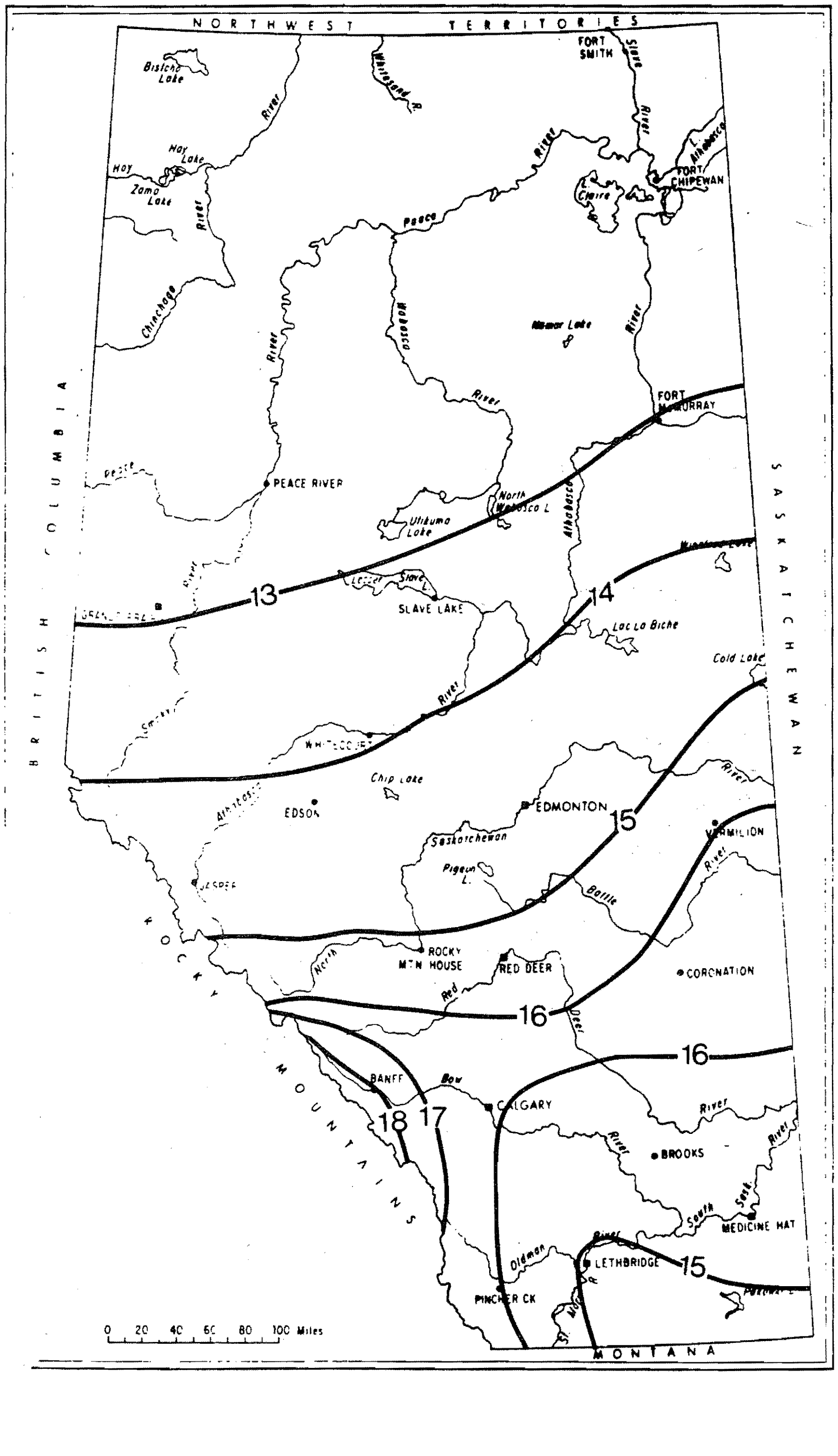

Figure 102 Spatial variation of the maximum persisting 12-hour 1 000 mb dew point temperatures for May (°C).

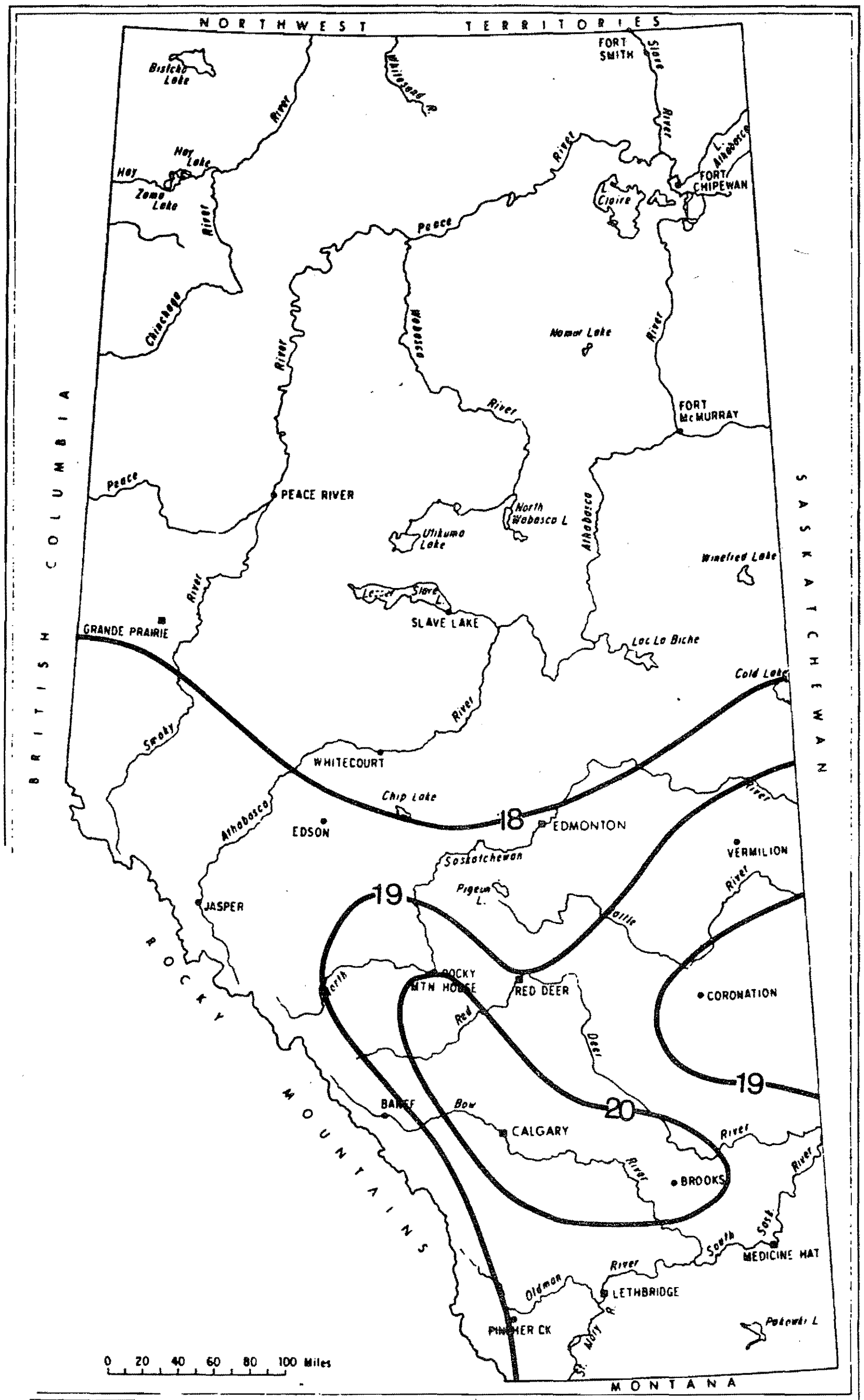

Figure 103 Spatial variation of the maximum persisting 12-hour 1 000 mb dew point temperatures for June (°C).

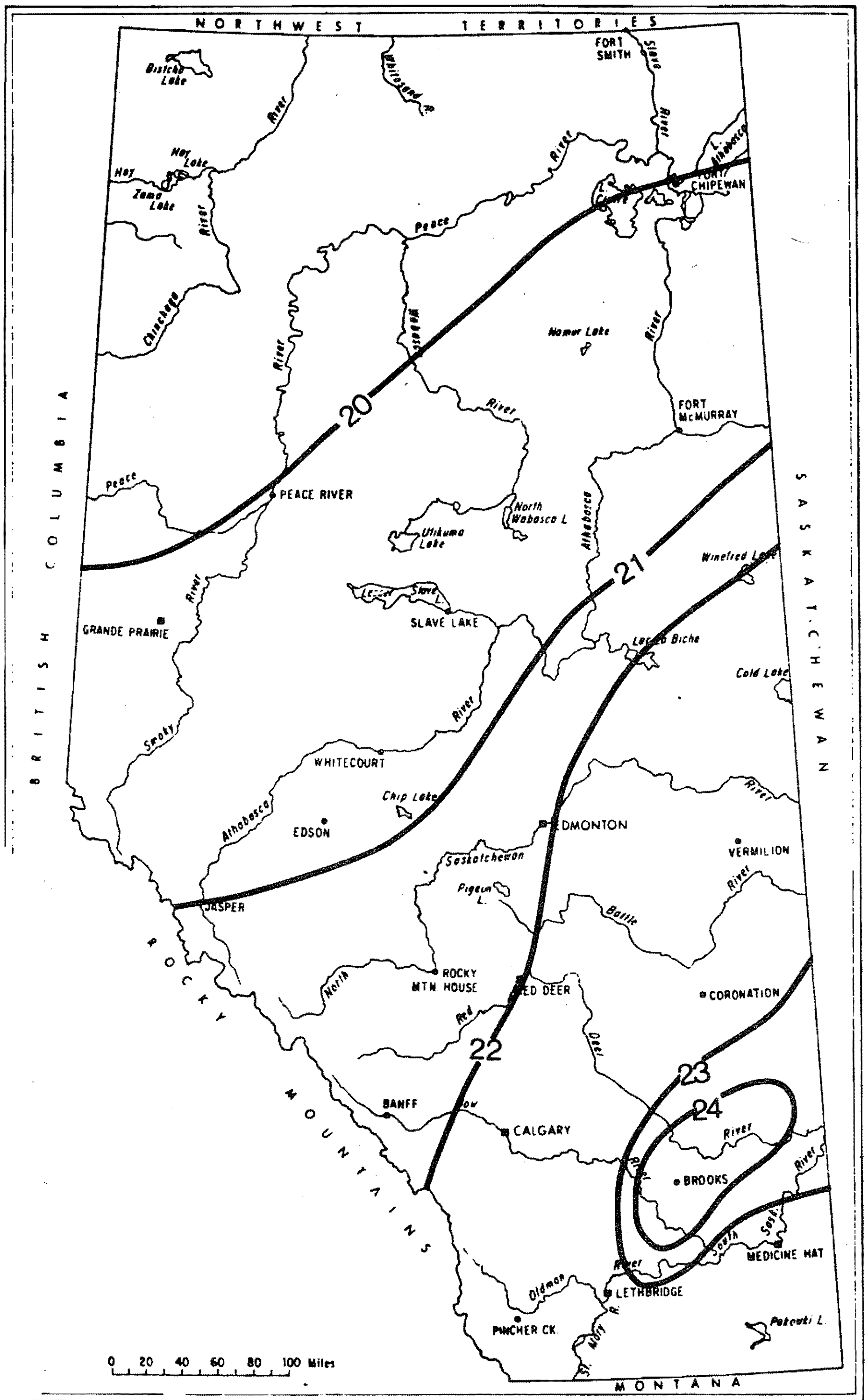

Figure 104 Spatial variation of the maximum persisting 12-hour 1 000 mb dew point temperatures for July (°C).

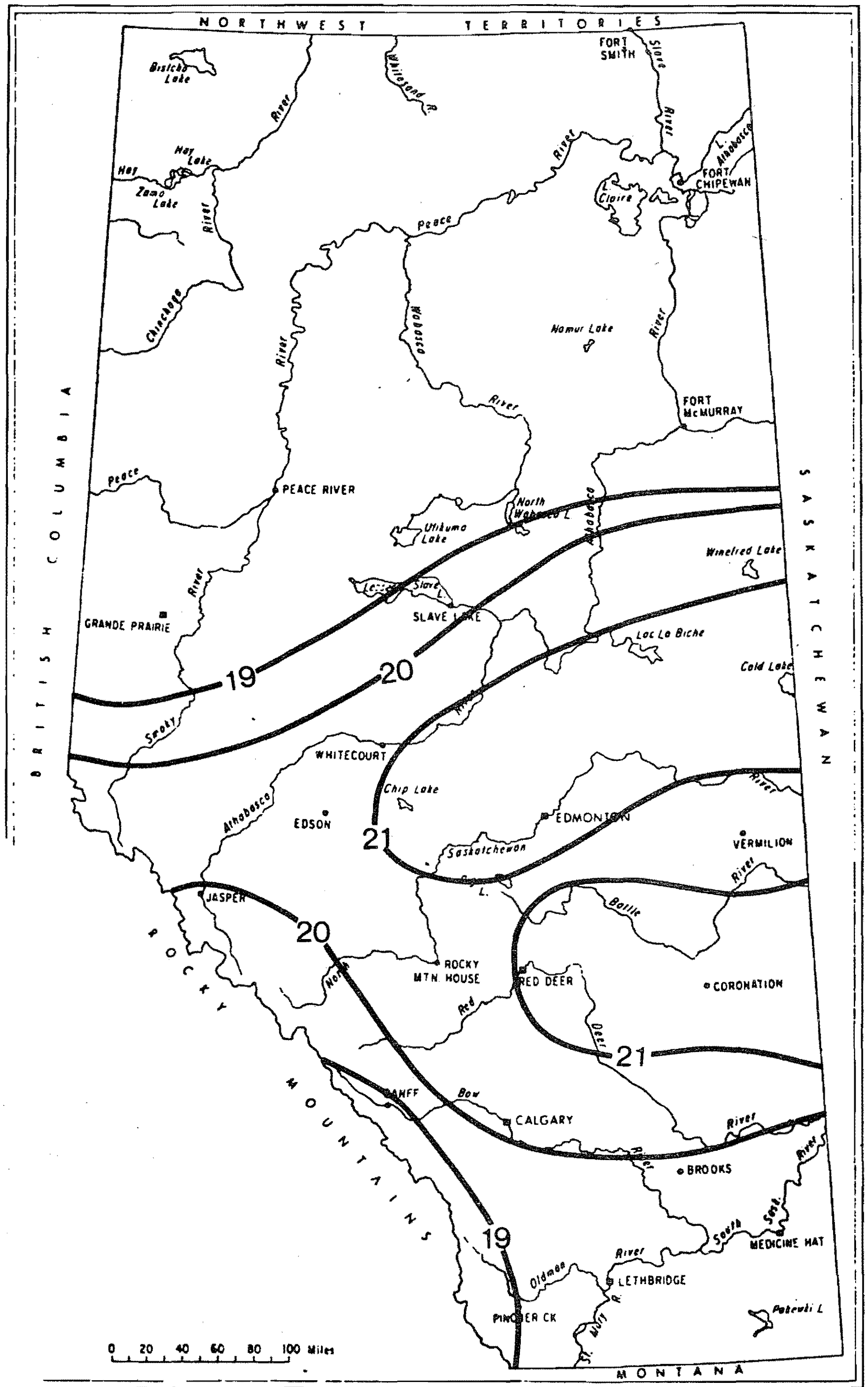

Figure 105 Spatial variation of the maximum persisting 12-hour 1 000 mb dew point temperatures for August (°C).

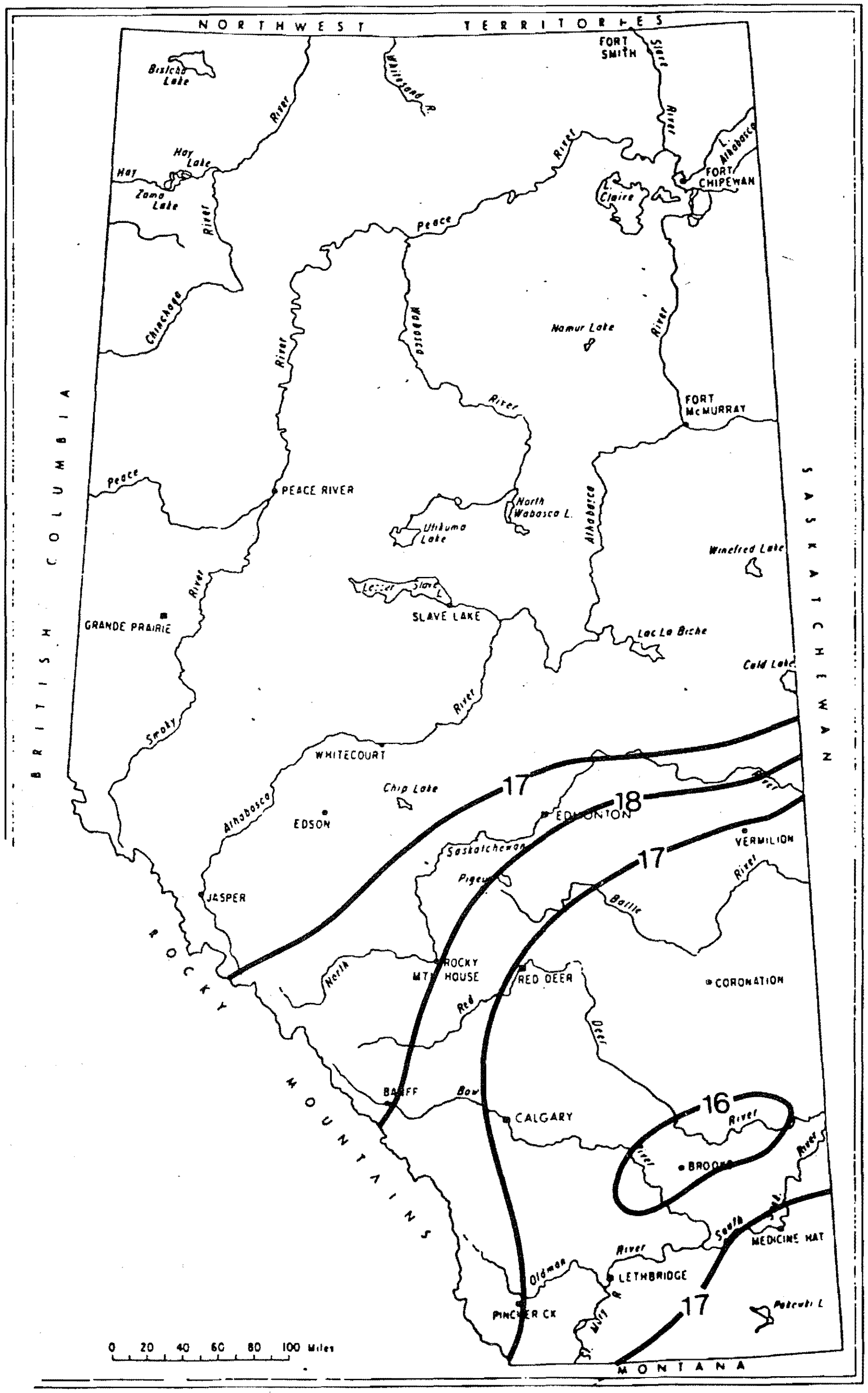

Figure 106 Spatial variation of the maximum persisting 12-hour 1 000 mb dew point temperatures for September (°C).

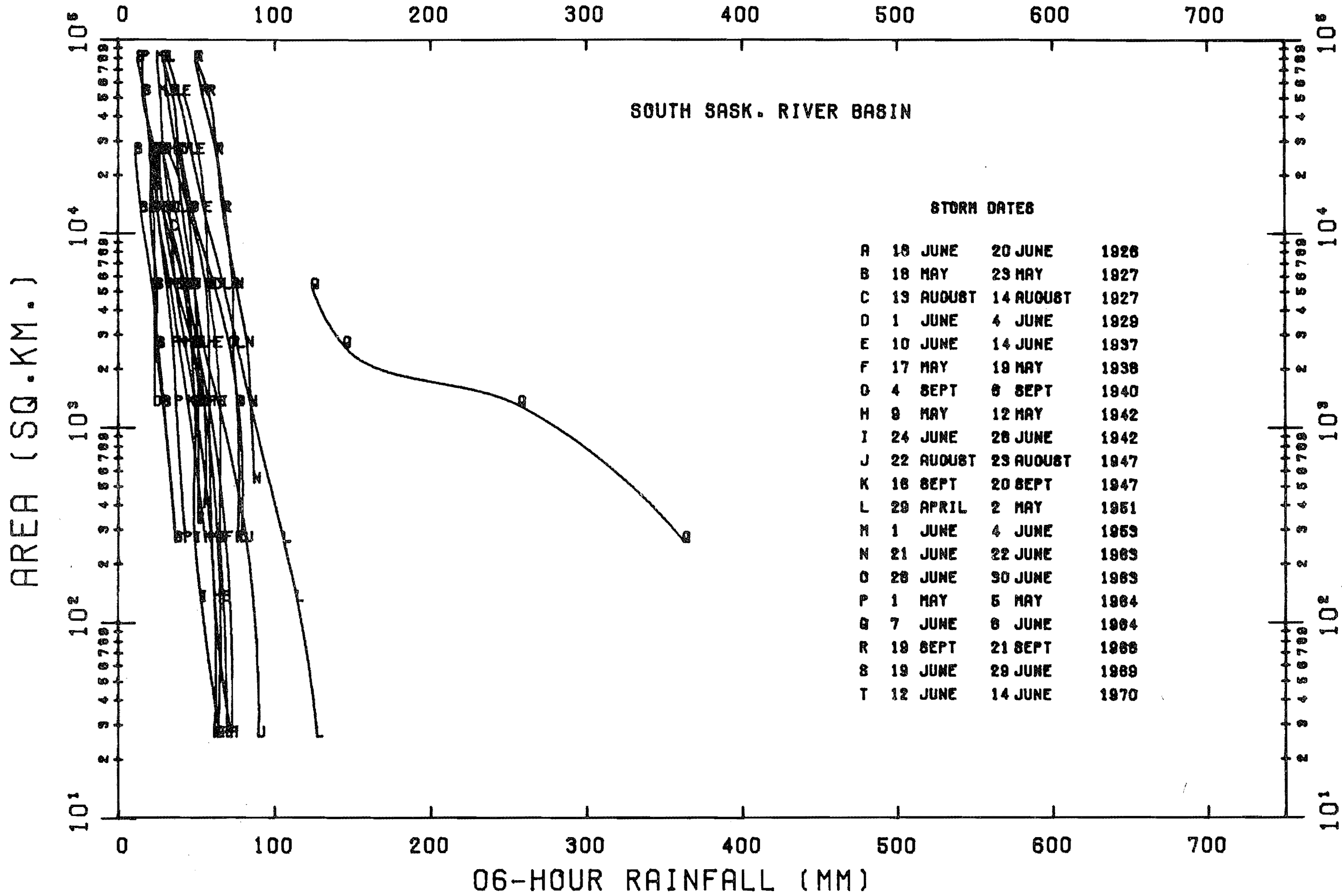

Figure 107 6-hour DAD curves for the South Saskatchewan River basin.

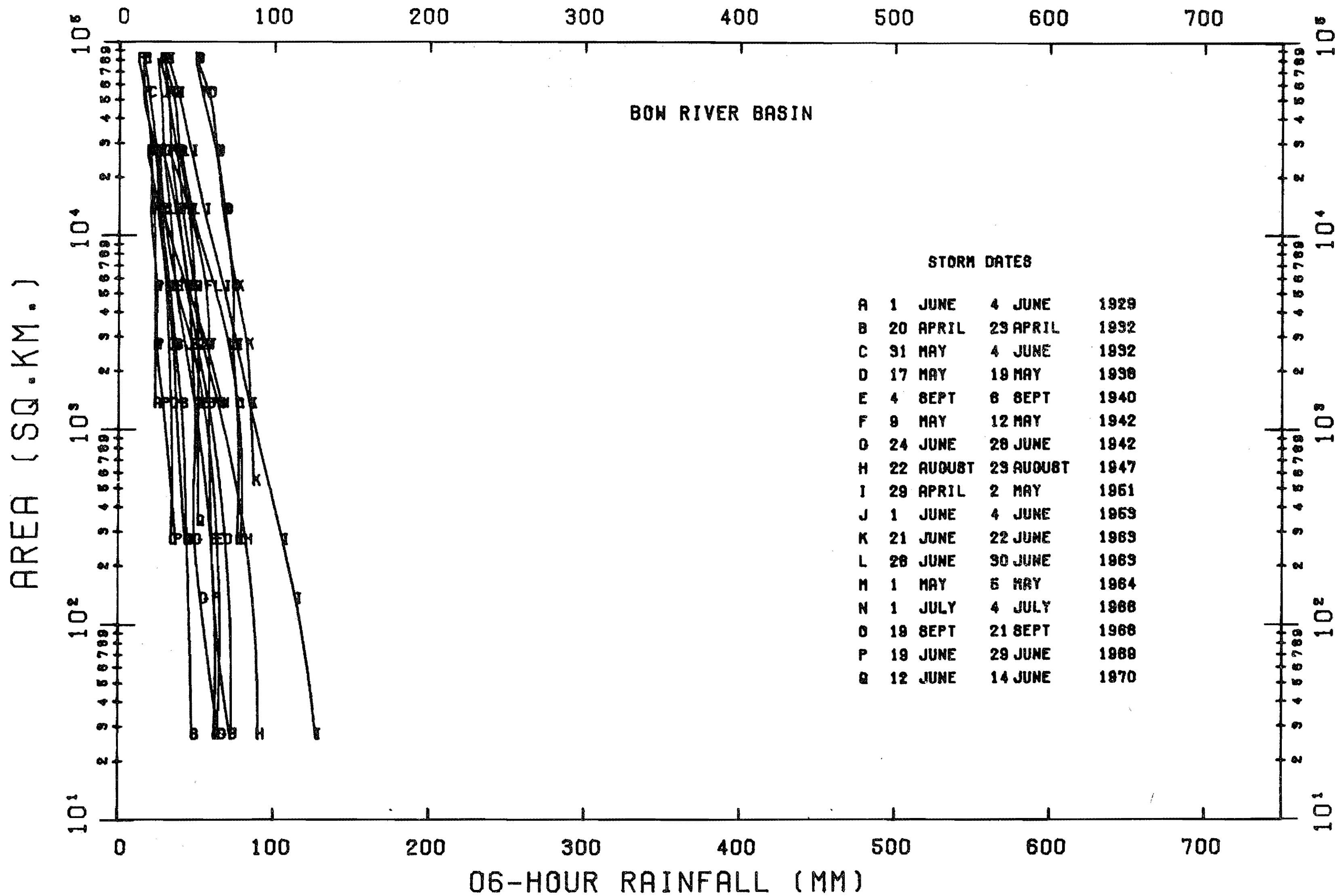

Figure 108 6-hour DAD curves for the Bow River basin.

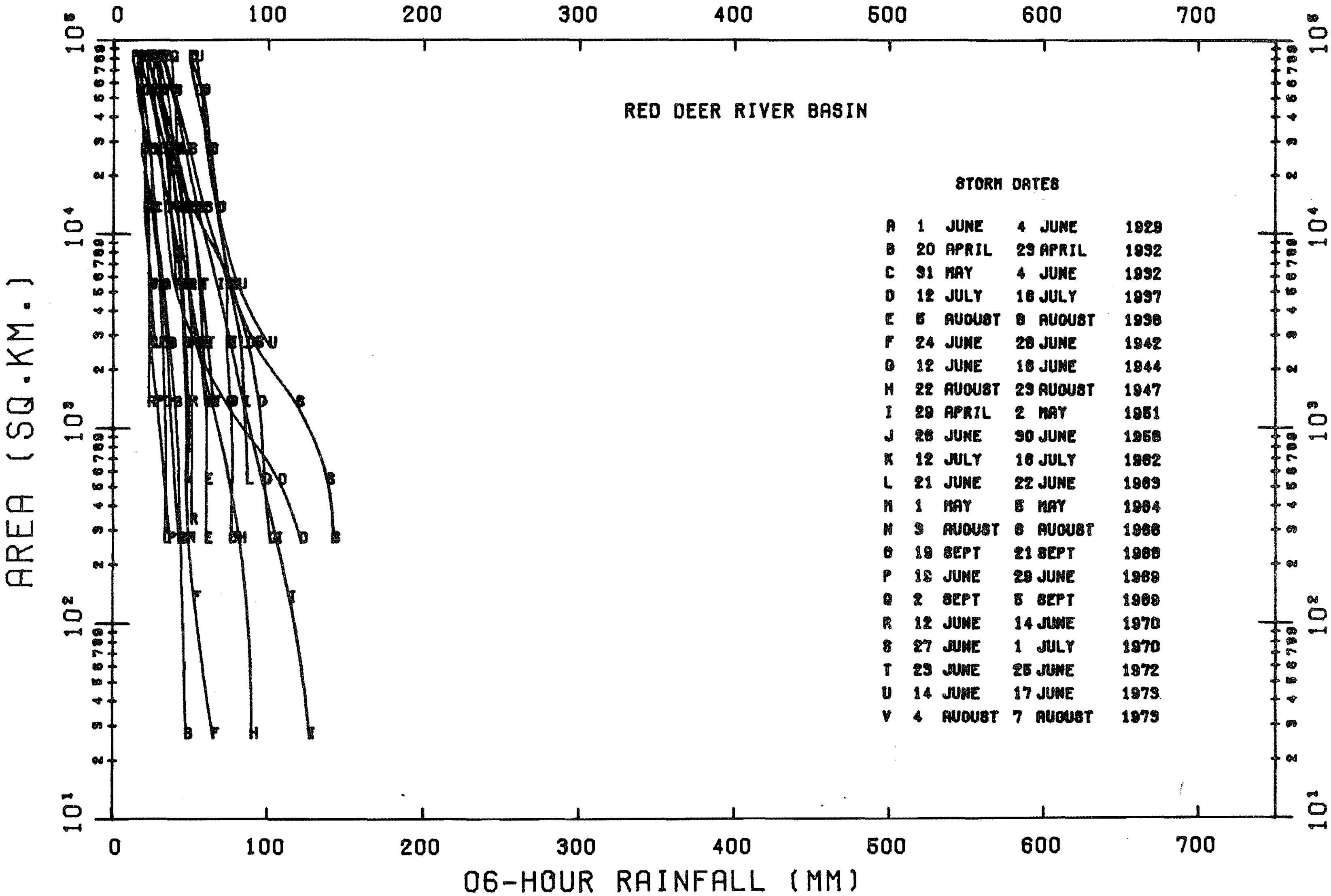

Figure 109 6-hour DAD curves for the Red Deer River basin.

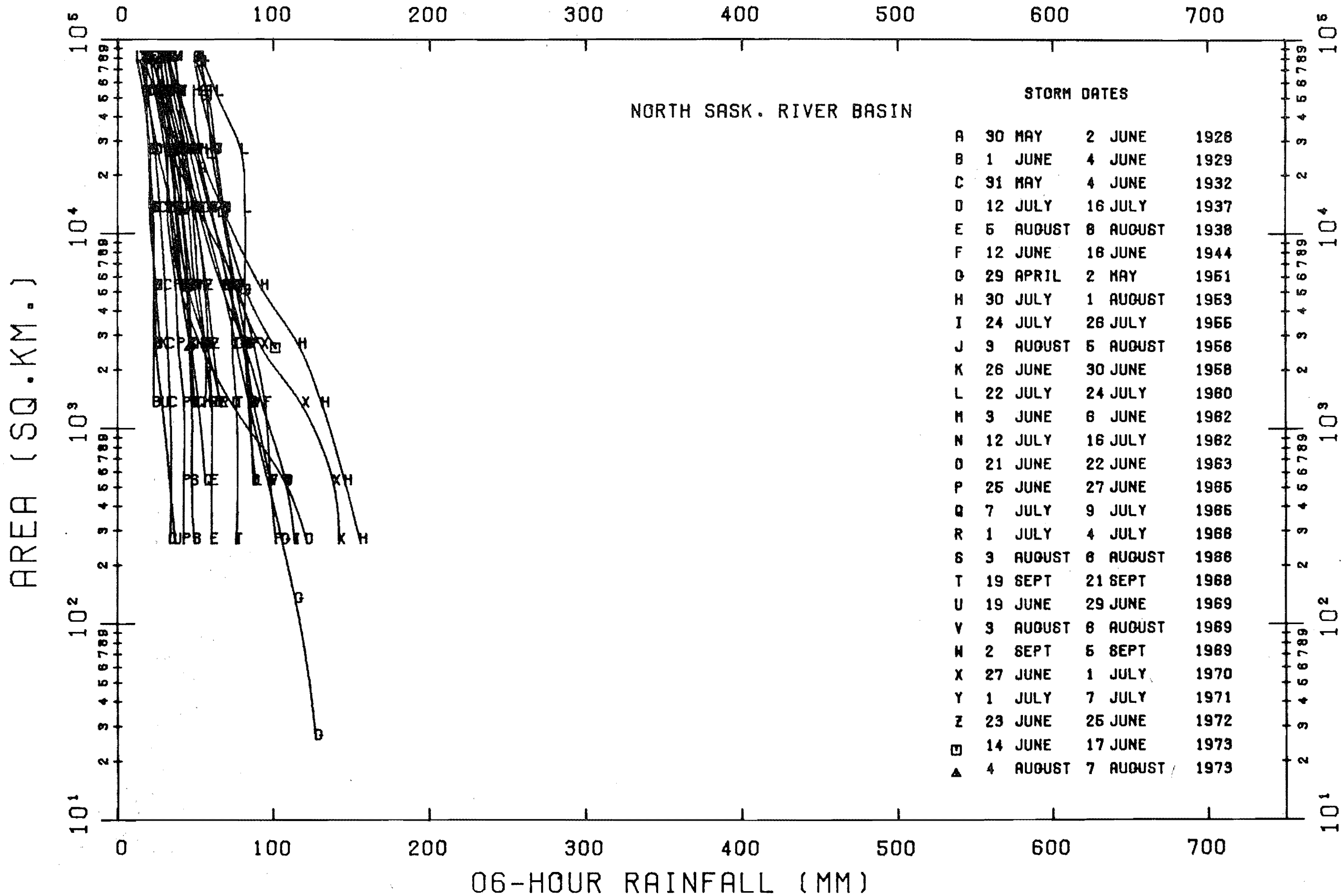

Figure 110 6-hour DAD curves for the North Saskatchewan River basin.

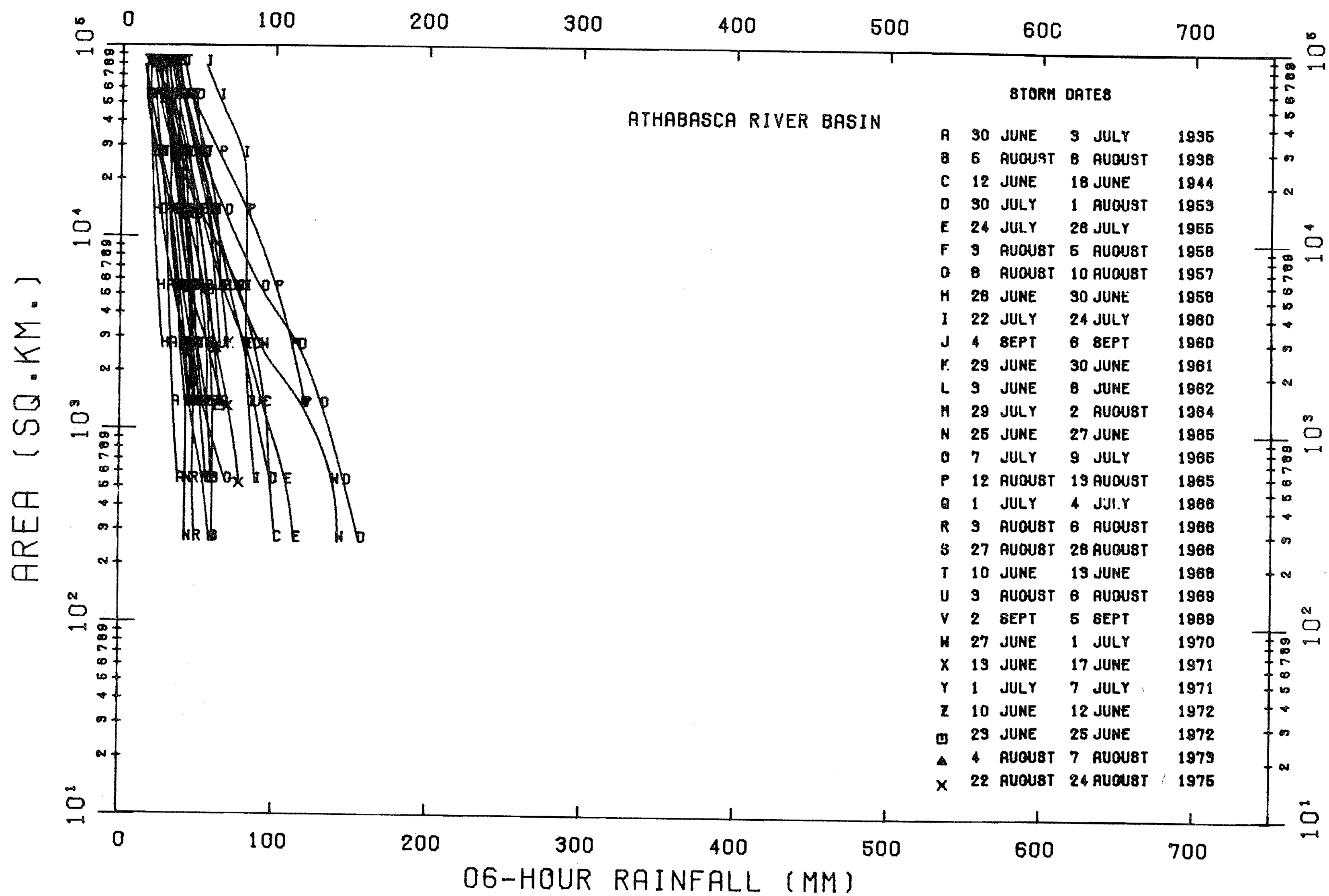

Figure 111 6-hour DAD curves for the Athabasca River basin.

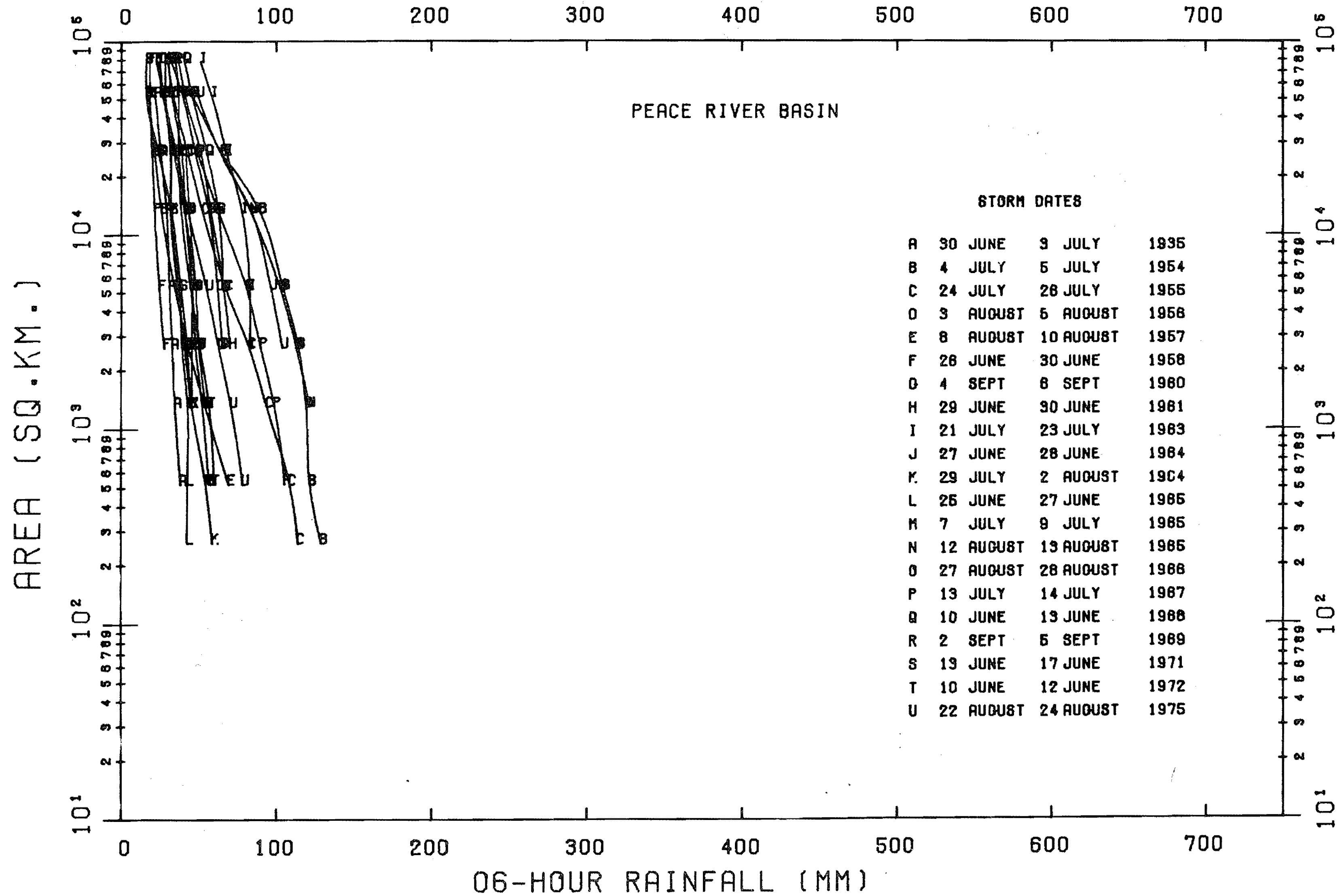

Figure 112 6-hour DAD curves for the Peace River basin.

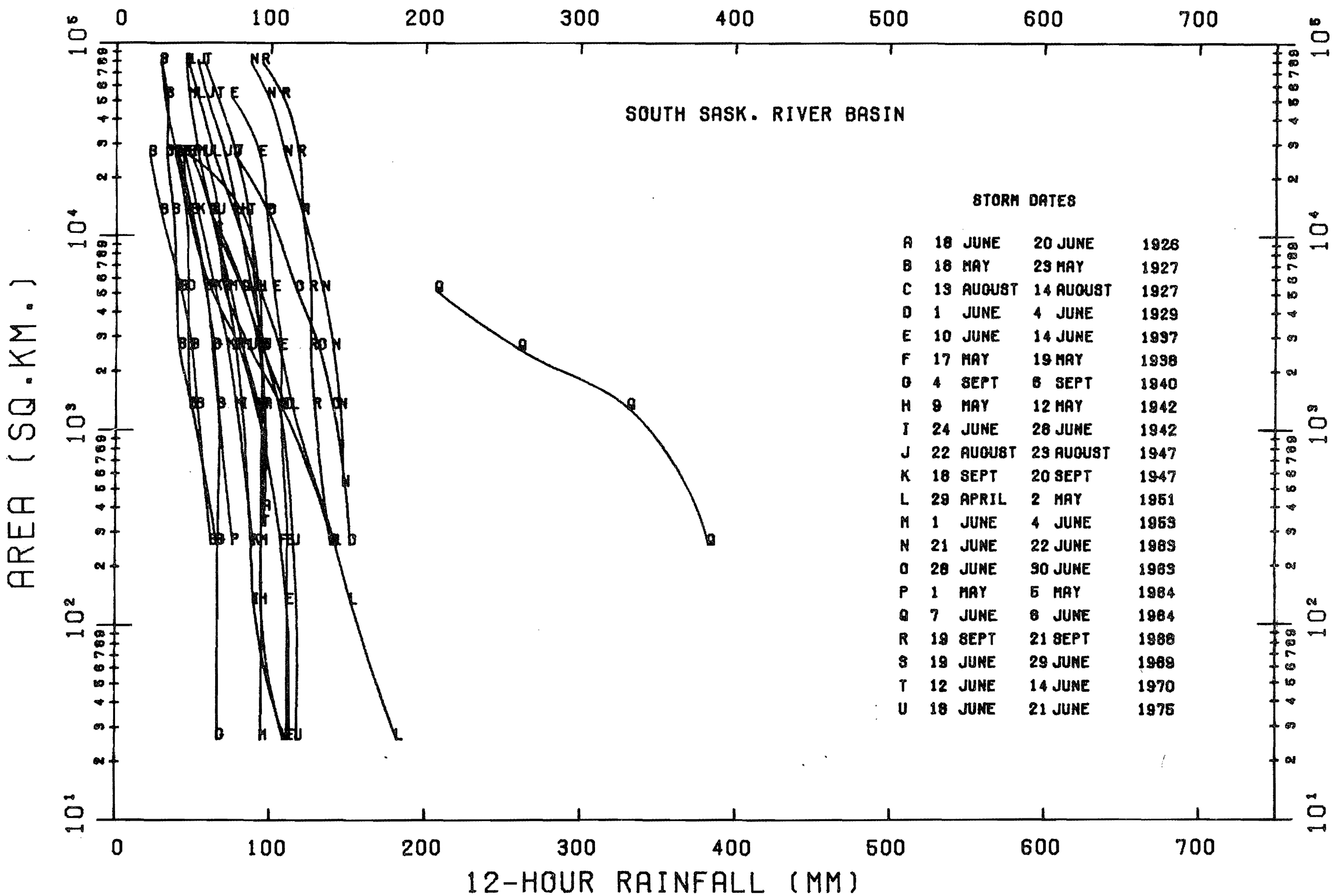

Figure 113 12-hour DAD curves for the South Saskatchewan River basin.

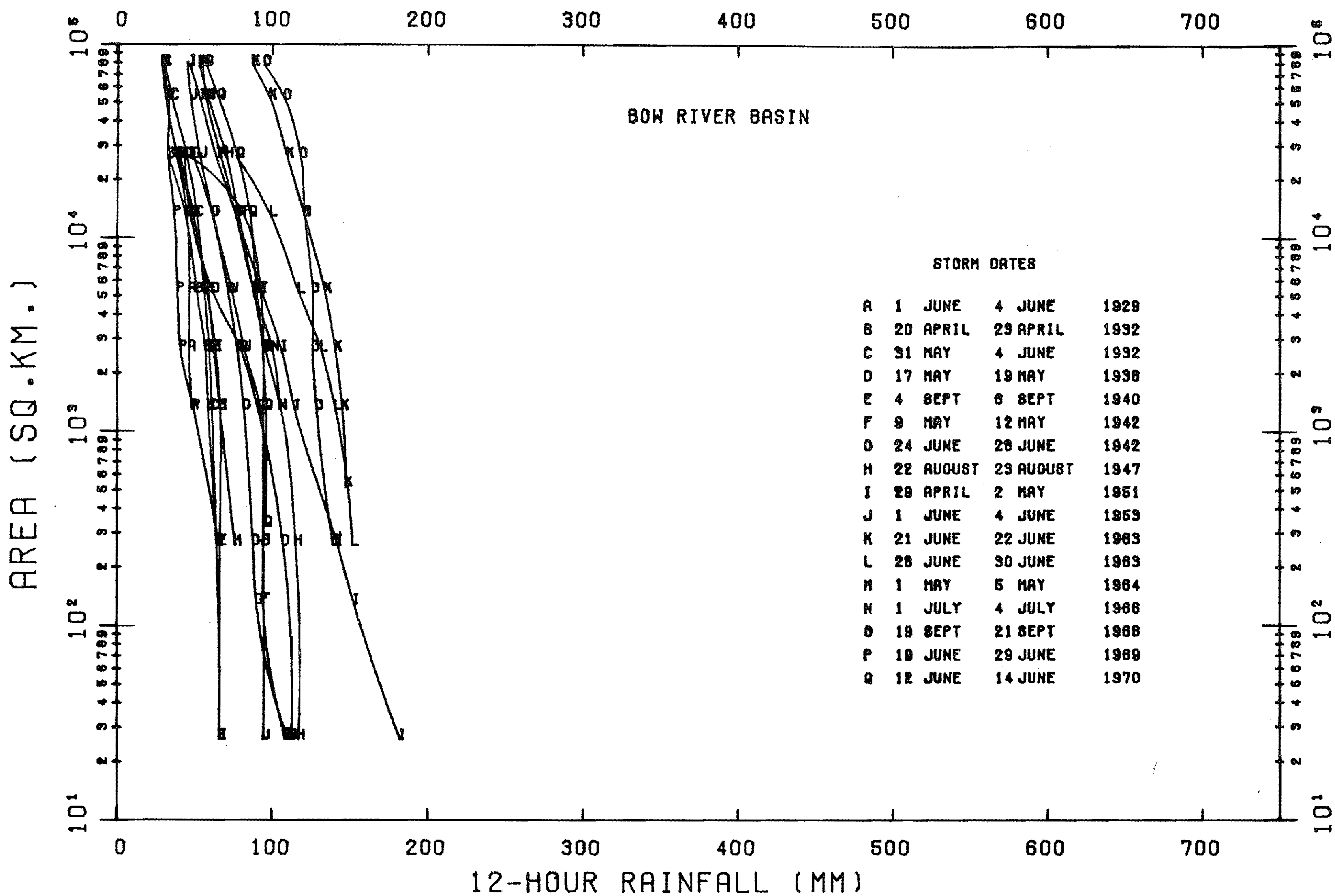

Figure 114 12-hour DAD curves for the Bow River basin.

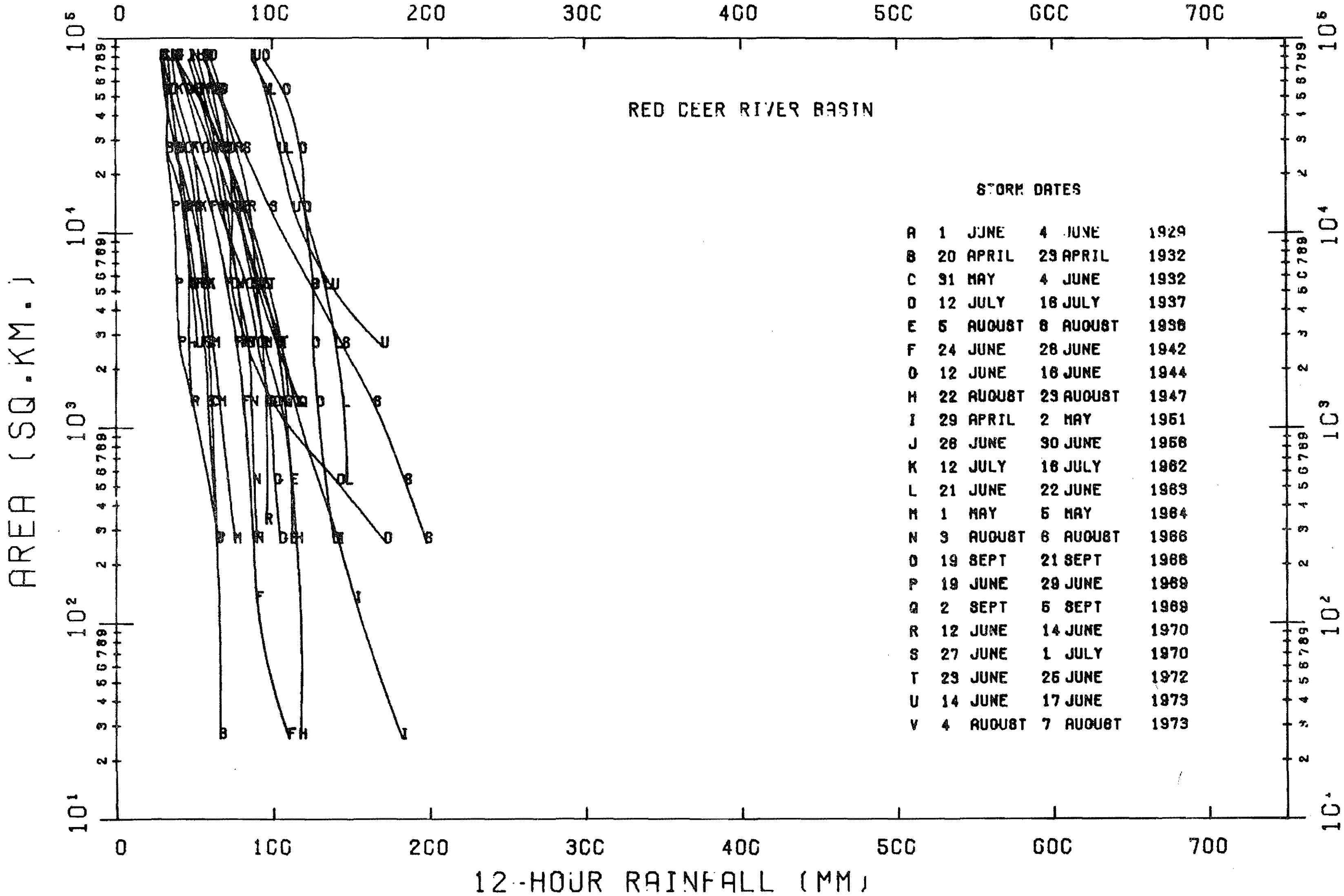

Figure 115 12-hour DAD curves for the Red Deer River basin.

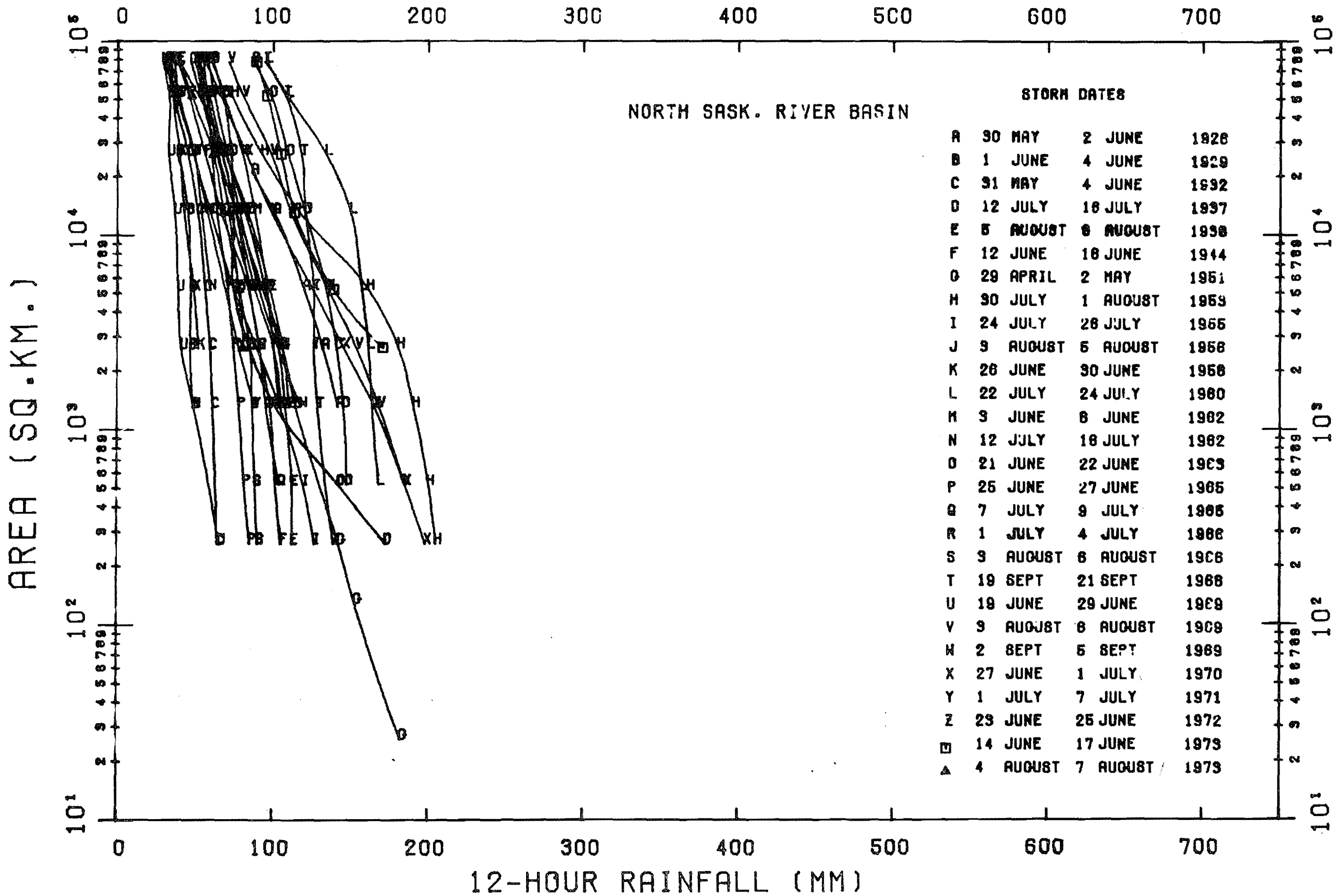

Figure 116 12-hour DAD curves for the North Saskatchewan River basin.

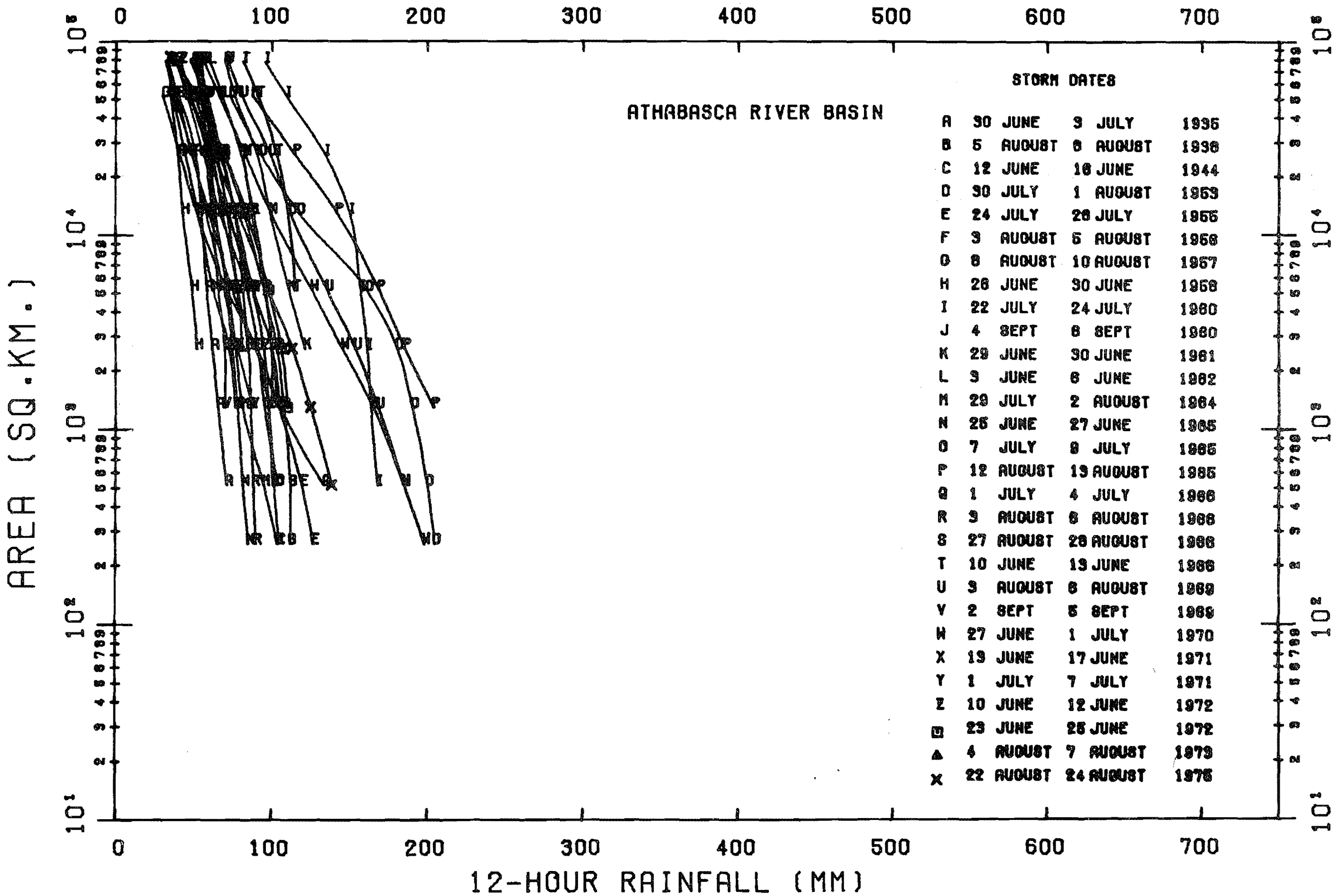

Figure 117 12-hour DAD curves for the Athabasca River basin.

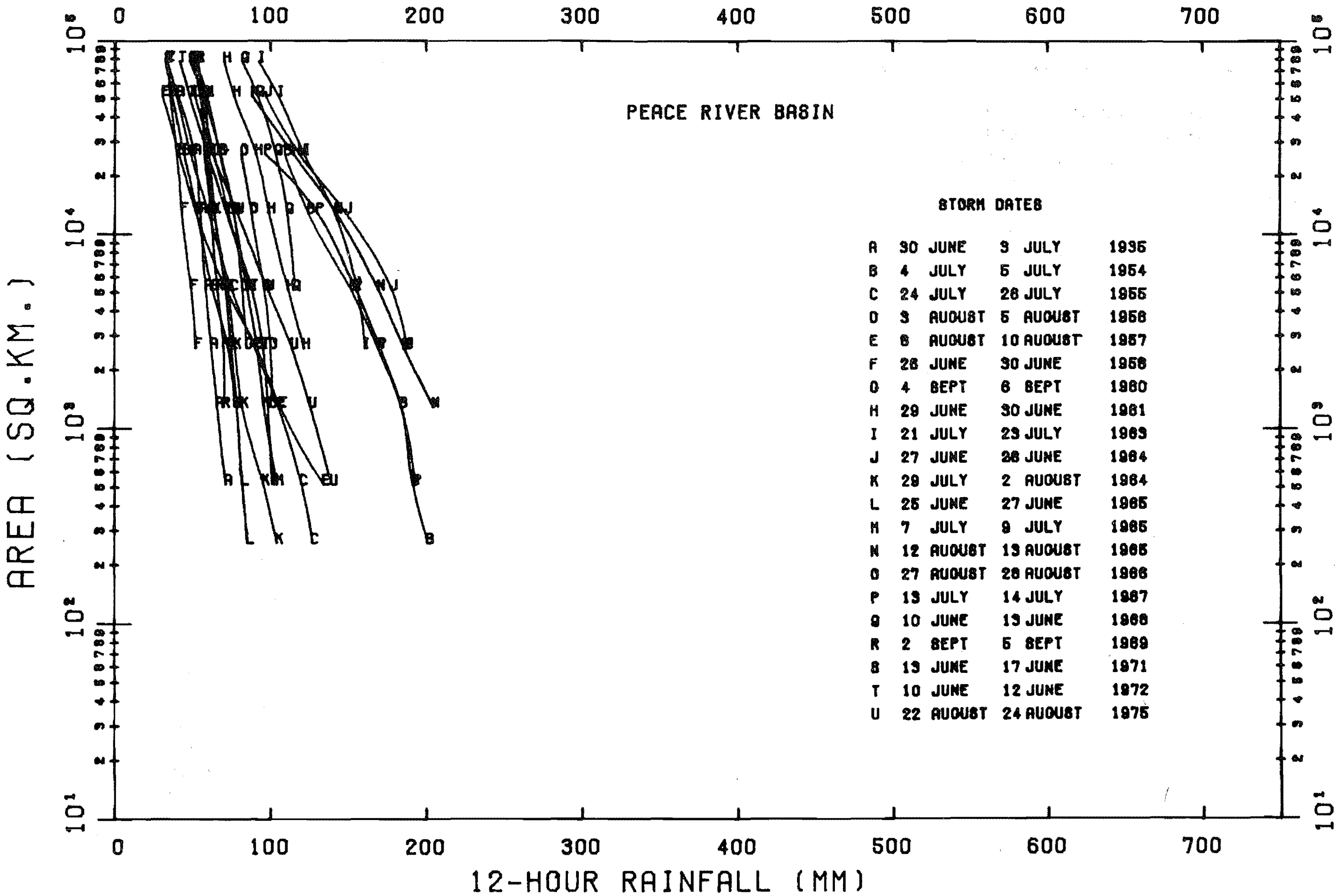

Figure 118 12-hour DAD curves for the Peace River basin.

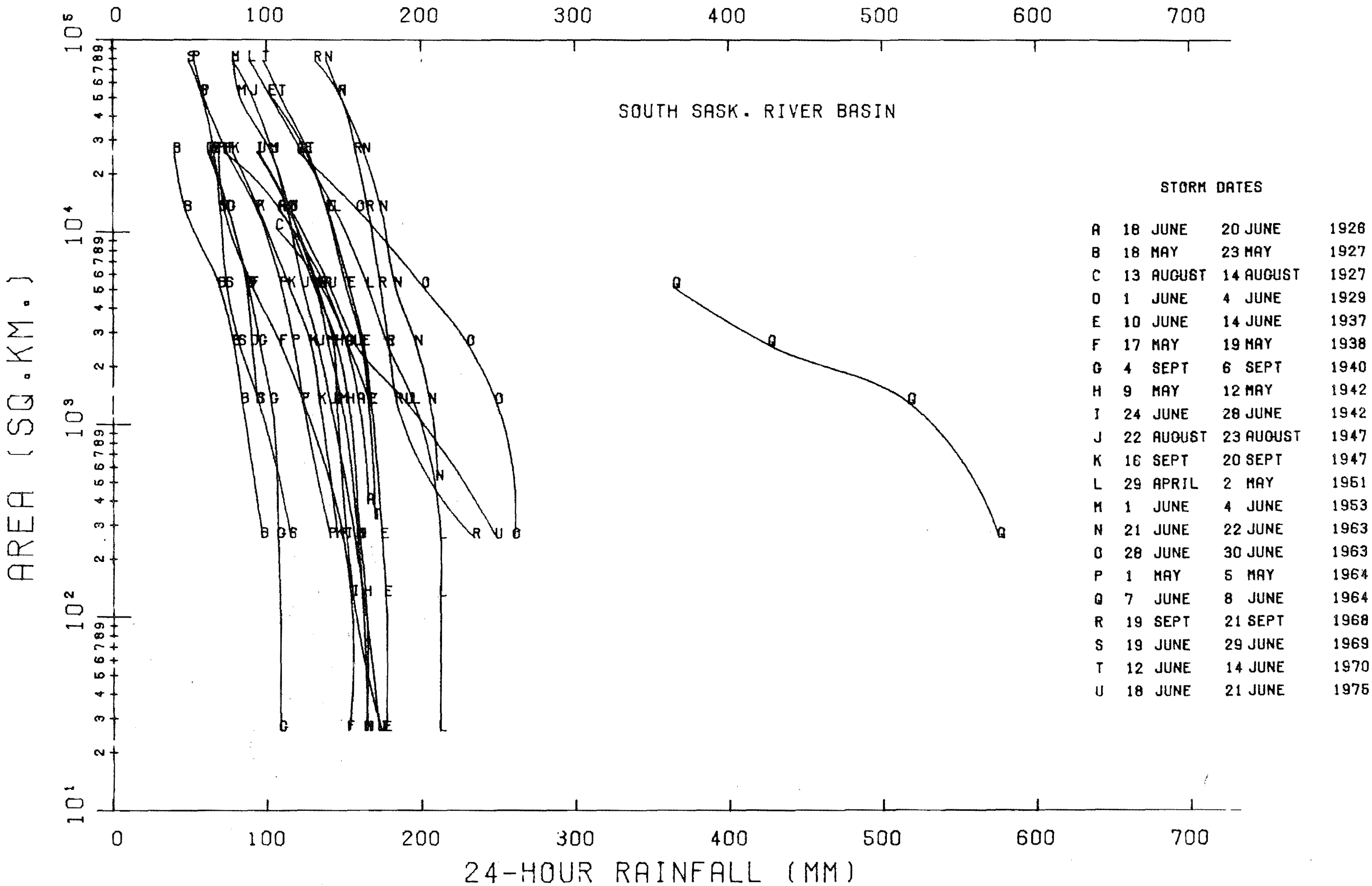

Figure 119 24-hour DAD curves for the South Saskatchewan River basin.

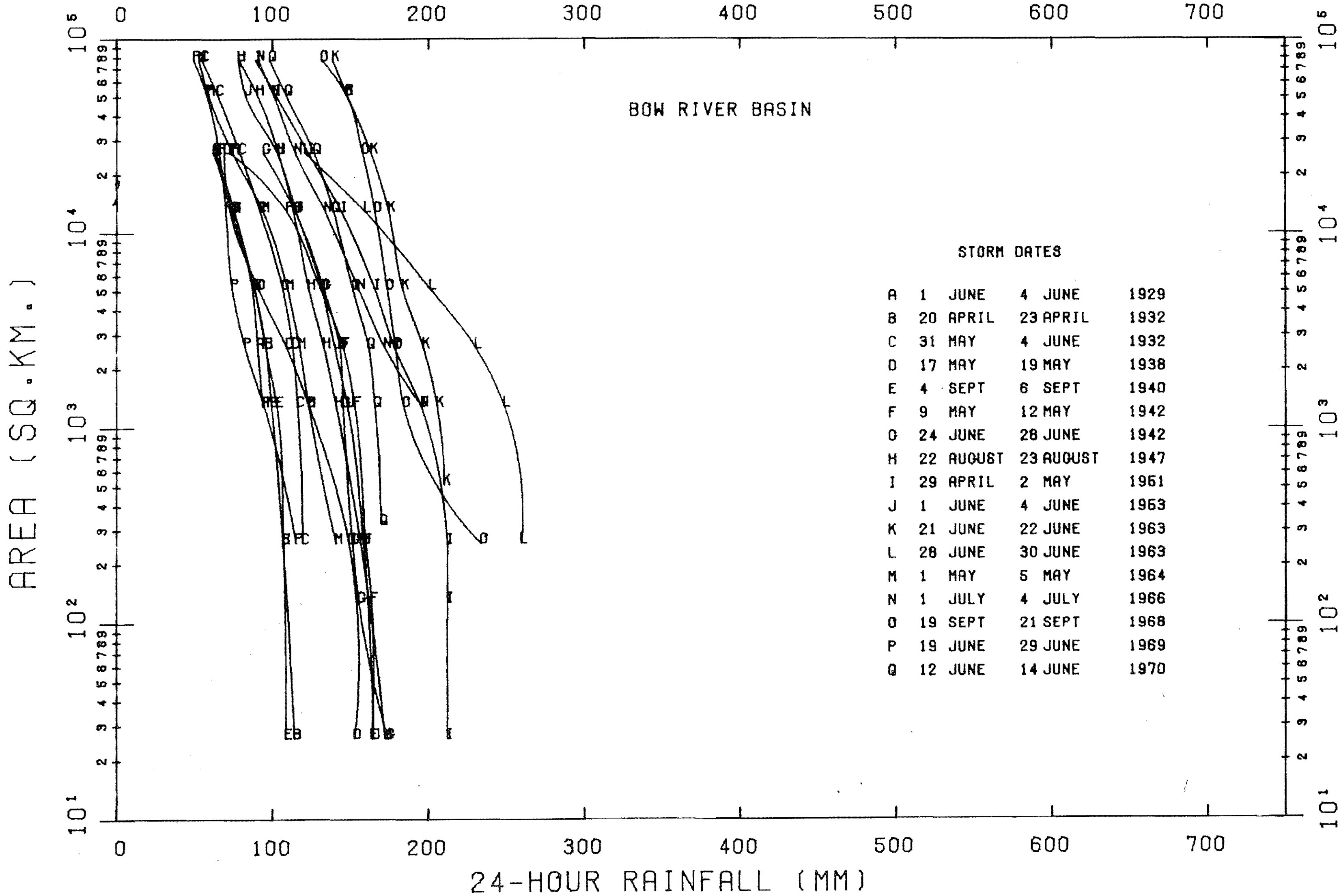

Figure 120 24-hour DAD curves for the Bow River basin.

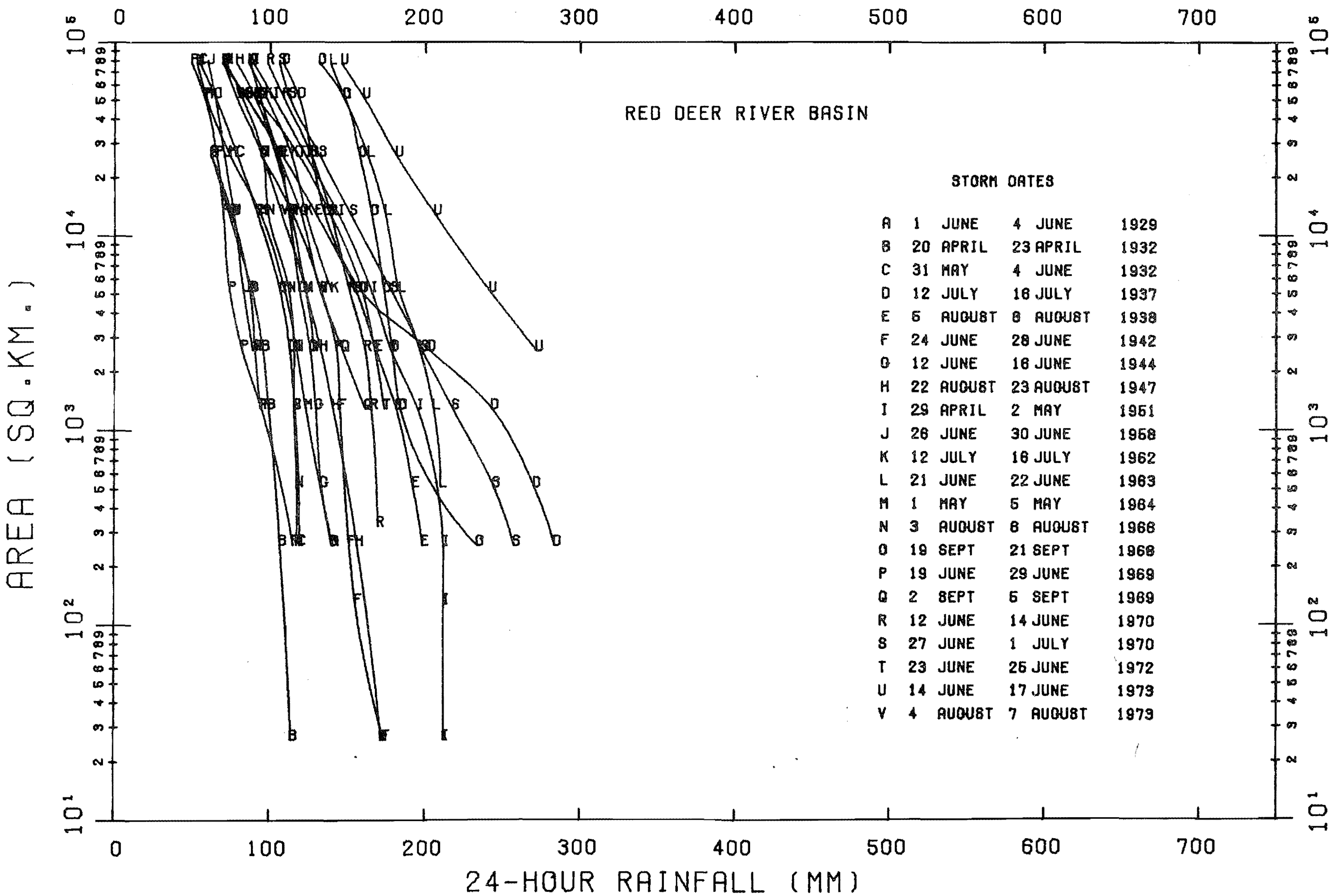

Figure 121 24-hour DAD curves for the Red Deer River basin.

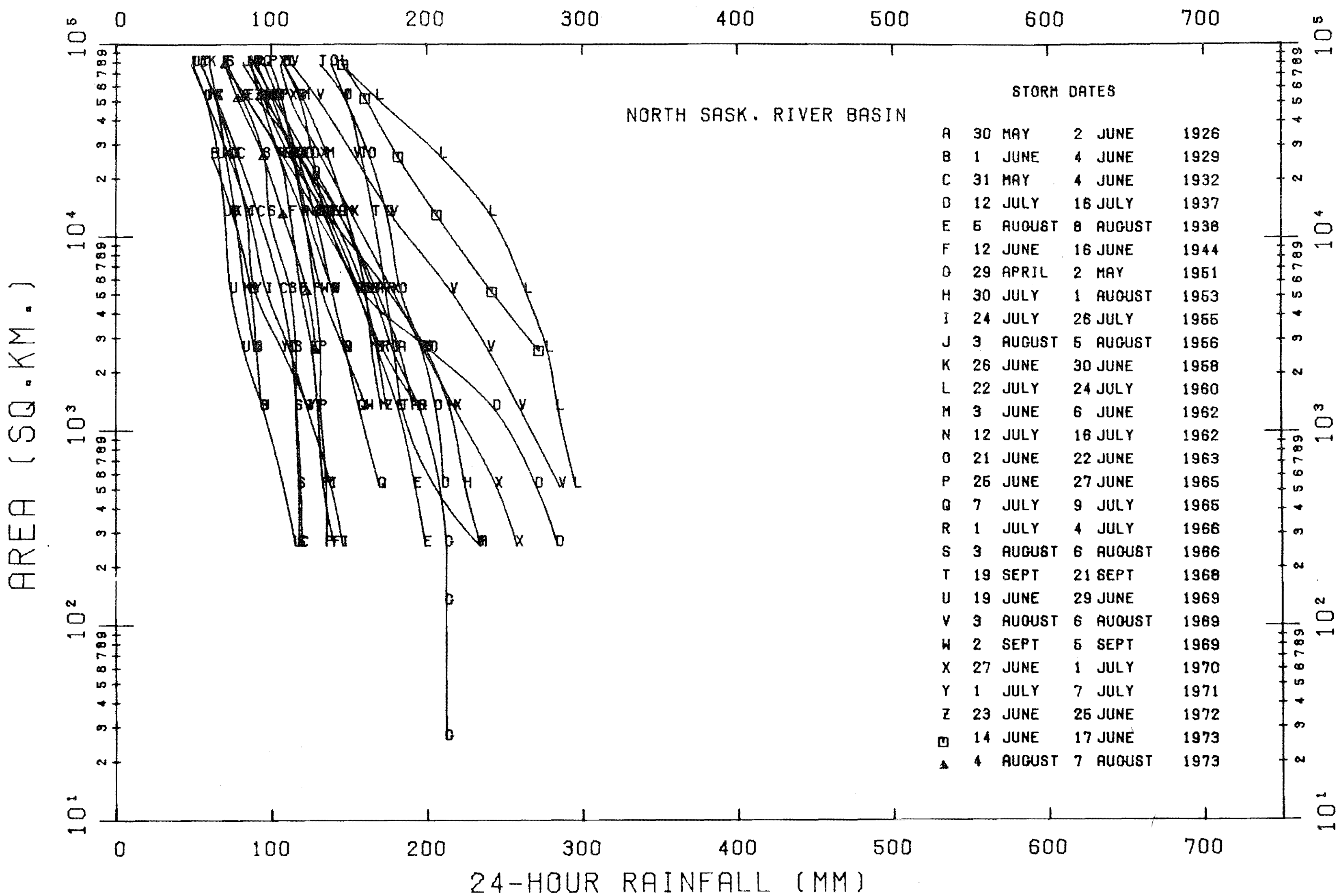

Figure 122 24-hour DAD curves for the North Saskatchewan River basin.

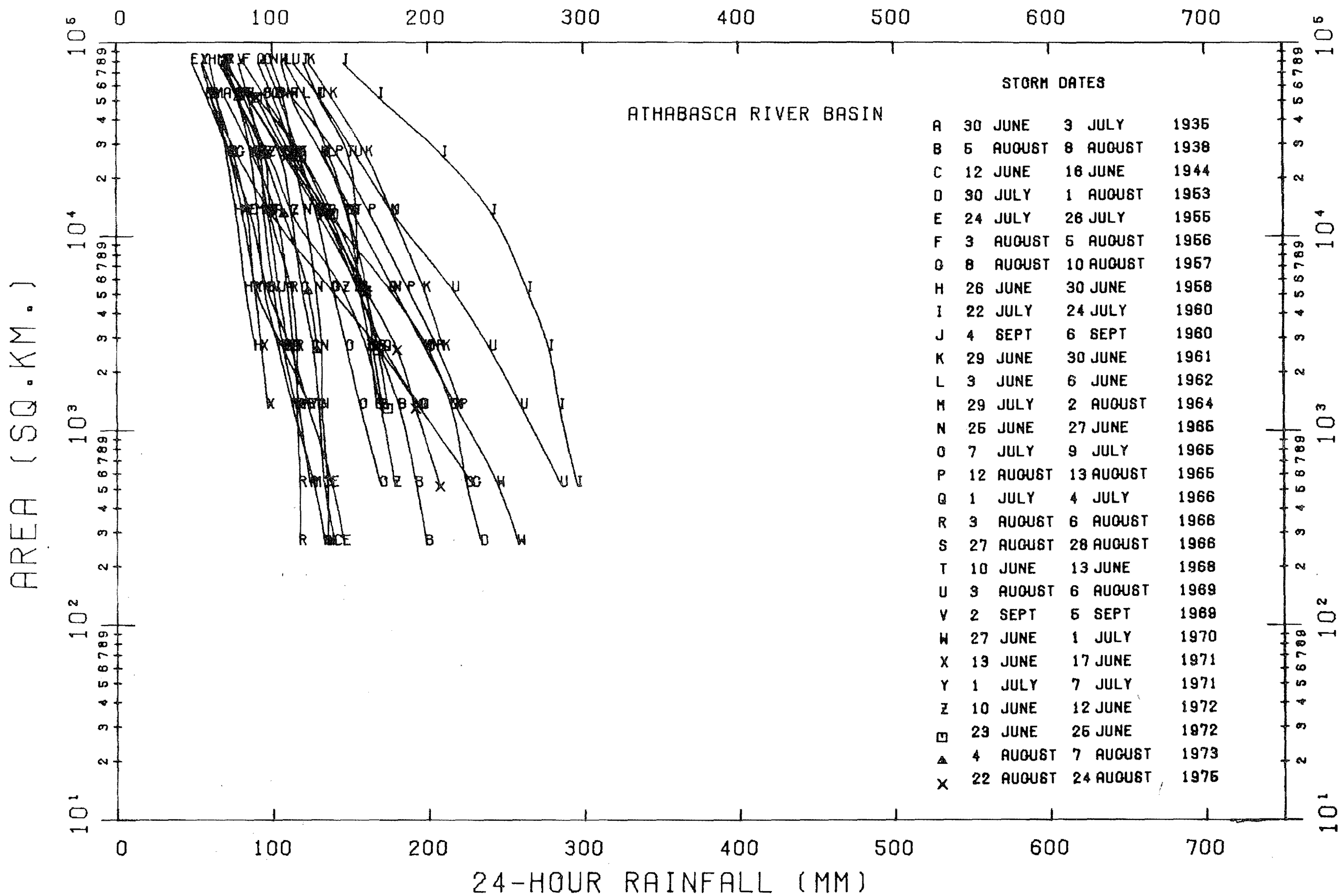

Figure 123 24-hour DAD curves for the Athabasca River basin.

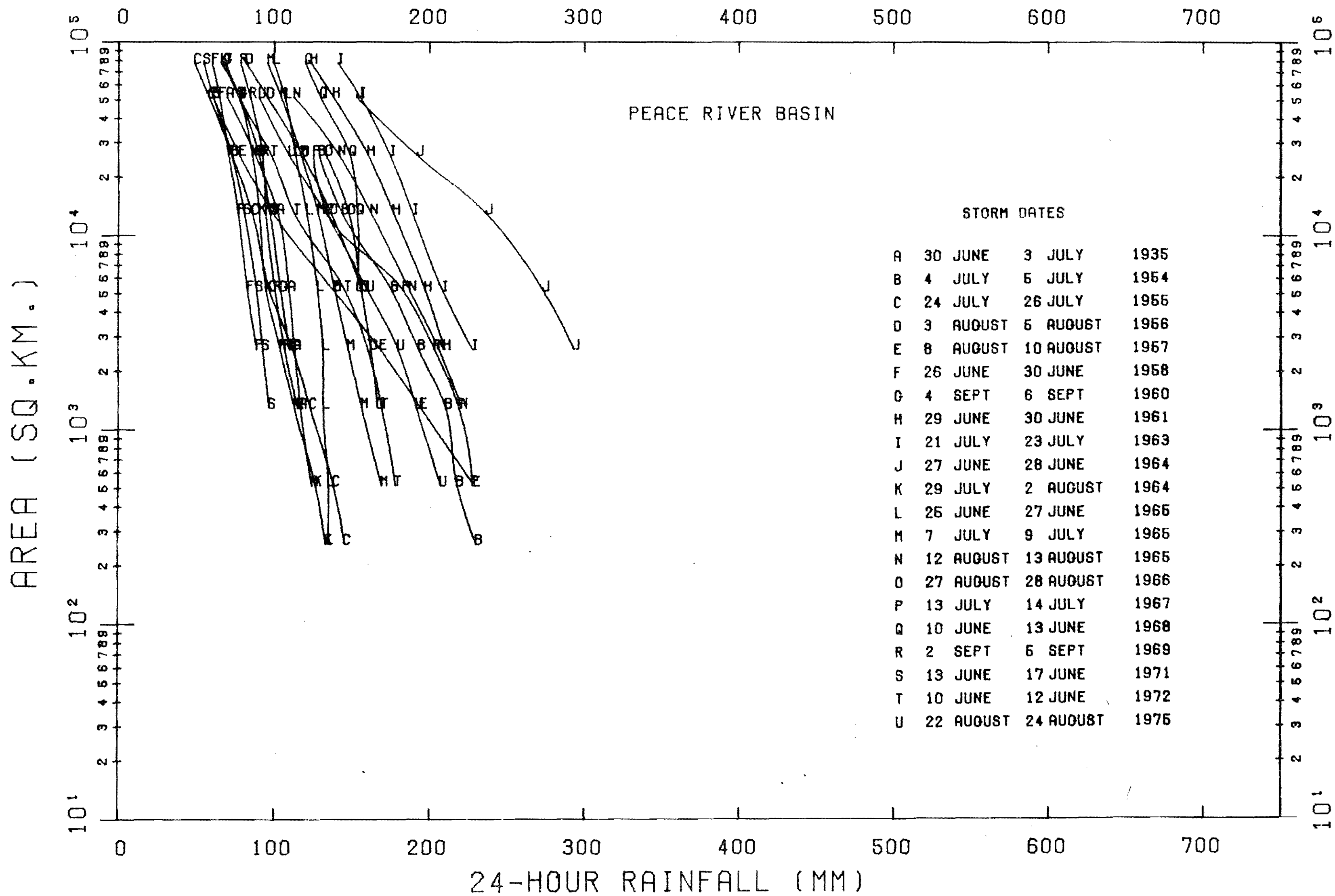

Figure 124 24-hour DAD curves for the Peace River basin.

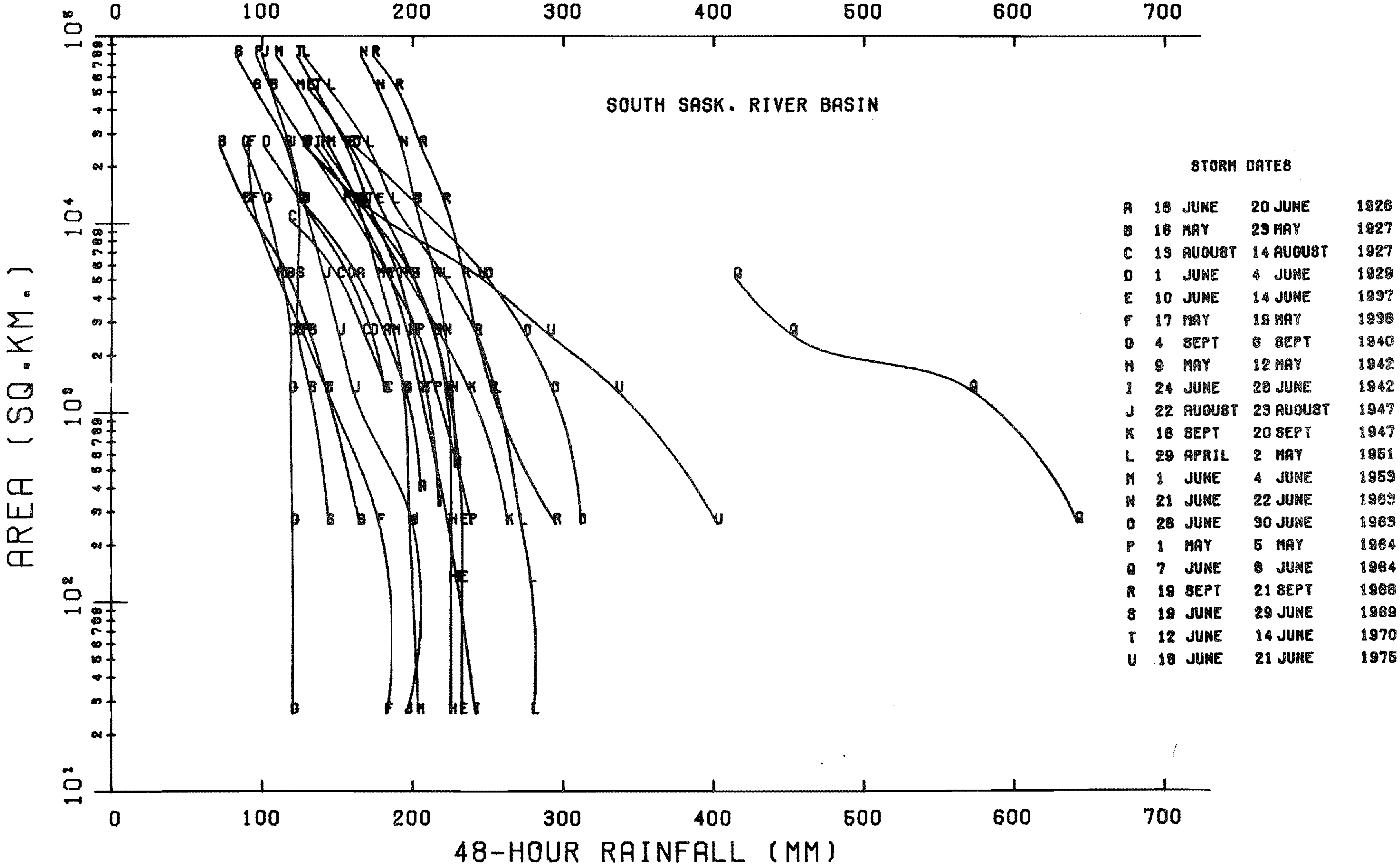

Figure 125 48-hour DAD curves for the South Saskatchewan River basin.

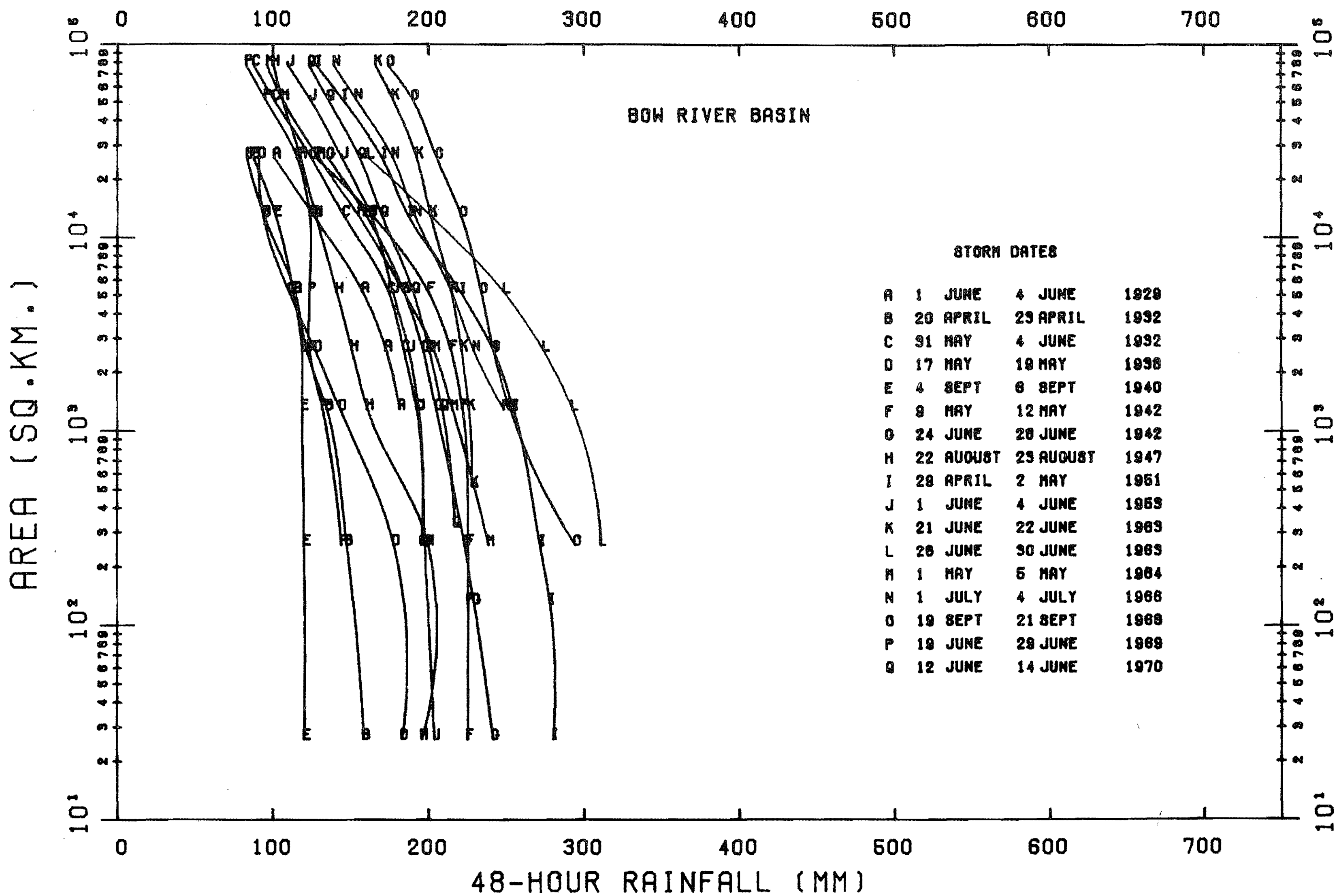

Figure 126 48-hour DAD curves for the Bow River basin.

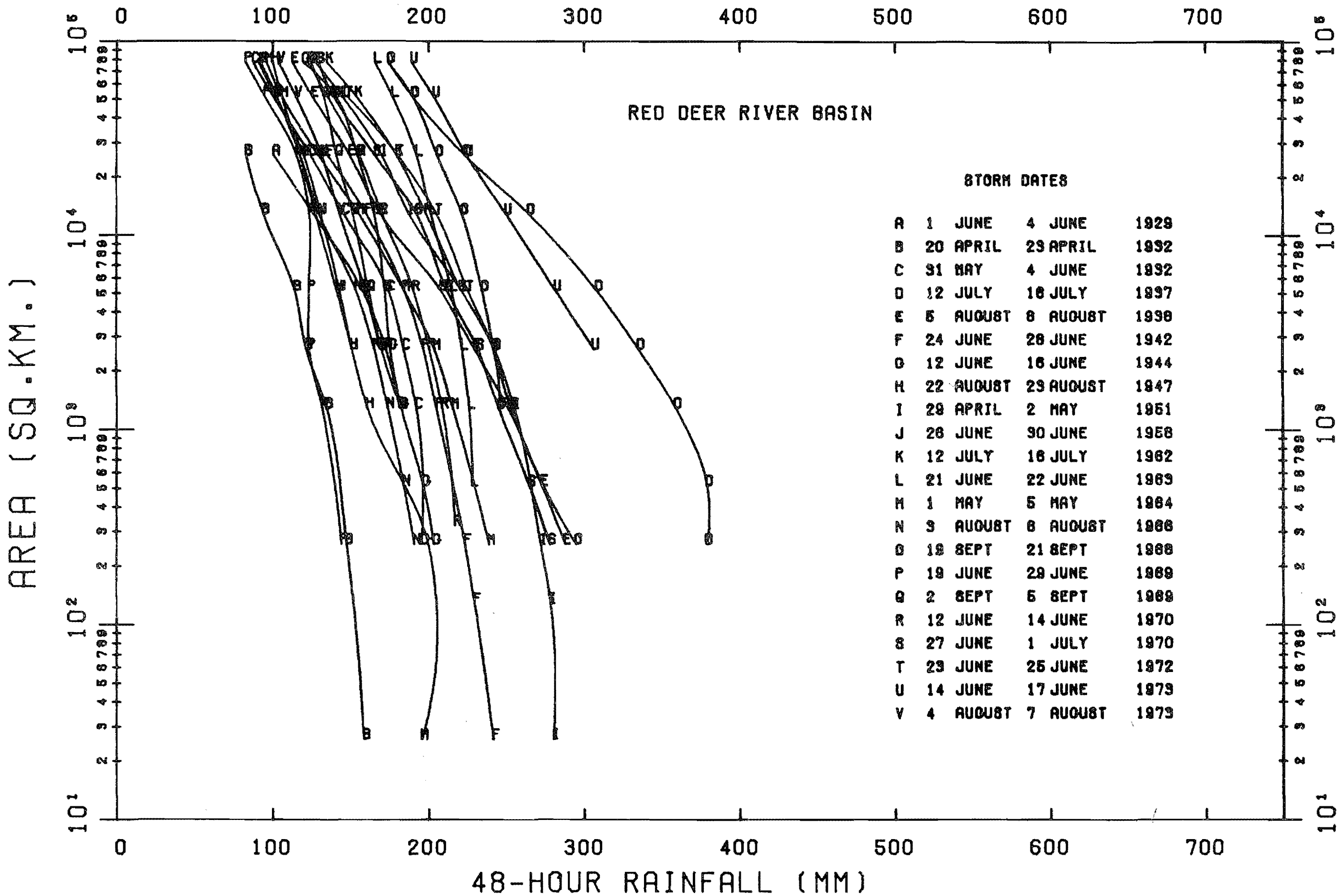

Figure 127 48-hour DAD curves for the Red Deer River basin.

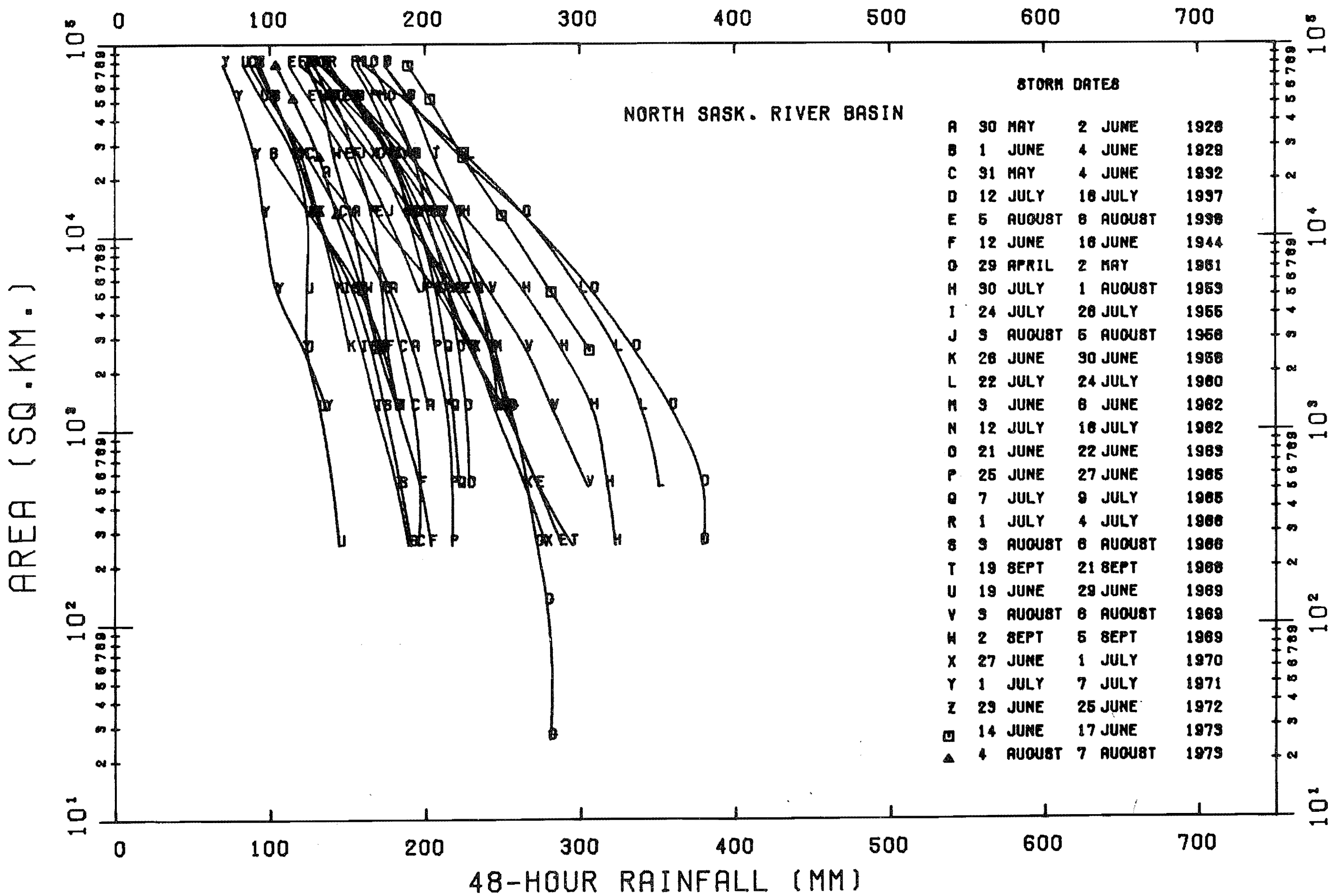

Figure 128 48-hour DAD curves for the North Saskatchewan River basin.

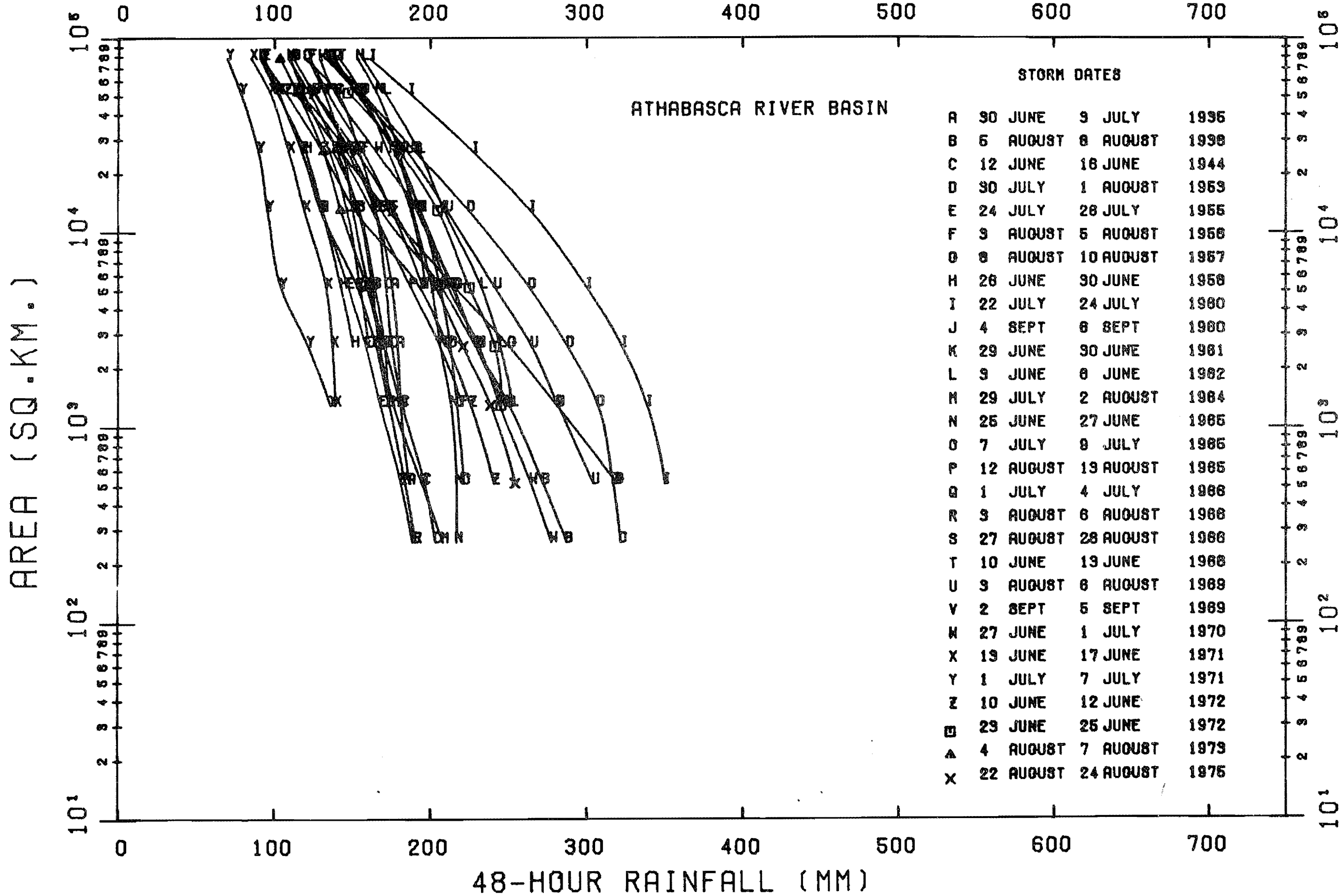

Figure 129 48-hour DAD curves for the Athabasca River basin.

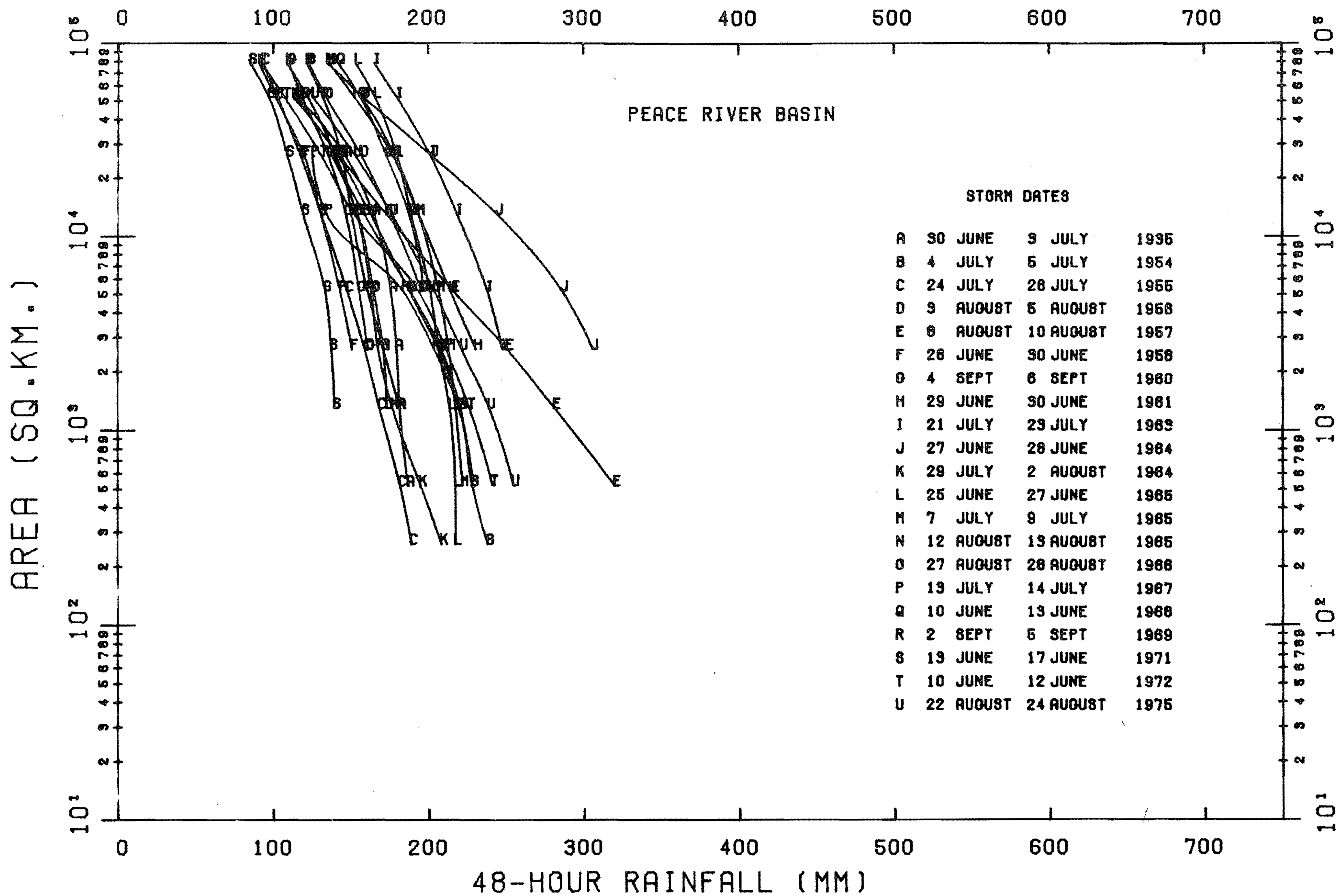

Figure 130 48-hour DAD curves for the Peace River basin.

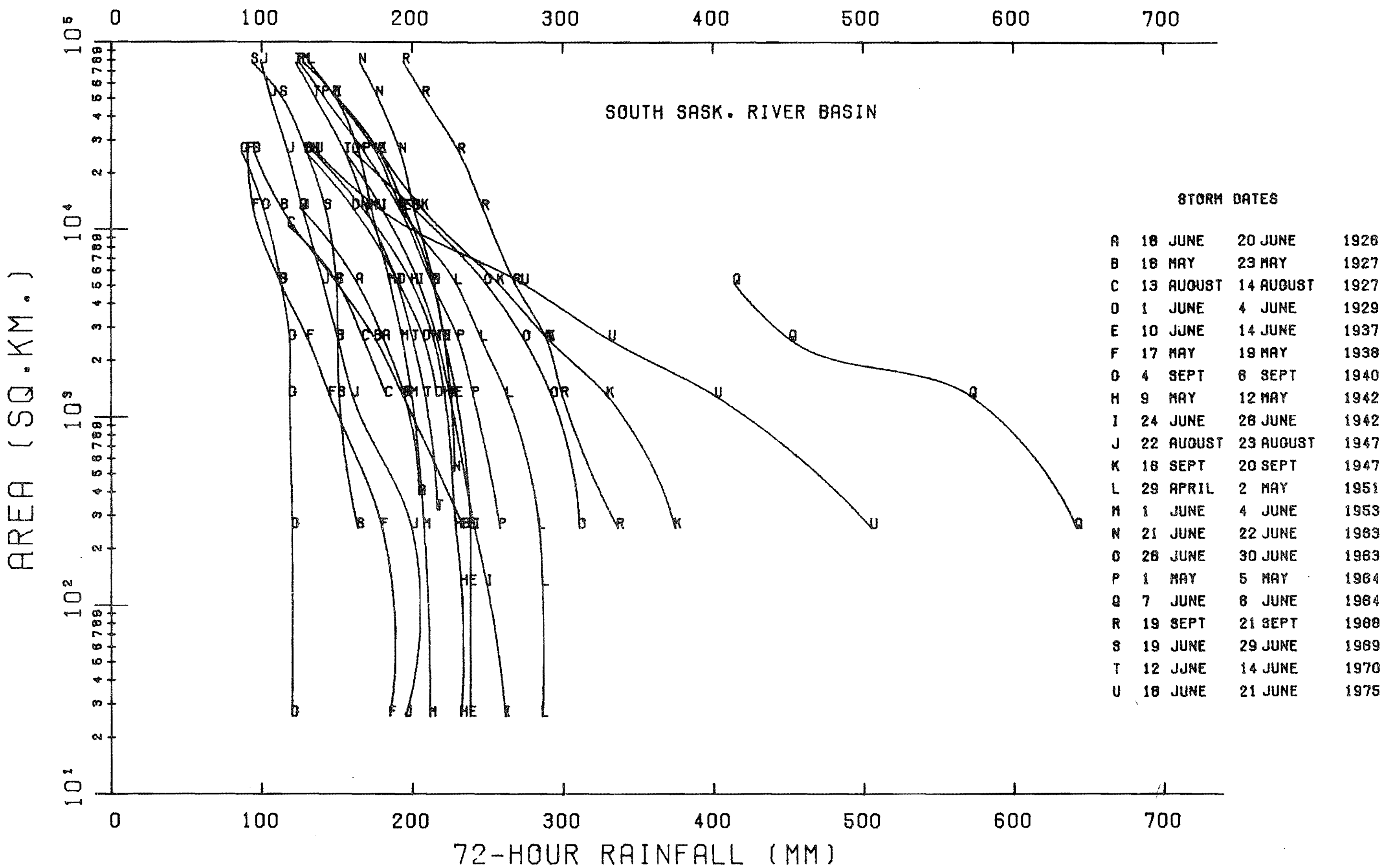

Figure 131 72-hour DAD curves for the South Saskatchewan River basin.

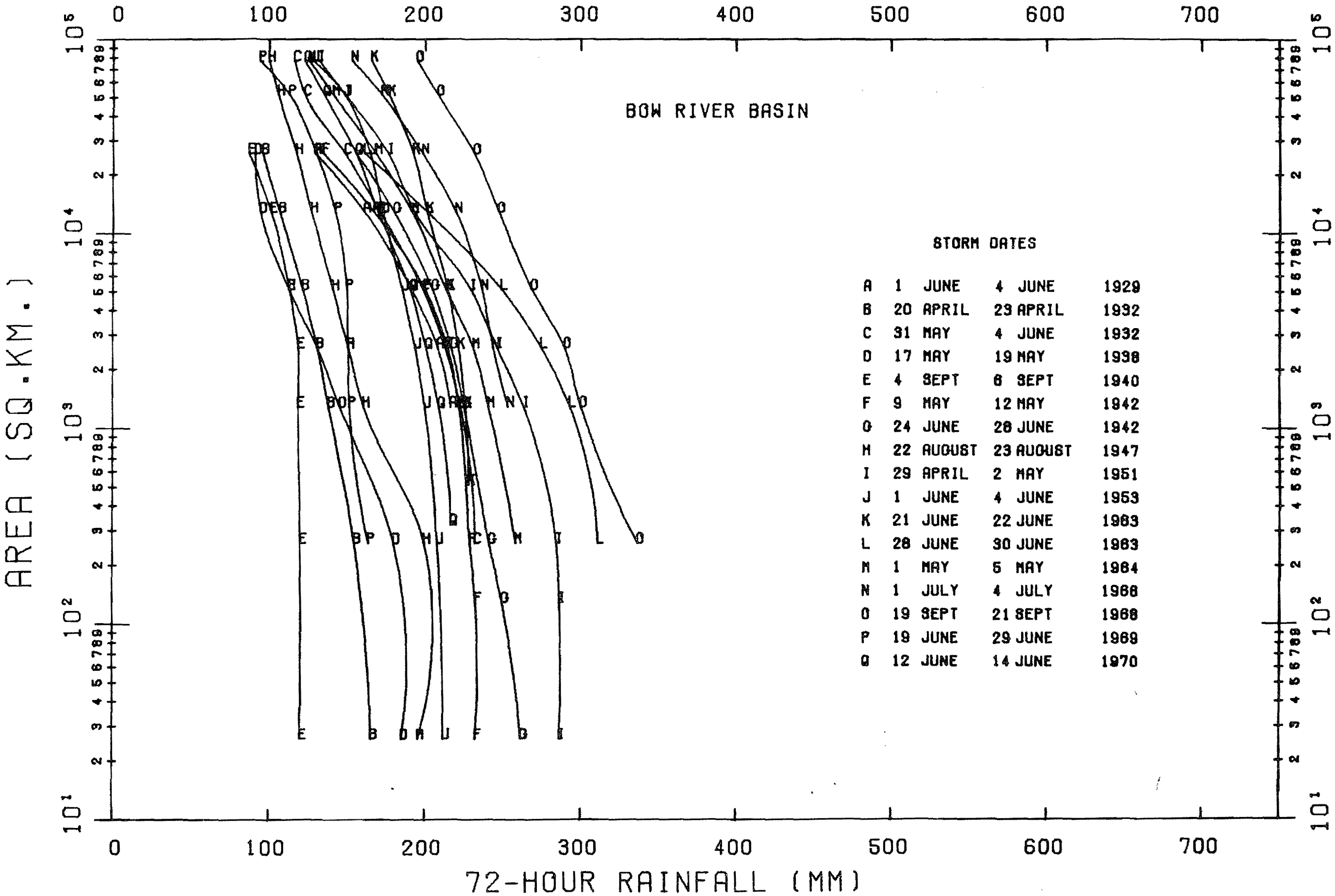

Figure 132 72-hour DAD curves for the Bow River basin.

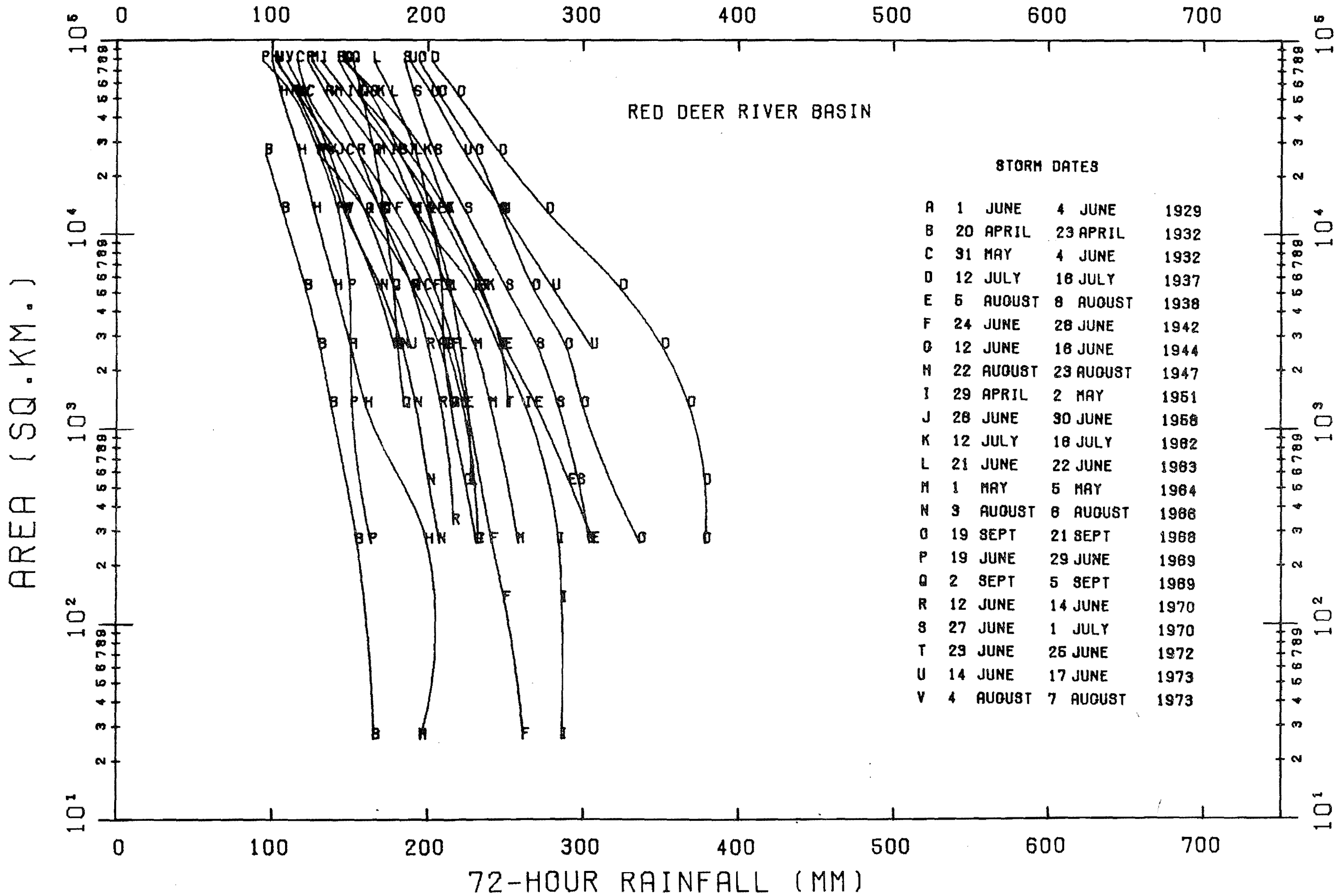

Figure 133 72-hour DAD curves for the Red Deer River basin.

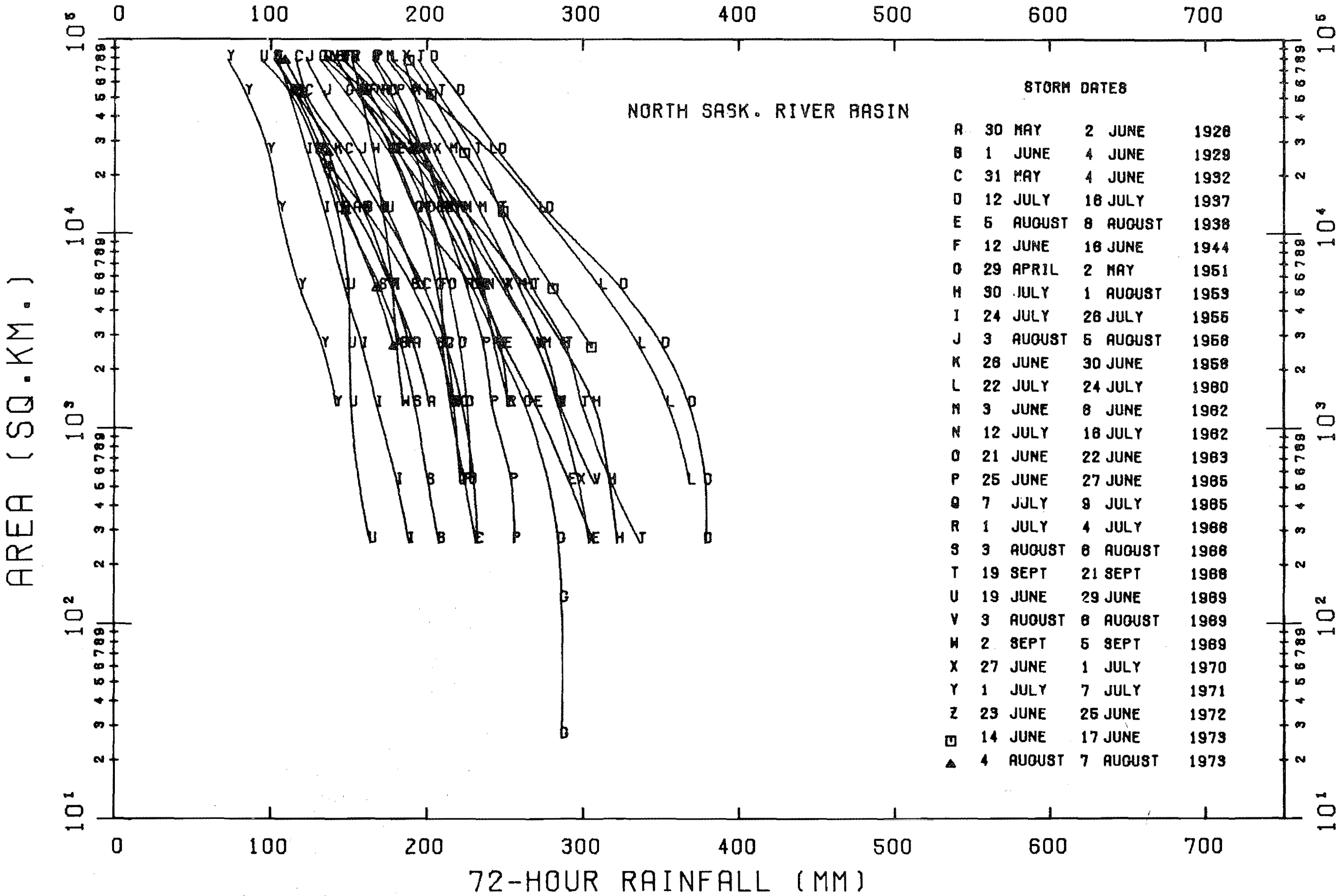

Figure 134 72-hour DAD curves for the North Saskatchewan River basin.

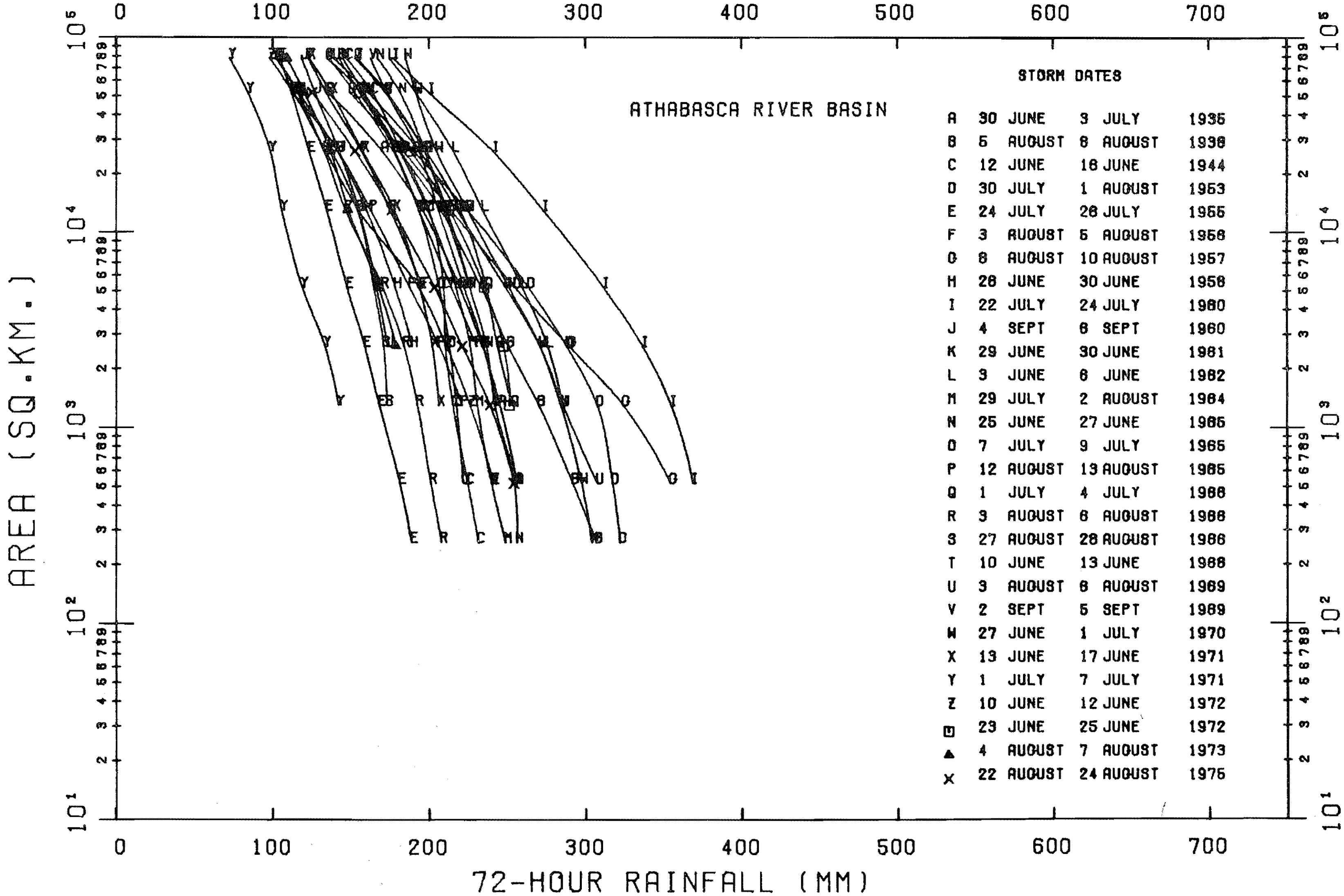

Figure 135 72-hour DAD curves for the Athabasca River basin.

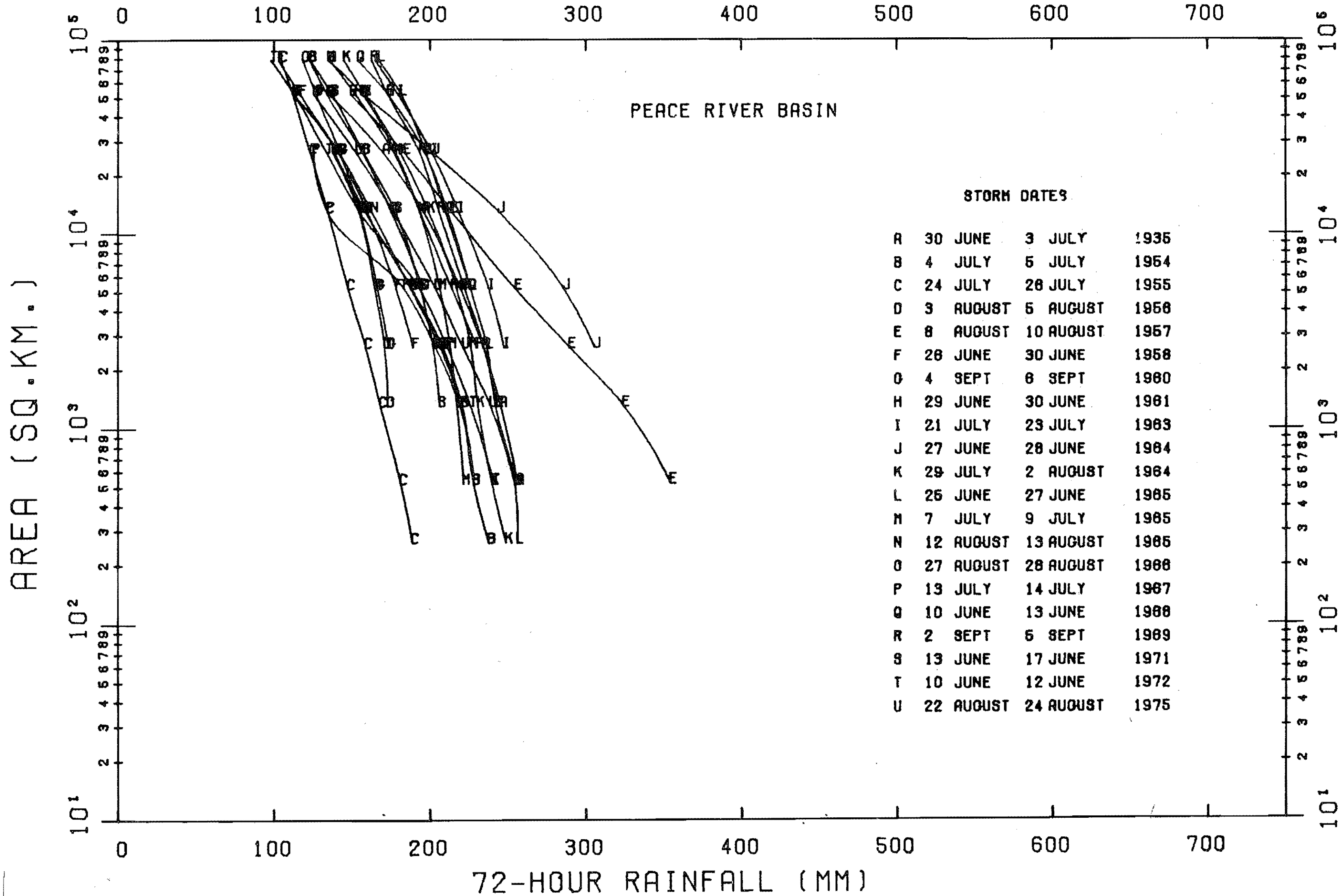

Figure 136 72-hour DAD curves for the Peace River basin.

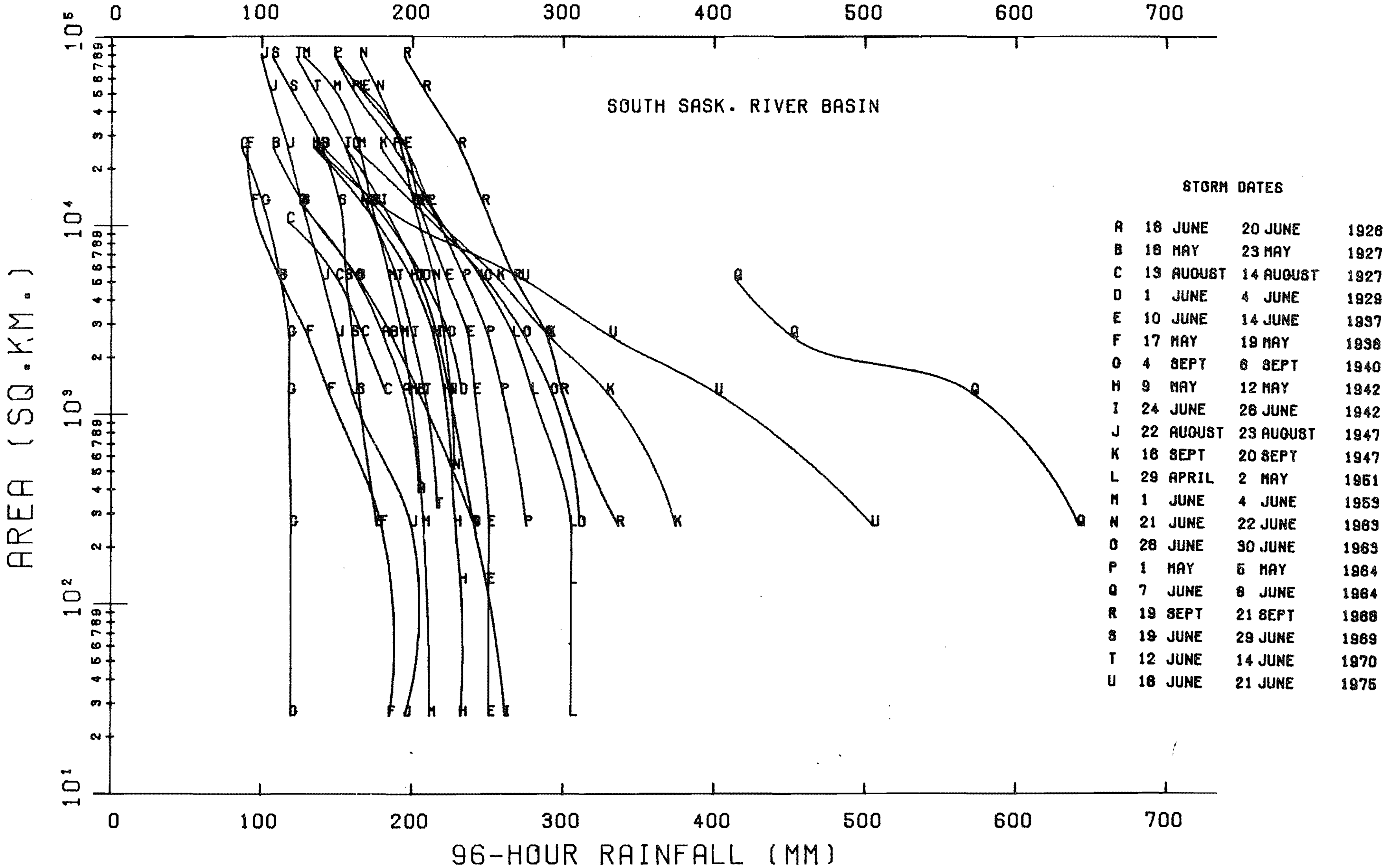

Figure 137 96-hour DAD curves for the South Saskatchewan River basin.

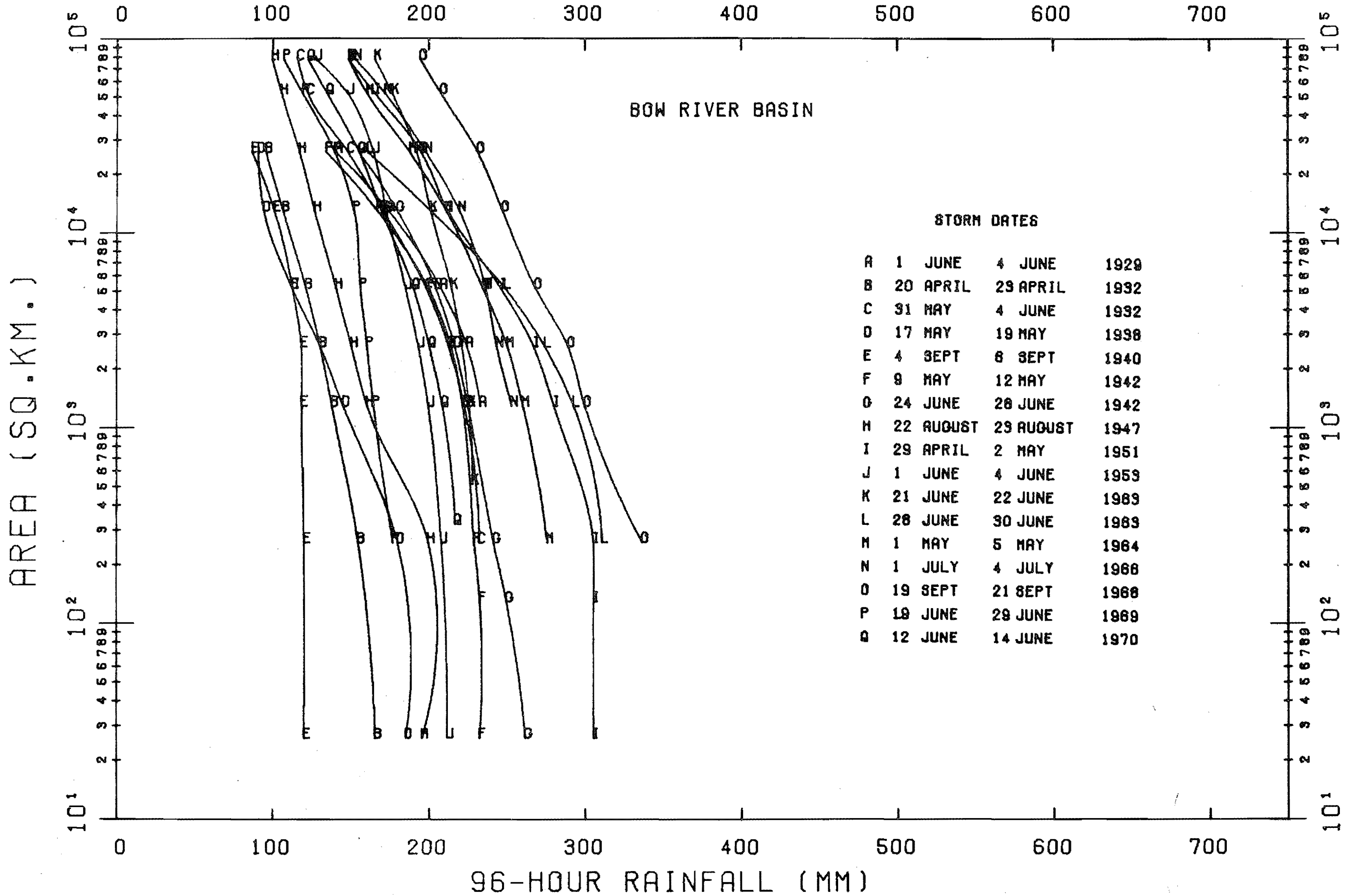

Figure 138 96-hour DAD curves for the Bow River basin.

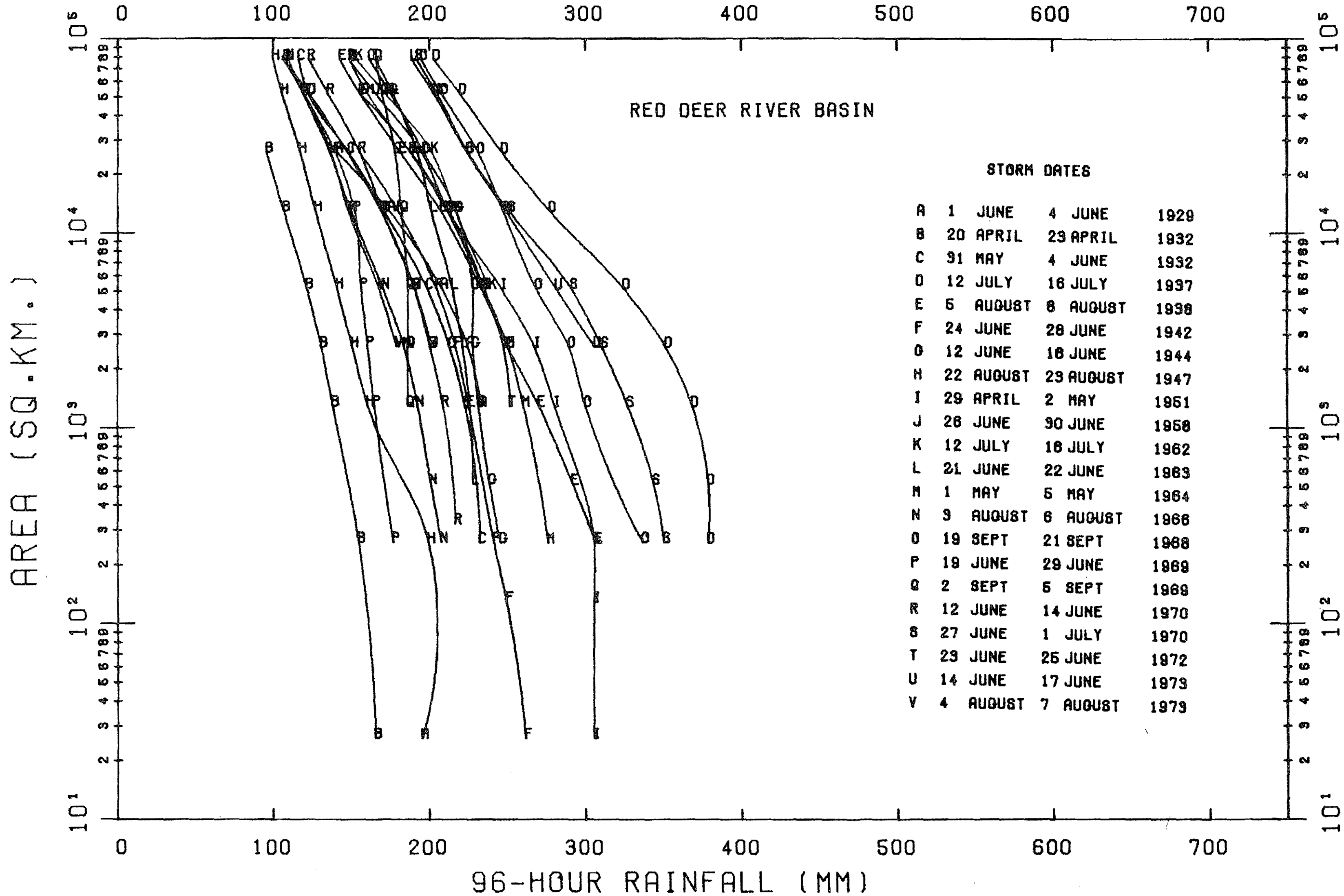

Figure 139 96-hour DAD curves for the Red Deer River basin.

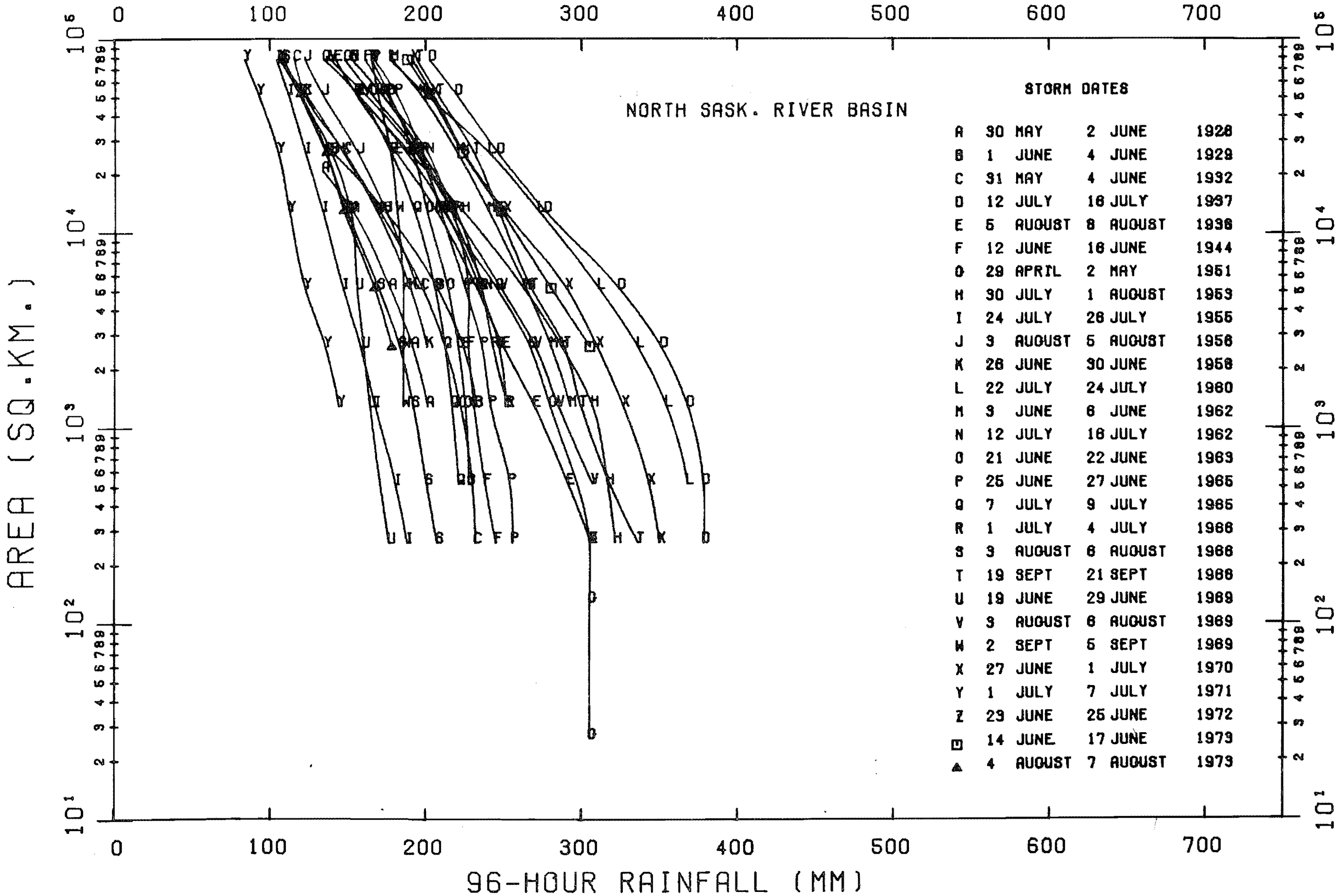

Figure 140 96-hour DAD curves for the North Saskatchewan River basin.

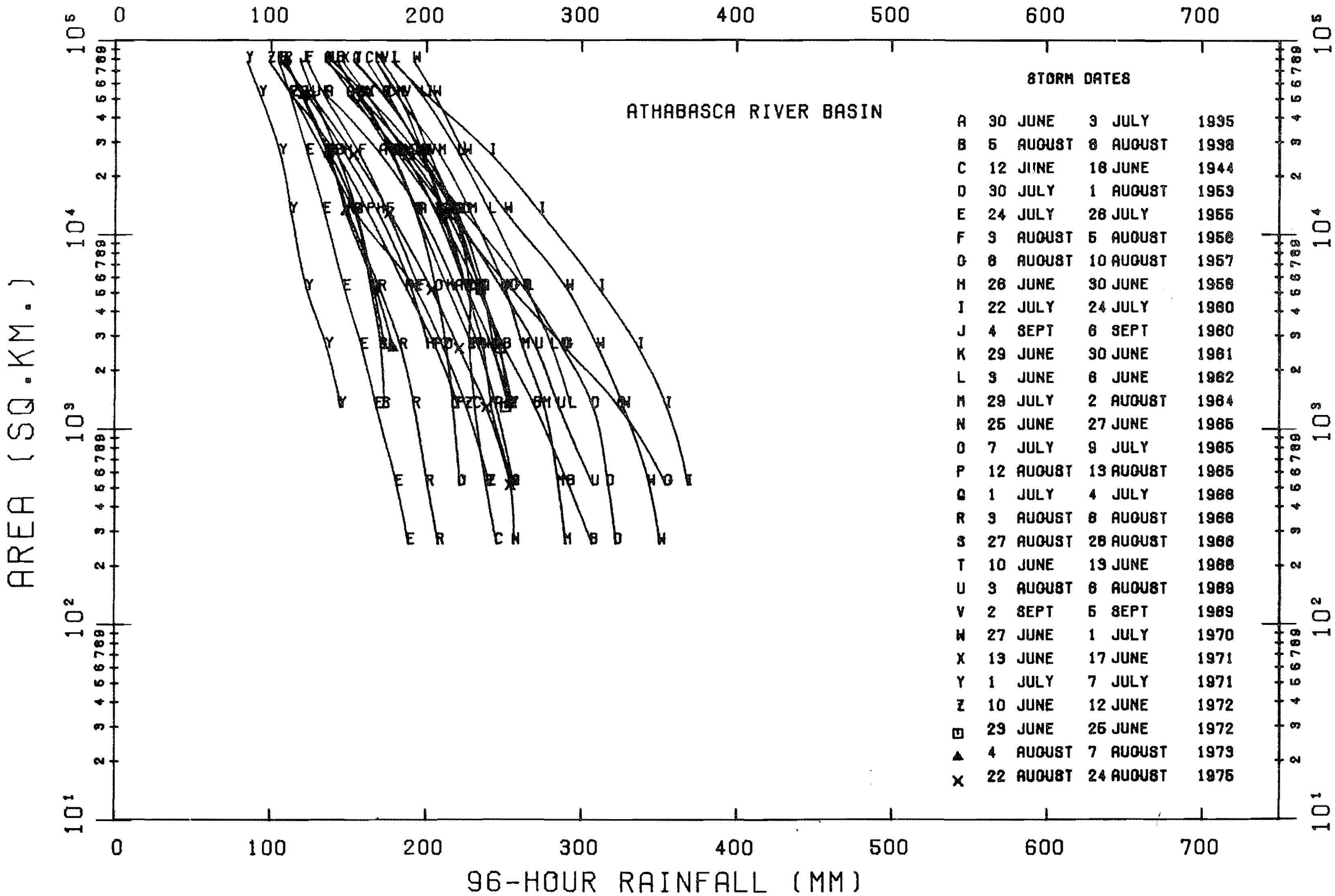

Figure 141 96-hour DAD curves for the Athabasca River basin.

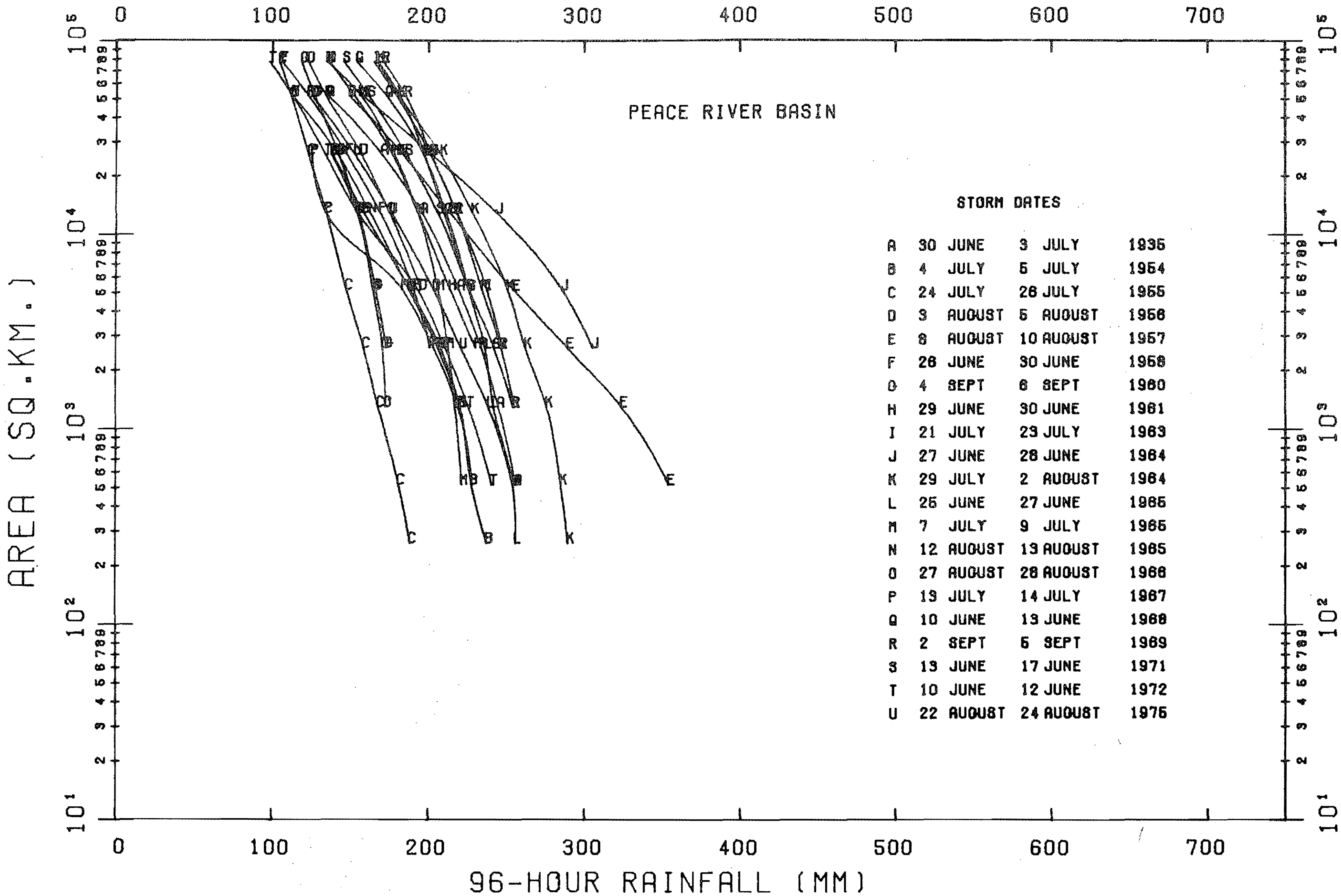

Figure 142 96-hour DAD curves for the Peace River basin.

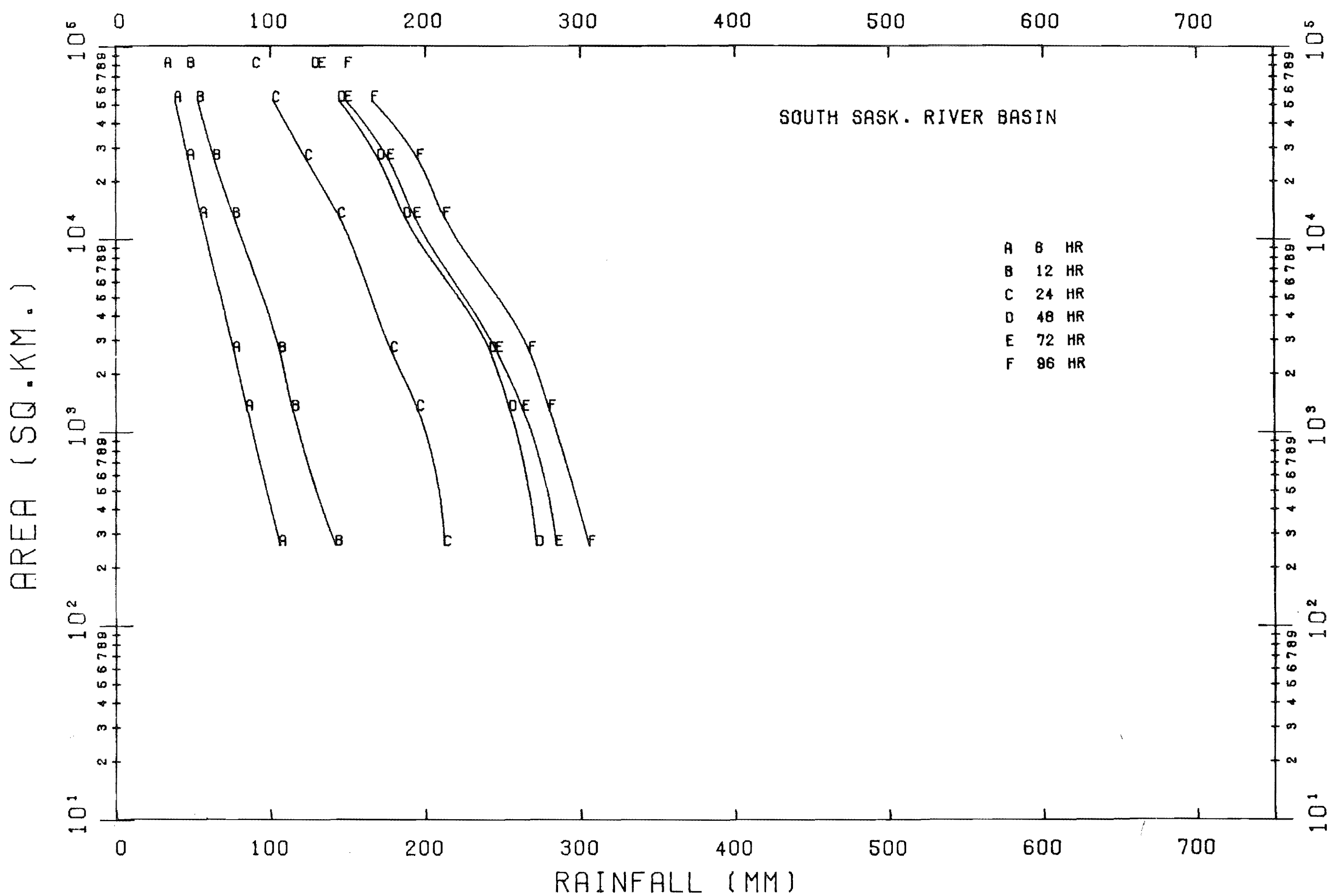

Figure 143 Envelope of the DAD curves for the South Saskatchewan River basin for April.

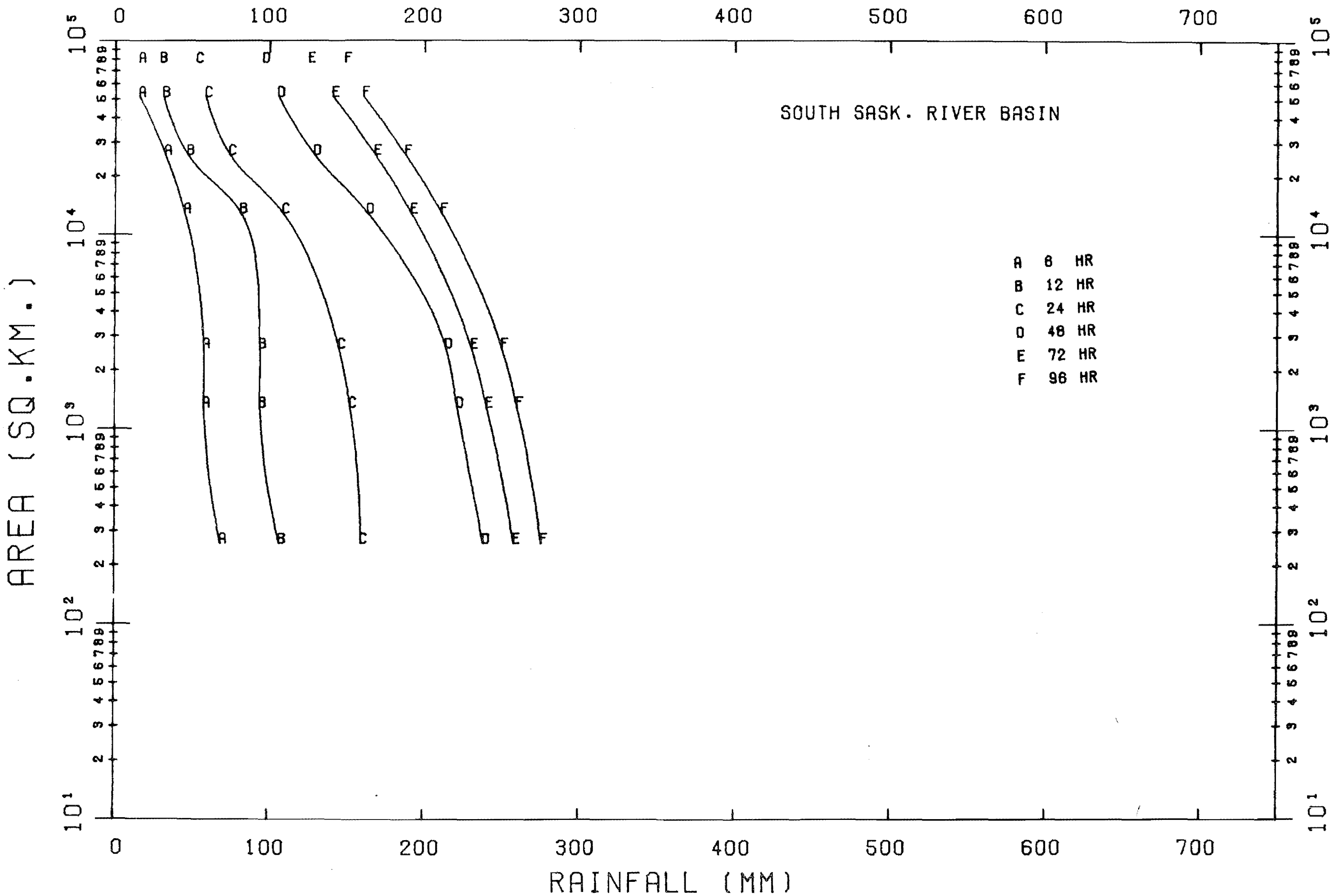

Figure 144 Envelope of the DAD curves for the South Saskatchewan River basin for May.

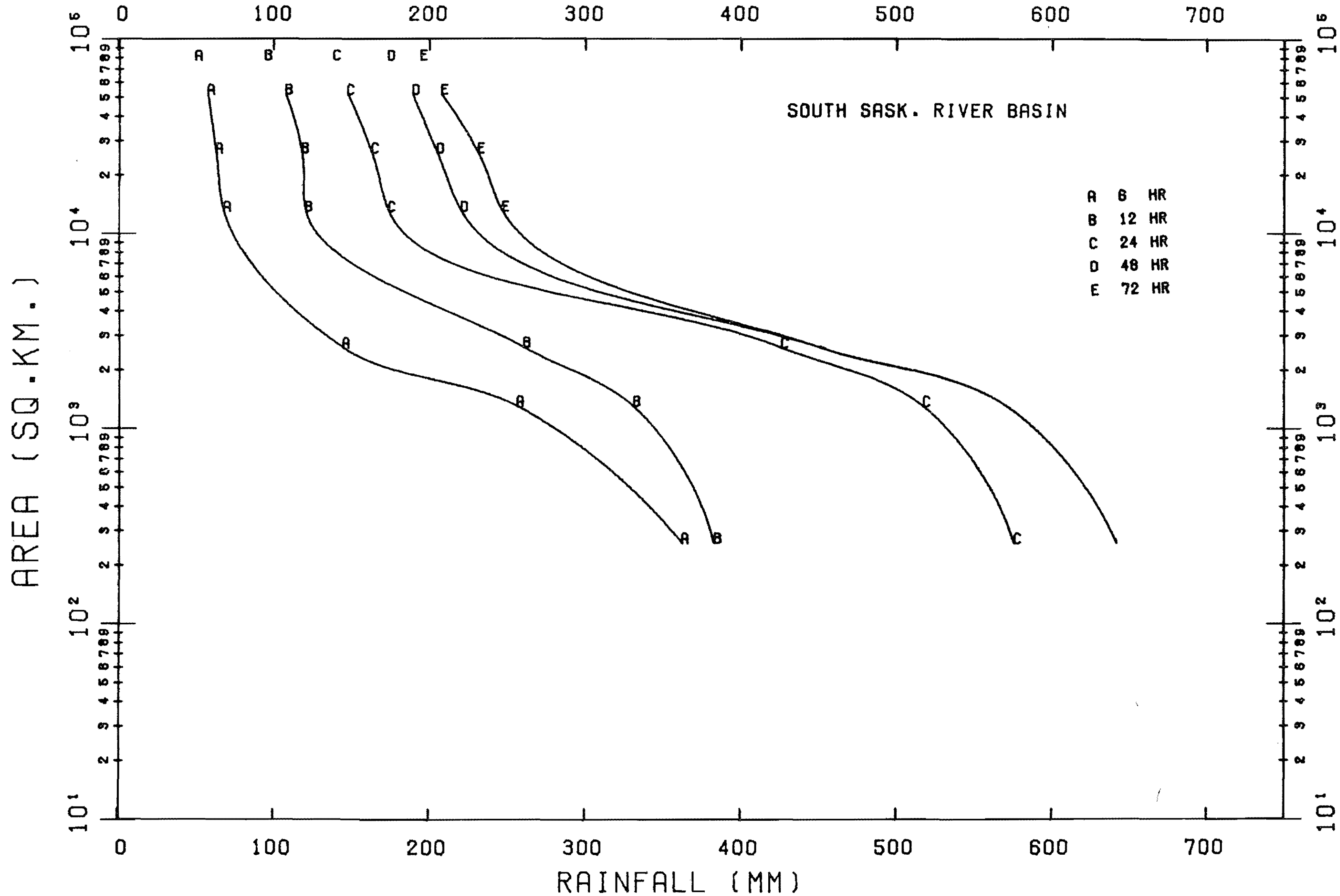

Figure 145 Envelope of the DAD curves for the South Saskatchewan River basin for June.

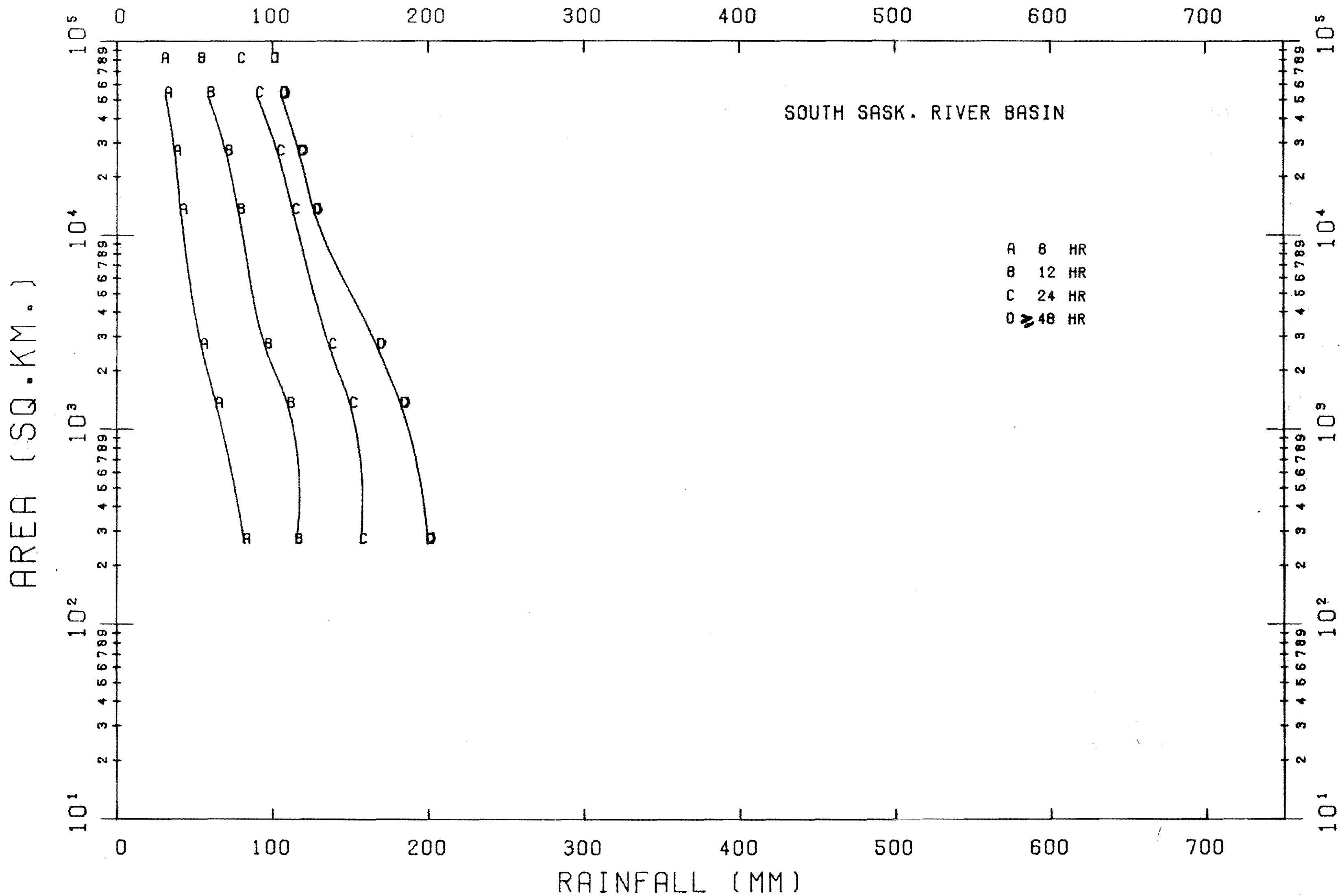

Figure 146 Envelope of the DAD curves for the South Saskatchewan River basin for August.

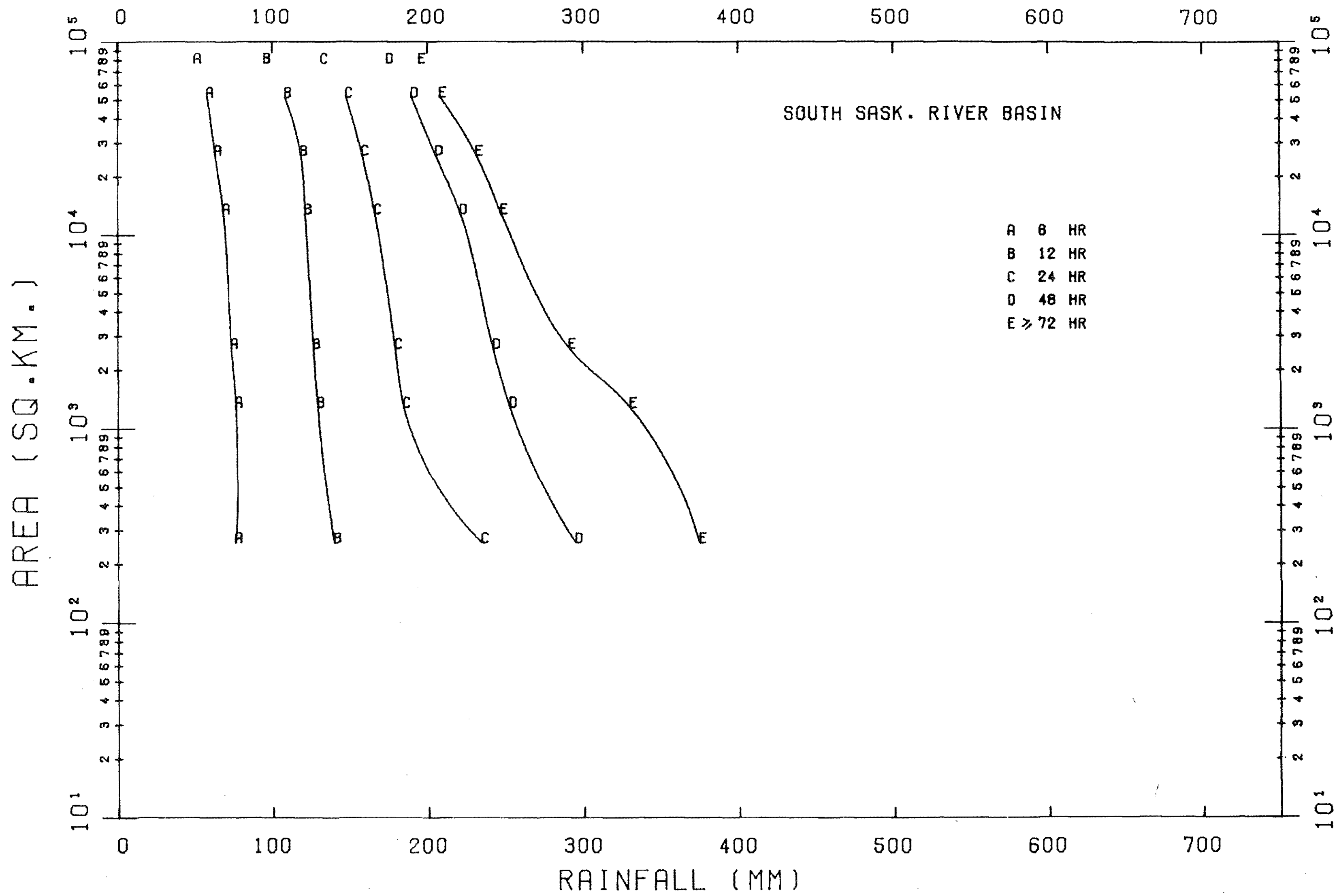

Figure 147 Envelope of the DAD curves for the South Saskatchewan River basin for September.

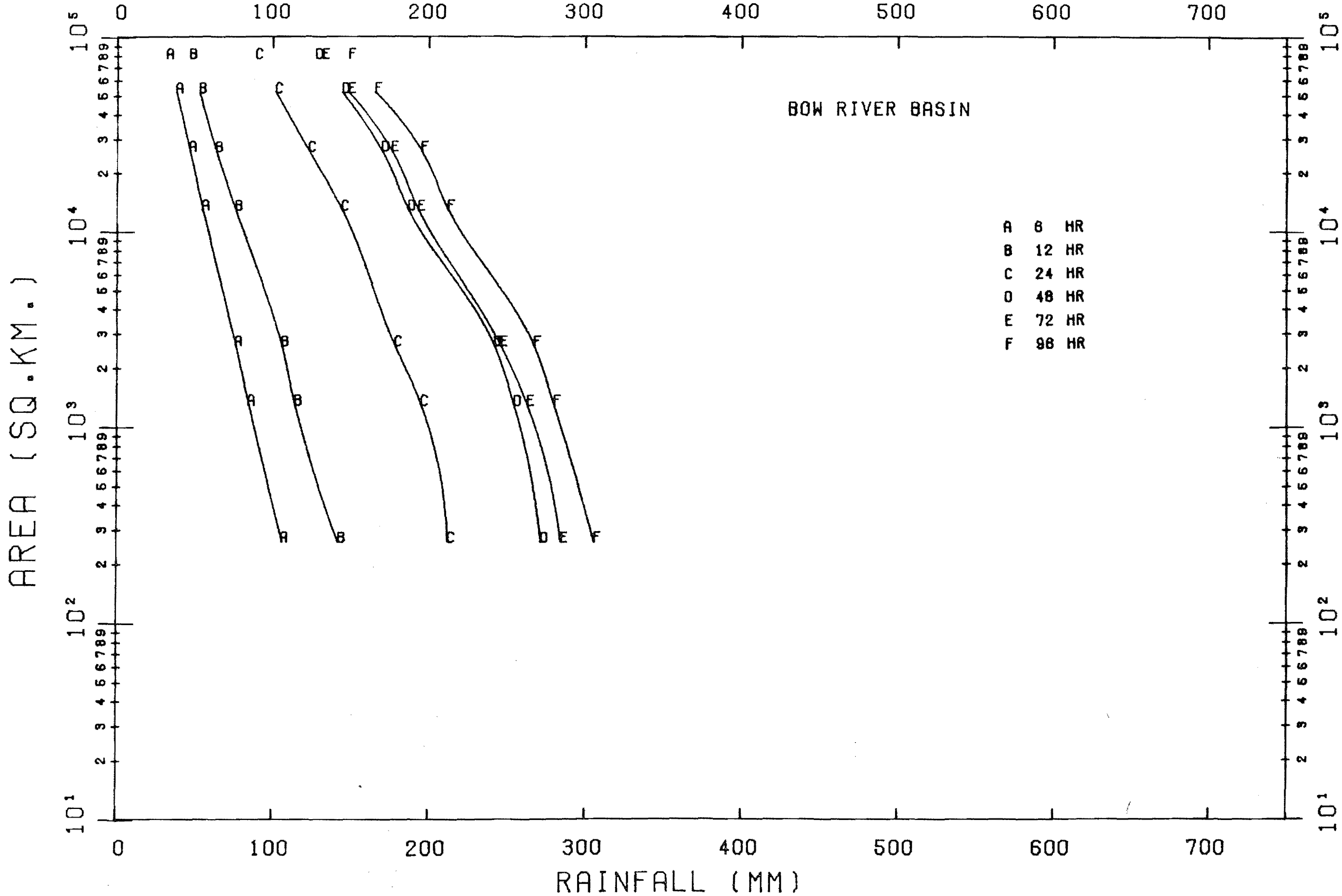

Figure 148 Envelope of the DAD curves for the Bow River basin for April.

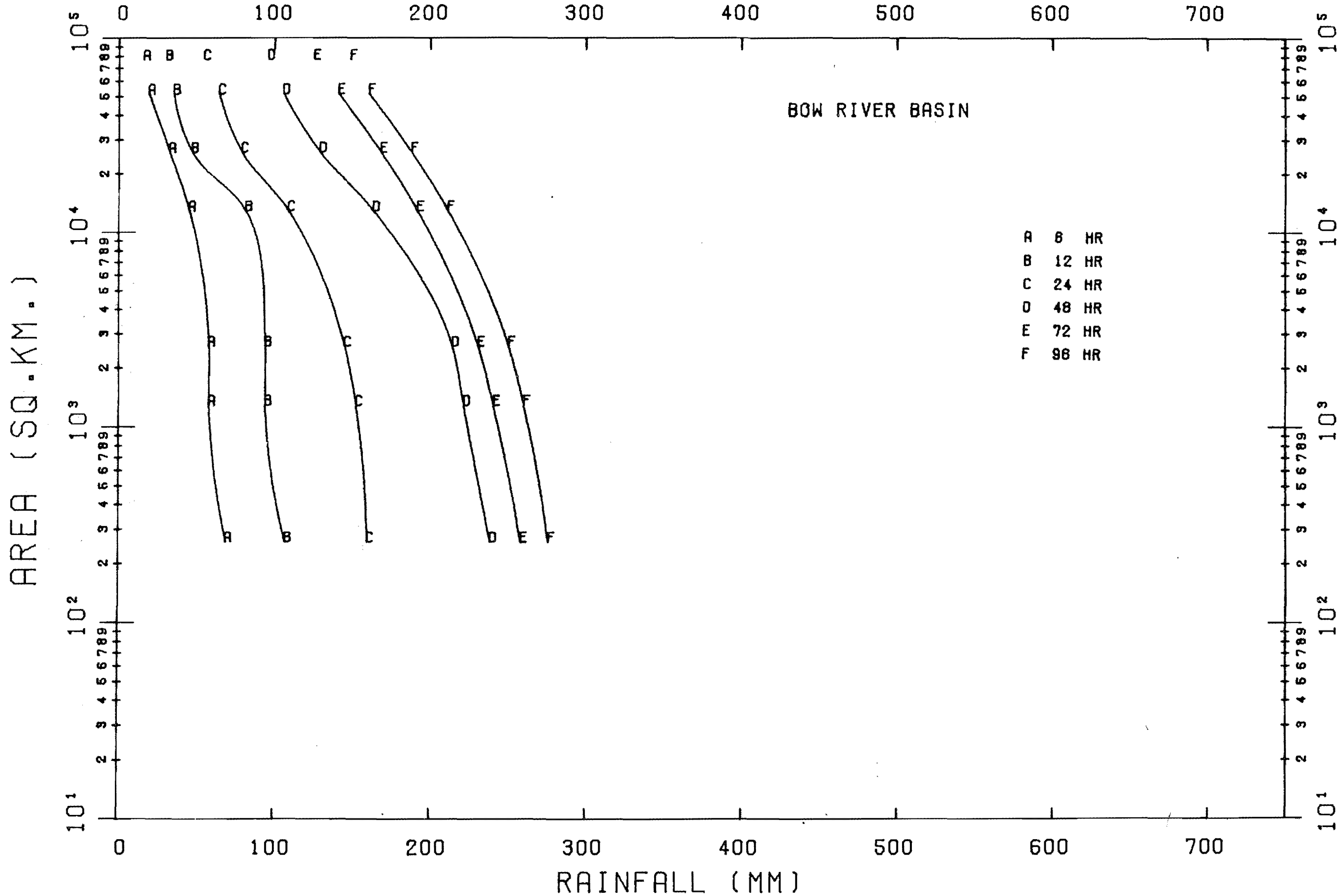

Figure 149 Envelope of the DAD curves for the Bow River basin for May.

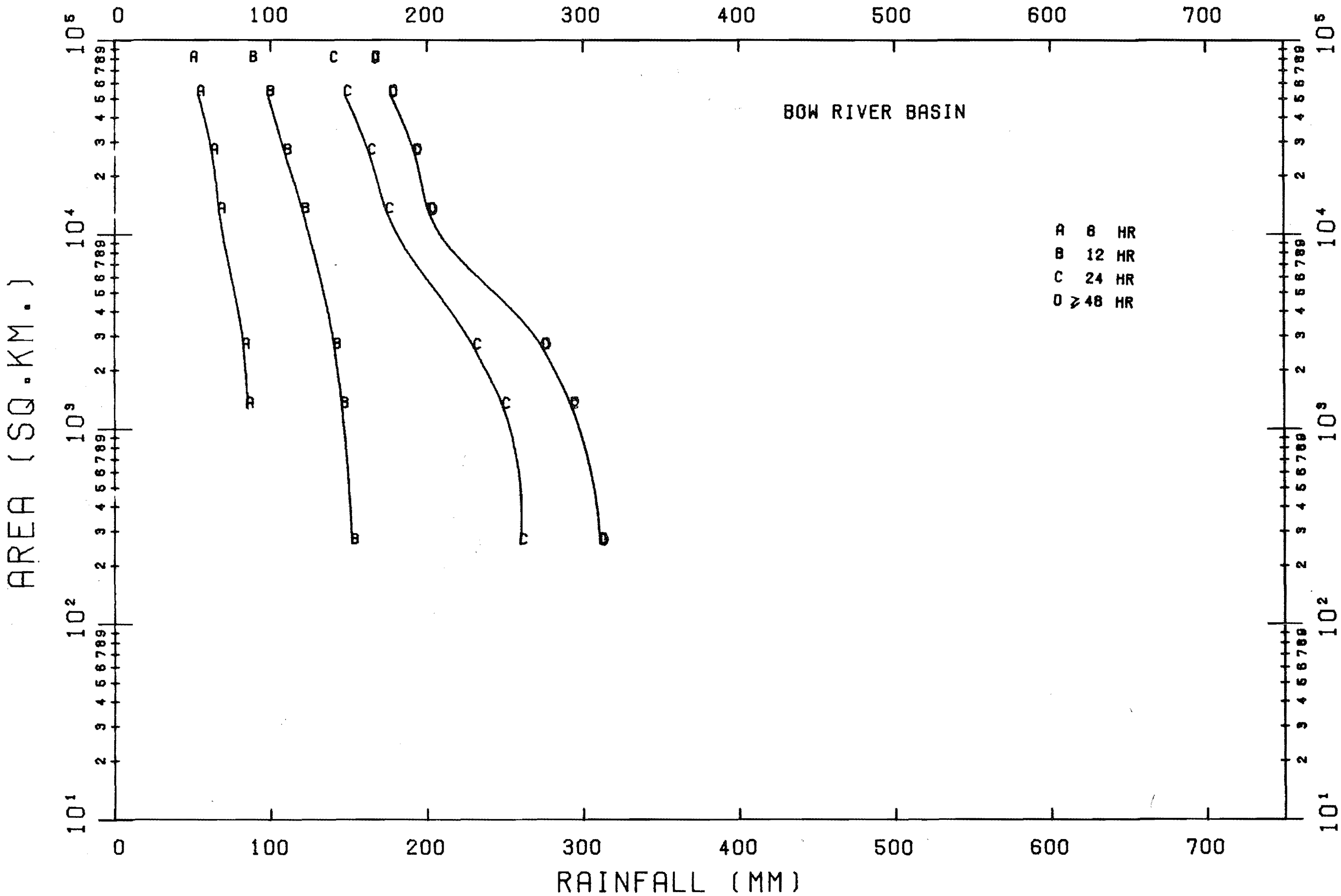

Figure 150 Envelope of the DAD curves for the Bow River basin for June.

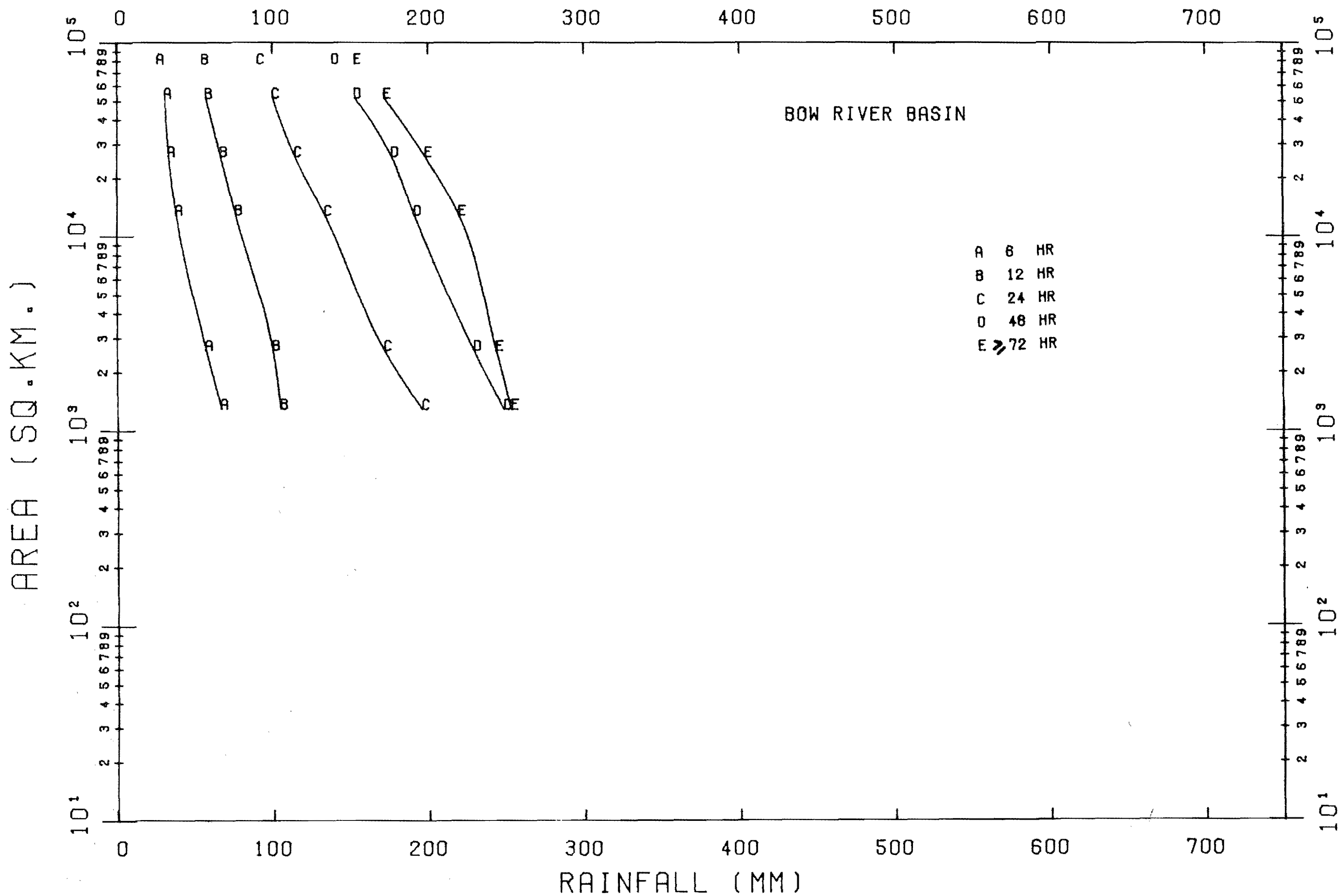

Figure 151 Envelope of the DAD curves for the Bow River basin for July.

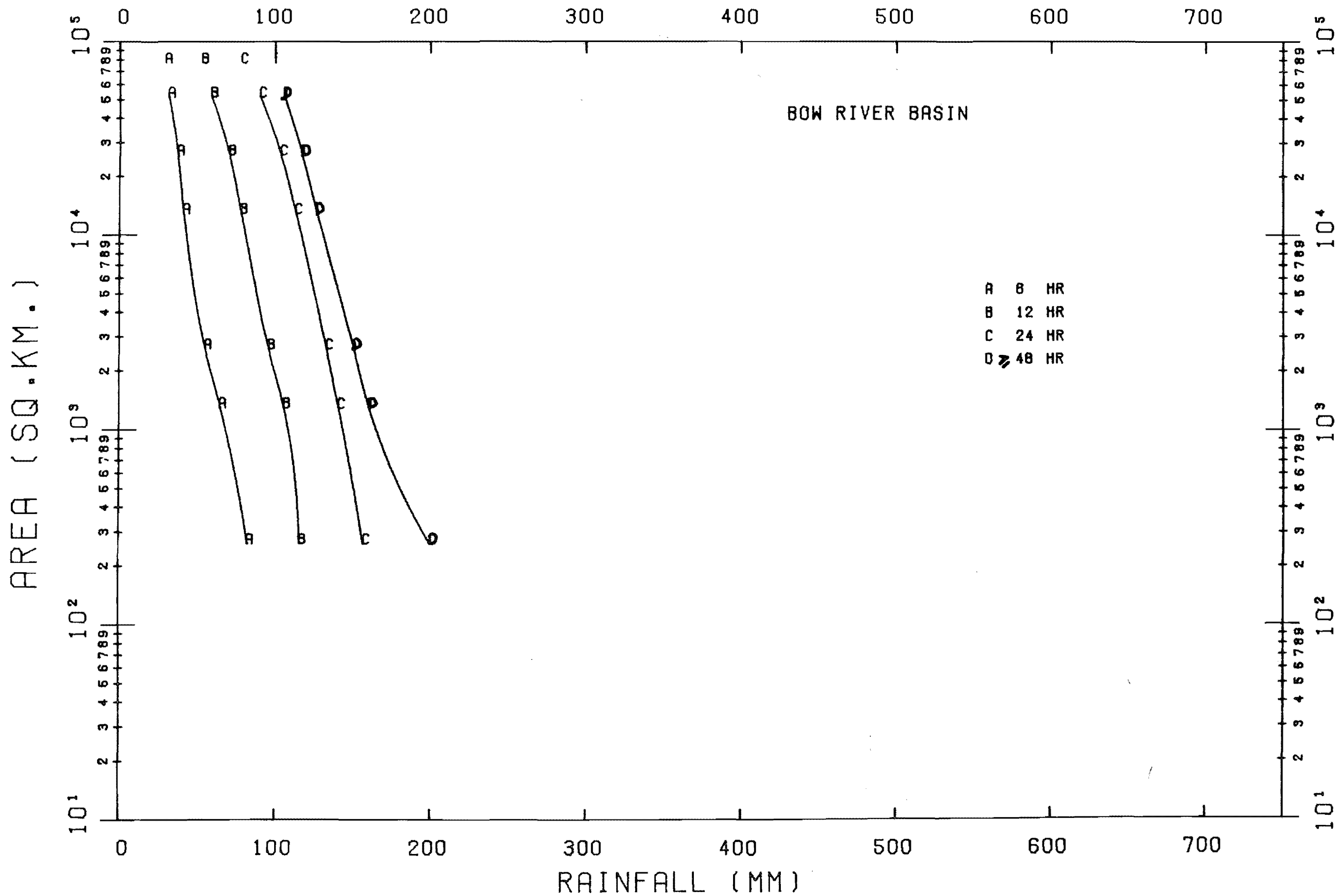

Figure 152 Envelope of the DAD curves for the Bow River basin for August.

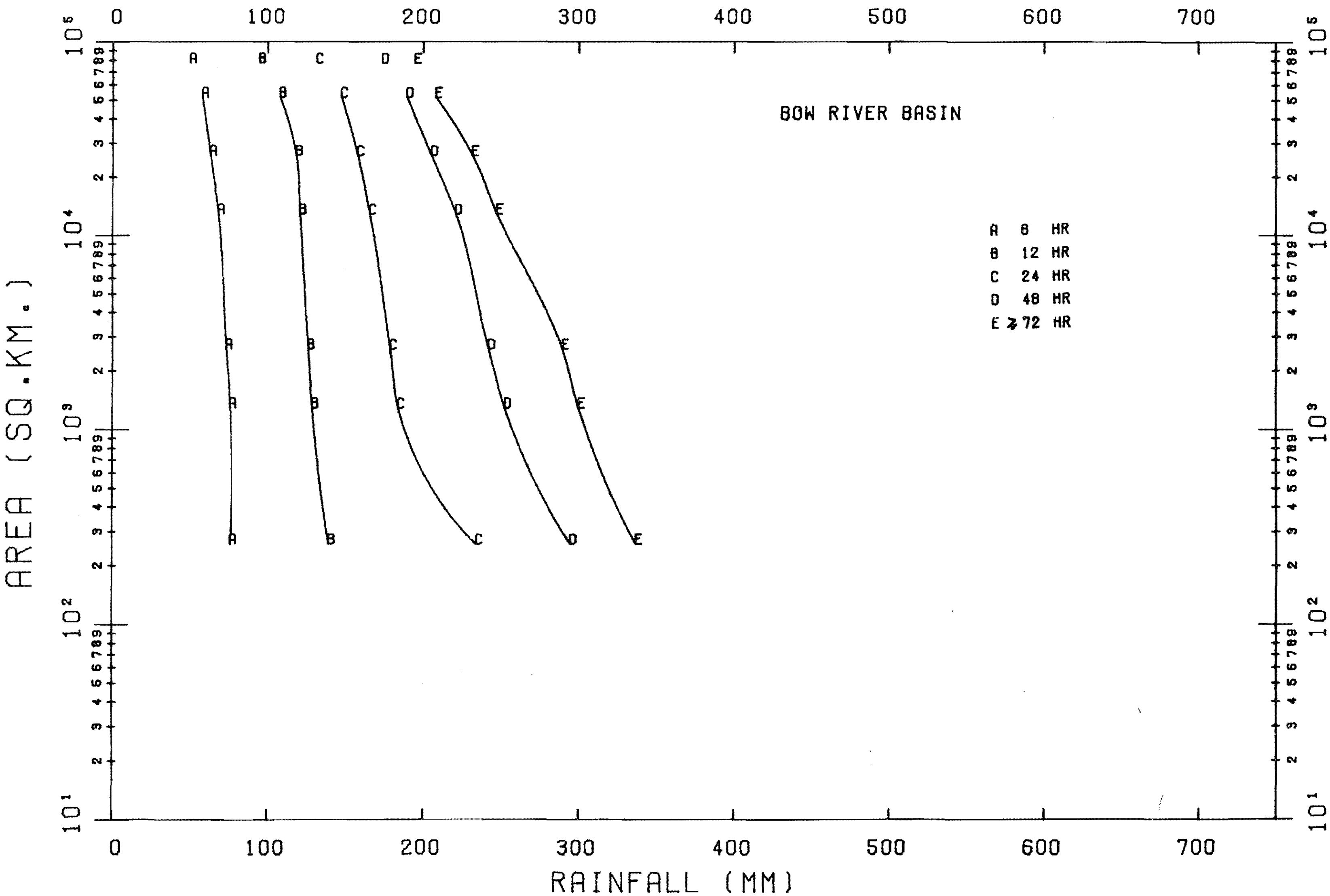

Figure 153 Envelope of the DAD curves for the Bow River basin for September.

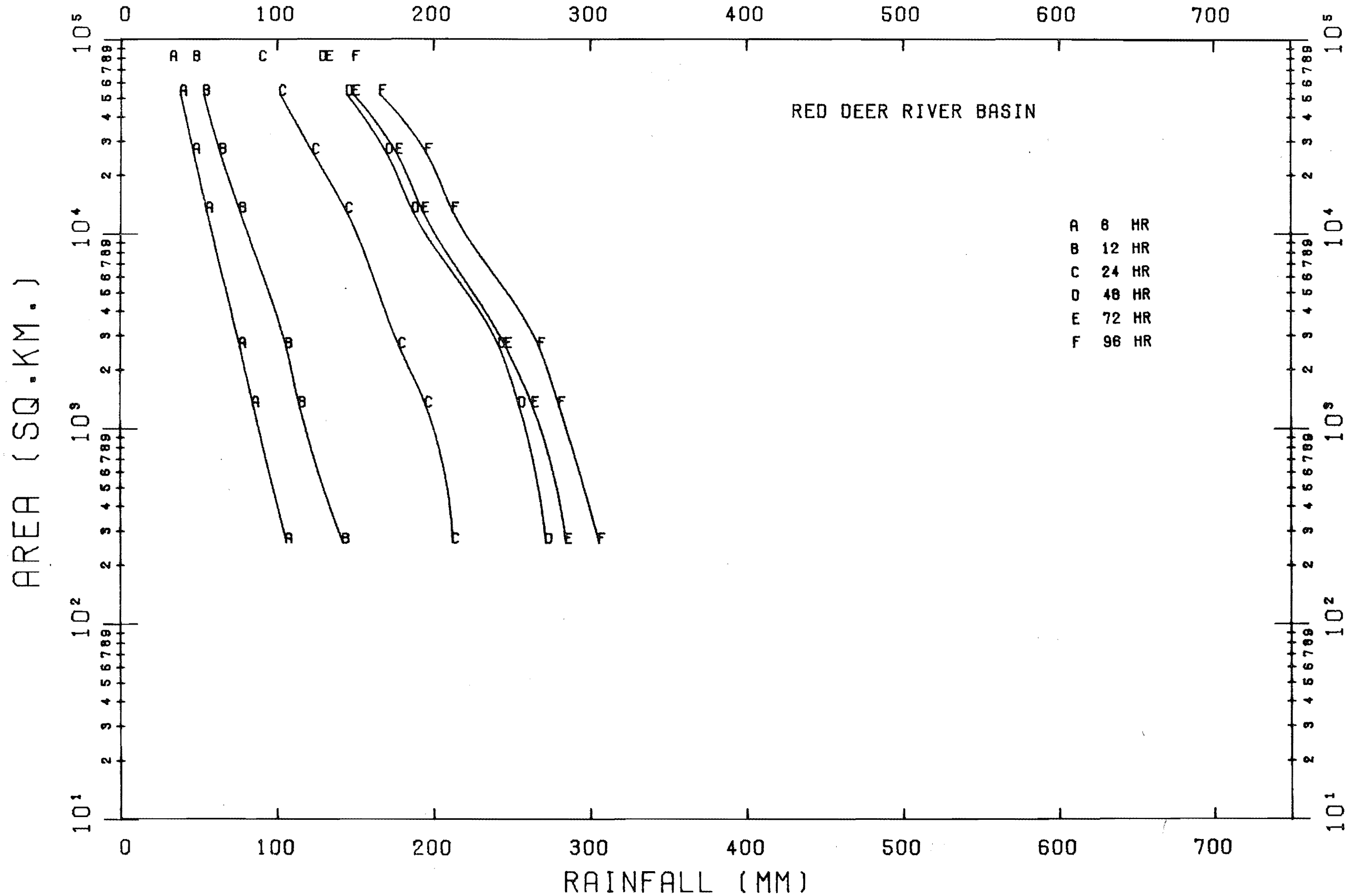

Figure 154 Envelope of the DAD curves for the Red Deer River basin for April.

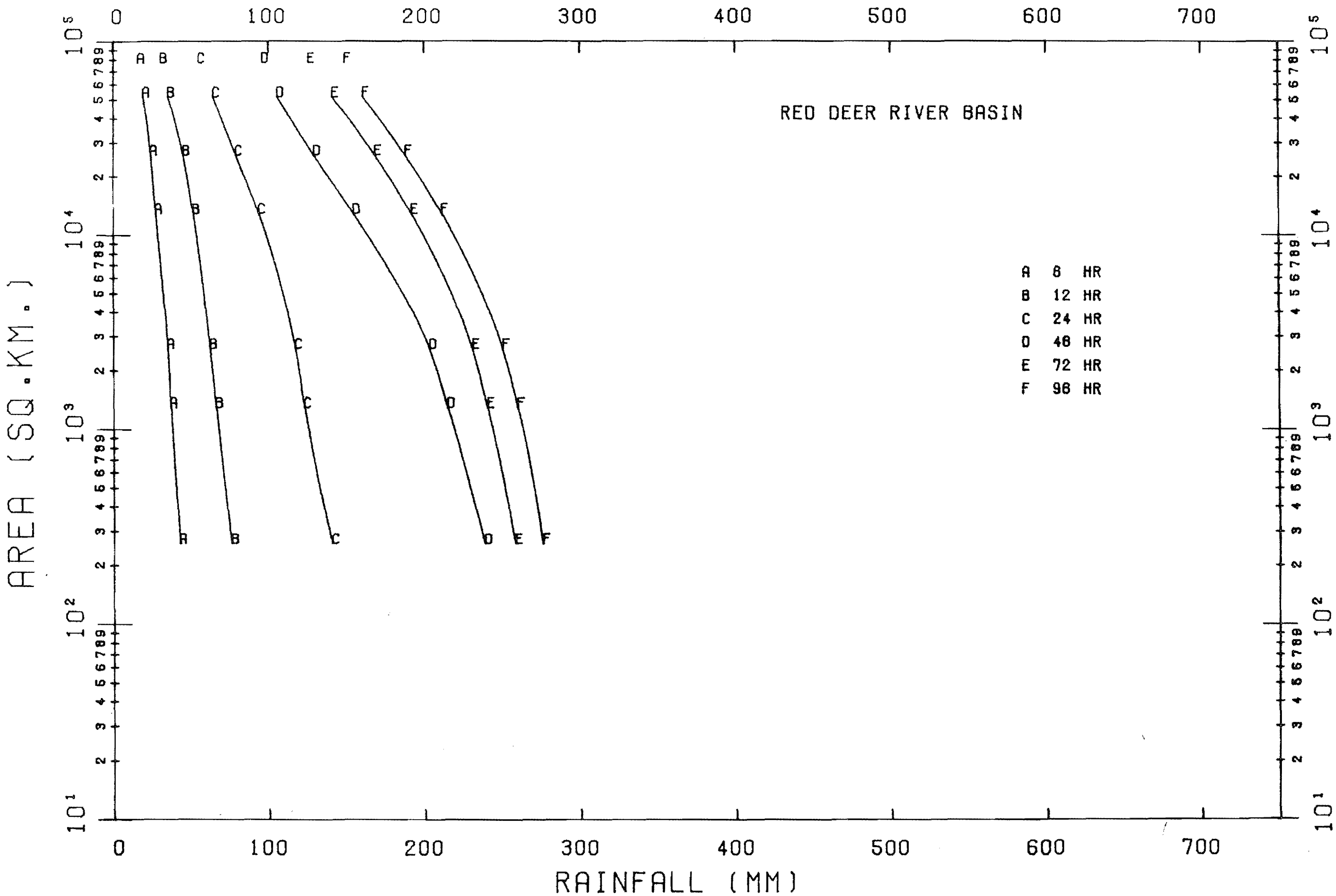

Figure 155 Envelope of the DAD curves for the Red Deer River basin for May.

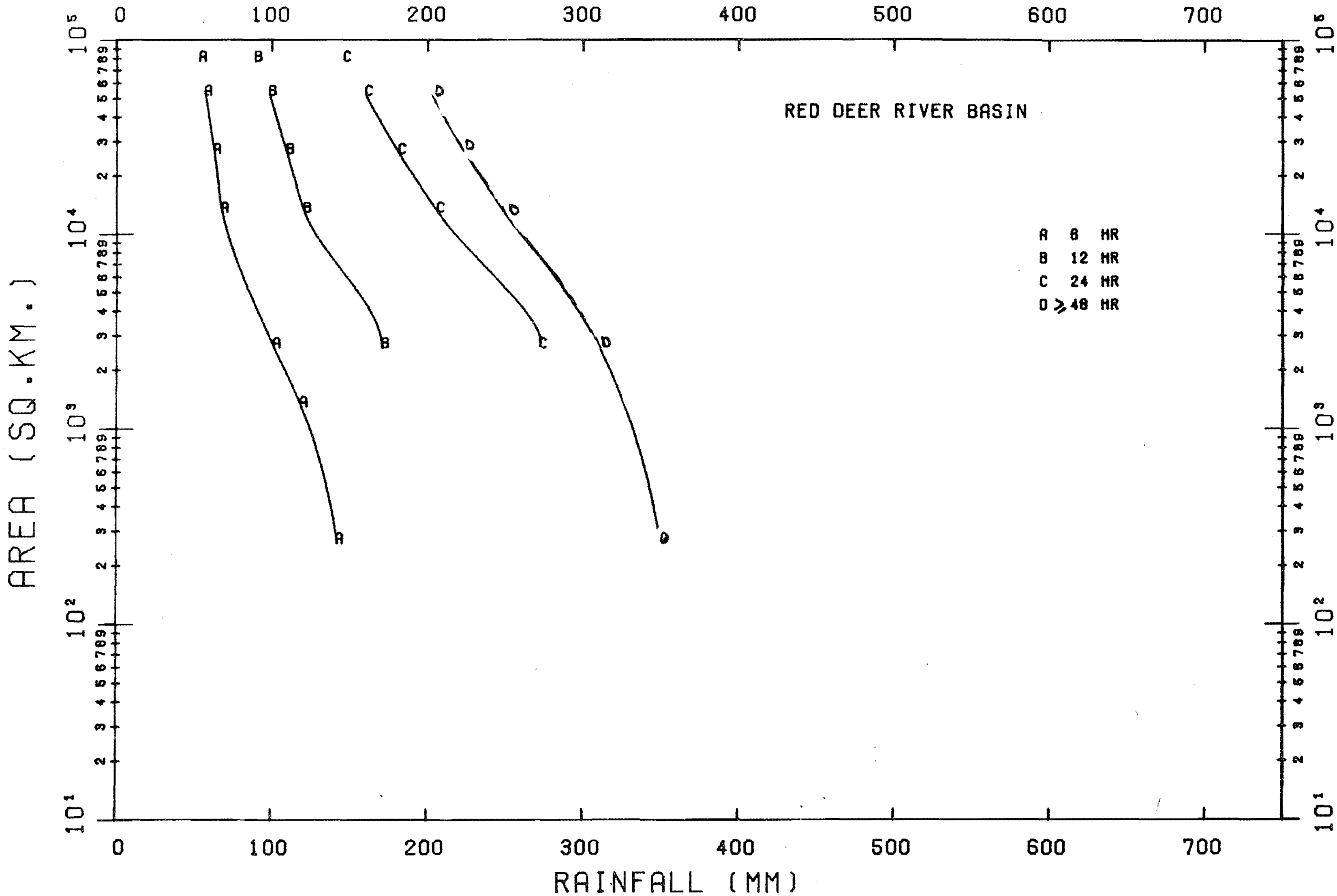

Figure 156 Envelope of the DAD curves for the Red Deer River basin for June.

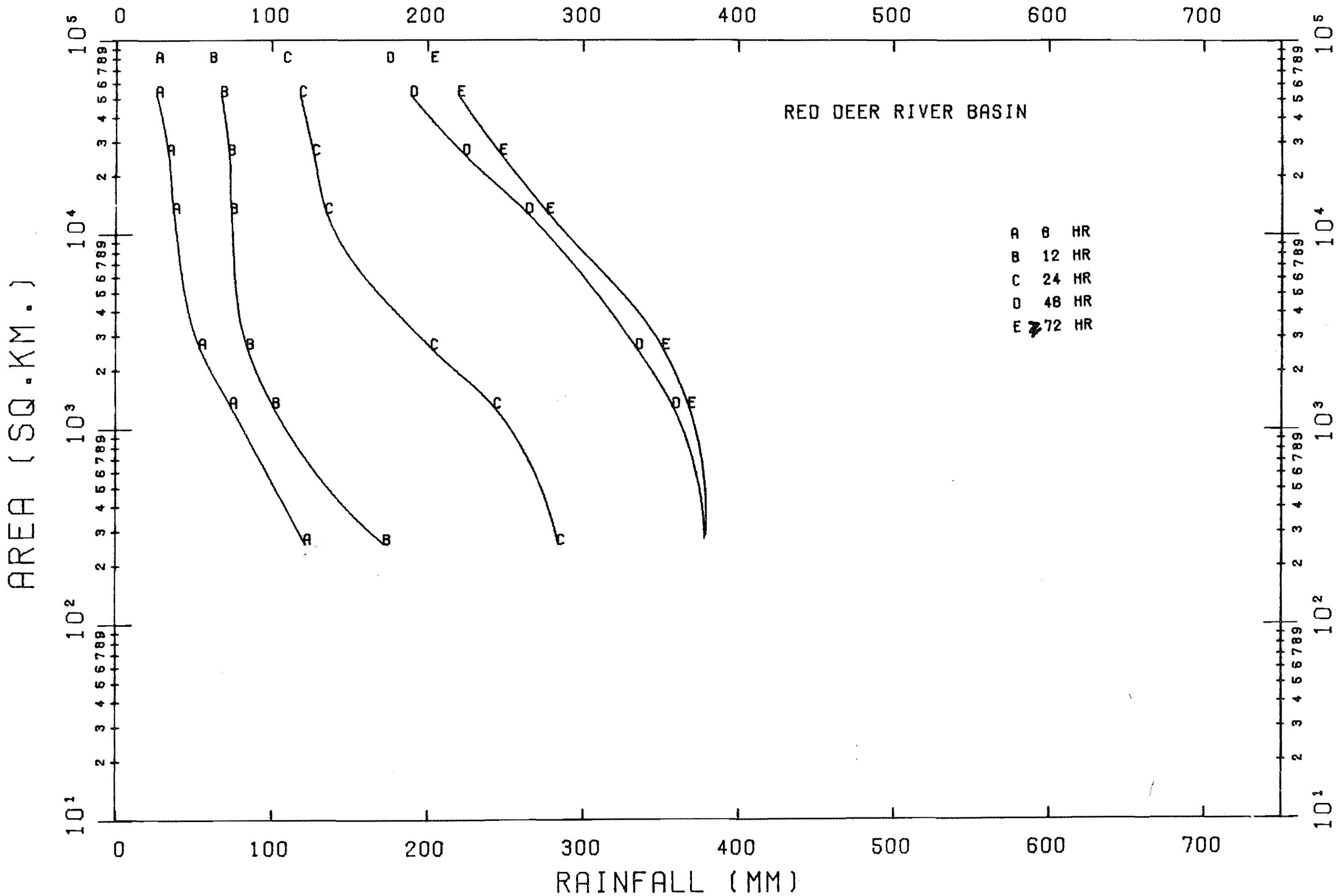

Figure 157 Envelope of the DAD curves for the Red Deer River basin for July.

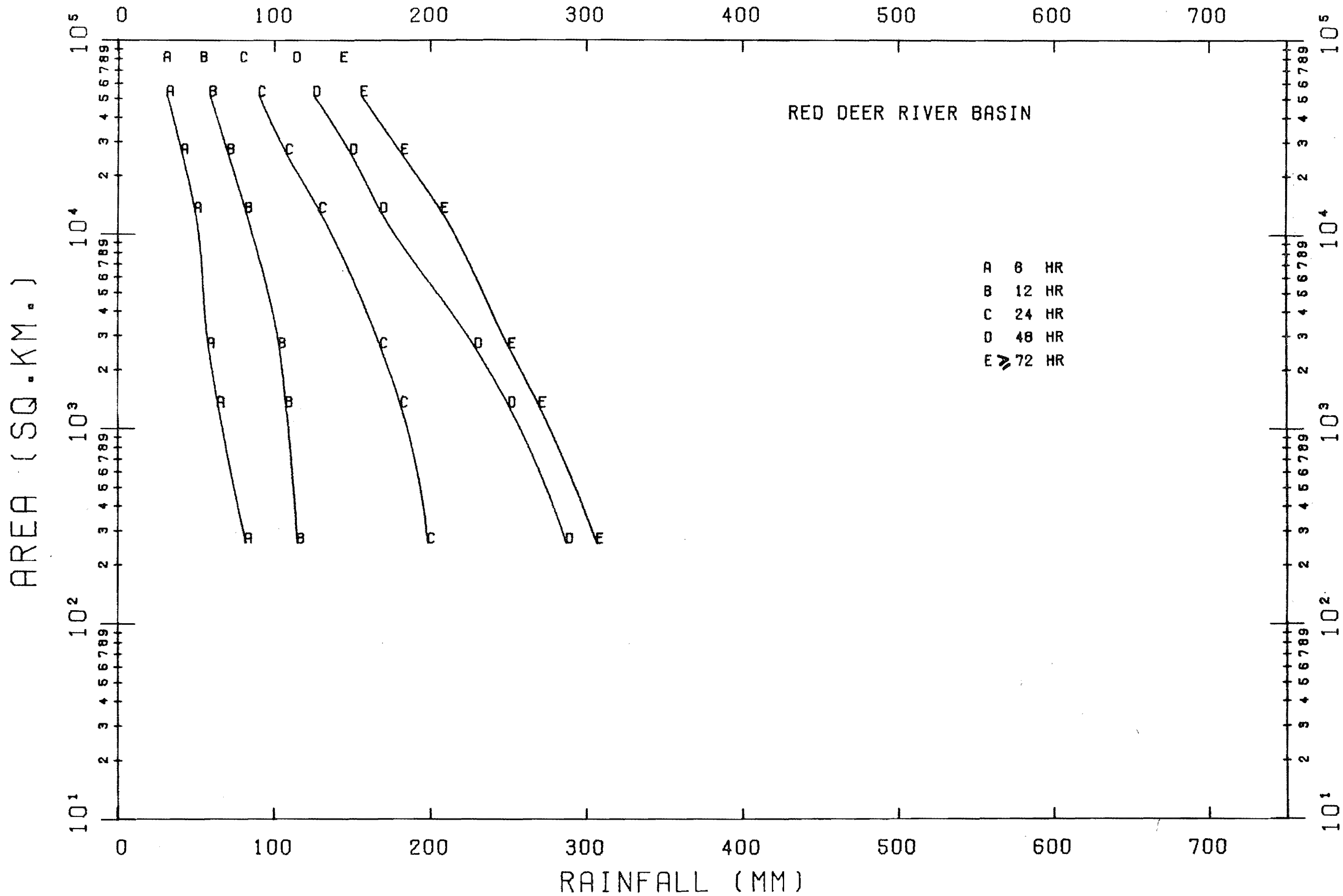

Figure 158 Envelope of the DAD curves for the Red Deer River basin for August.

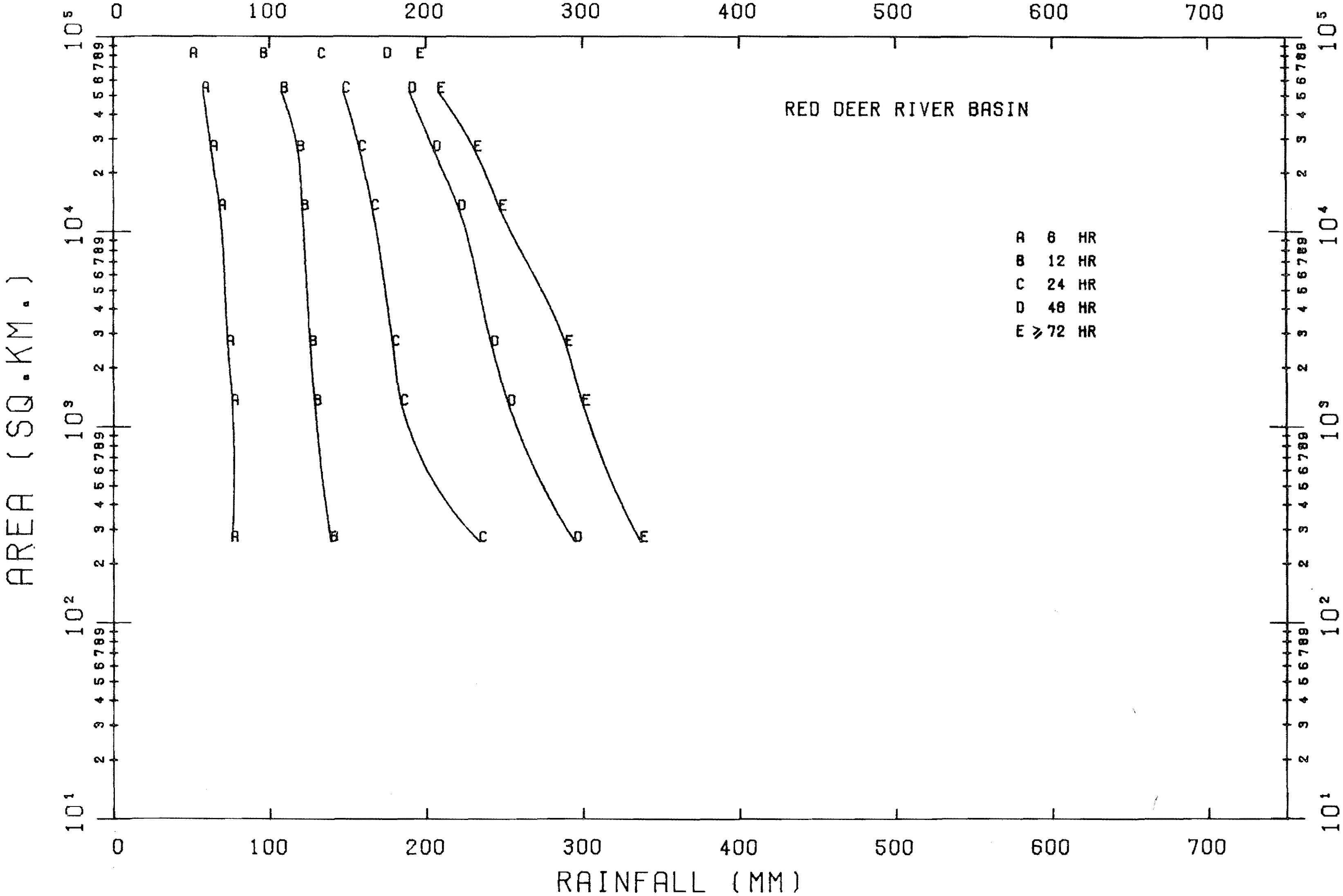

Figure 159 Envelope of the DAD curves for the Red Deer River basin for September.

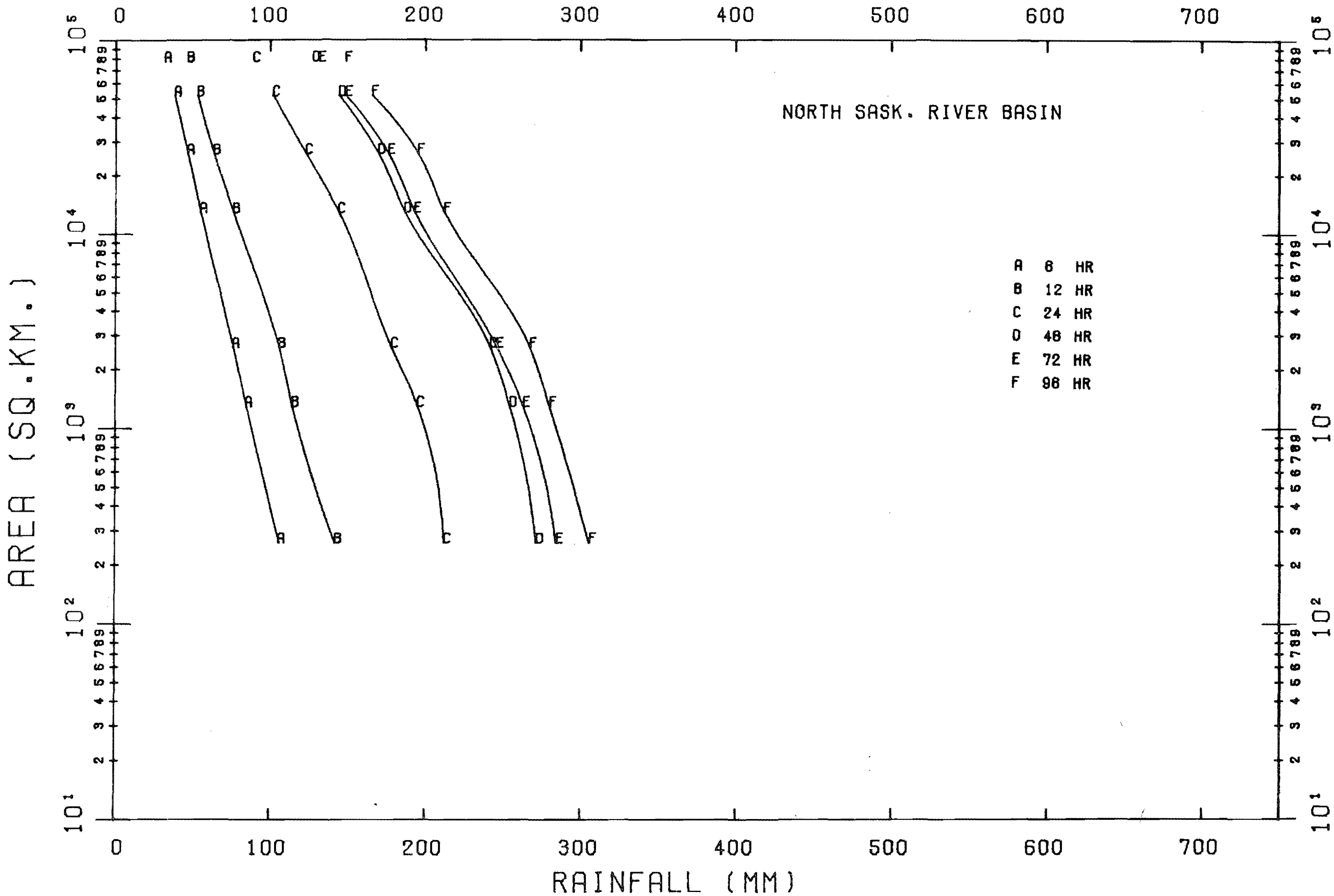

Figure 160 Envelope of the DAD curves for the North Saskatchewan River basin for April.

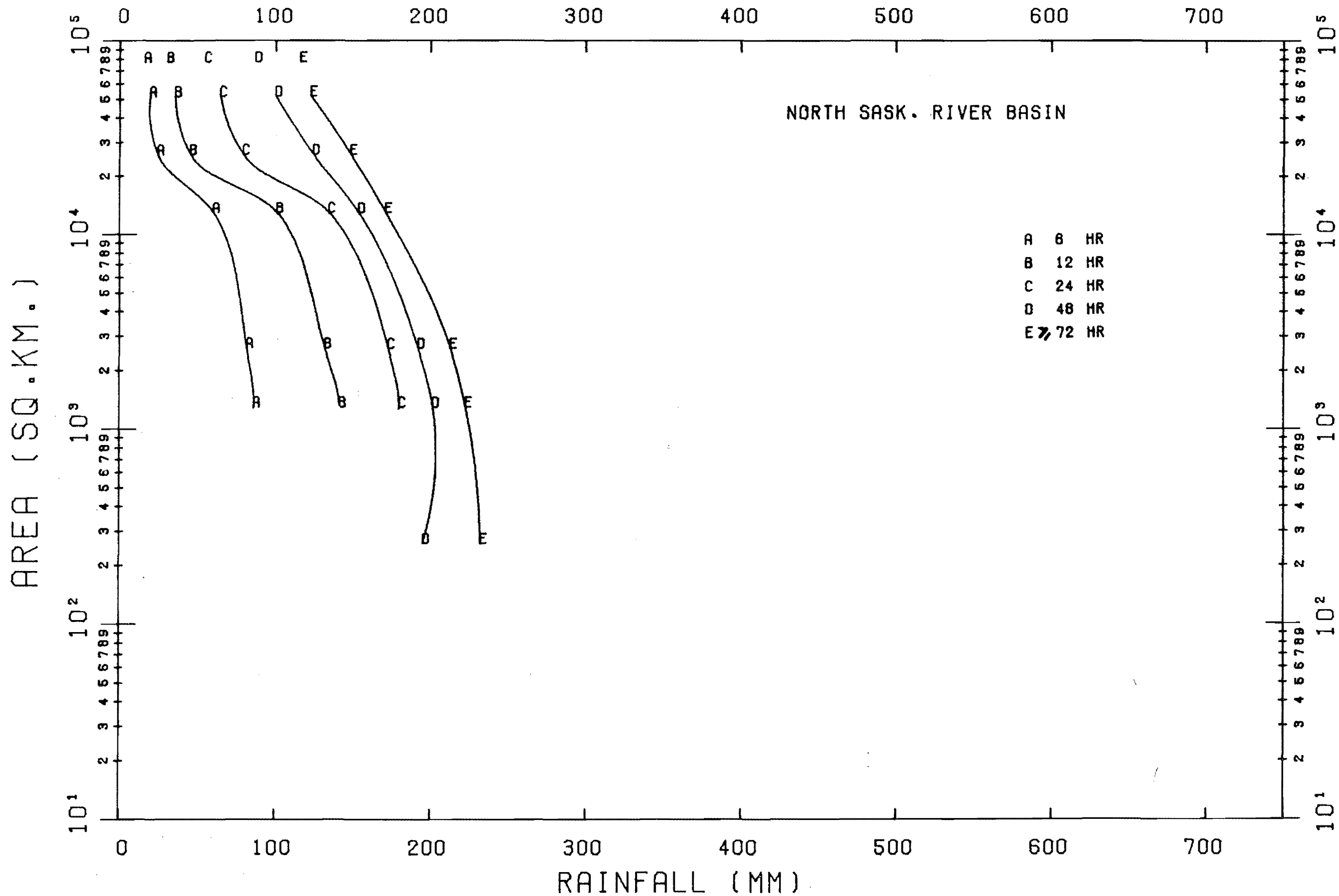

Figure 161 Envelope of the DAD curves for the North Saskatchewan River basin for May.

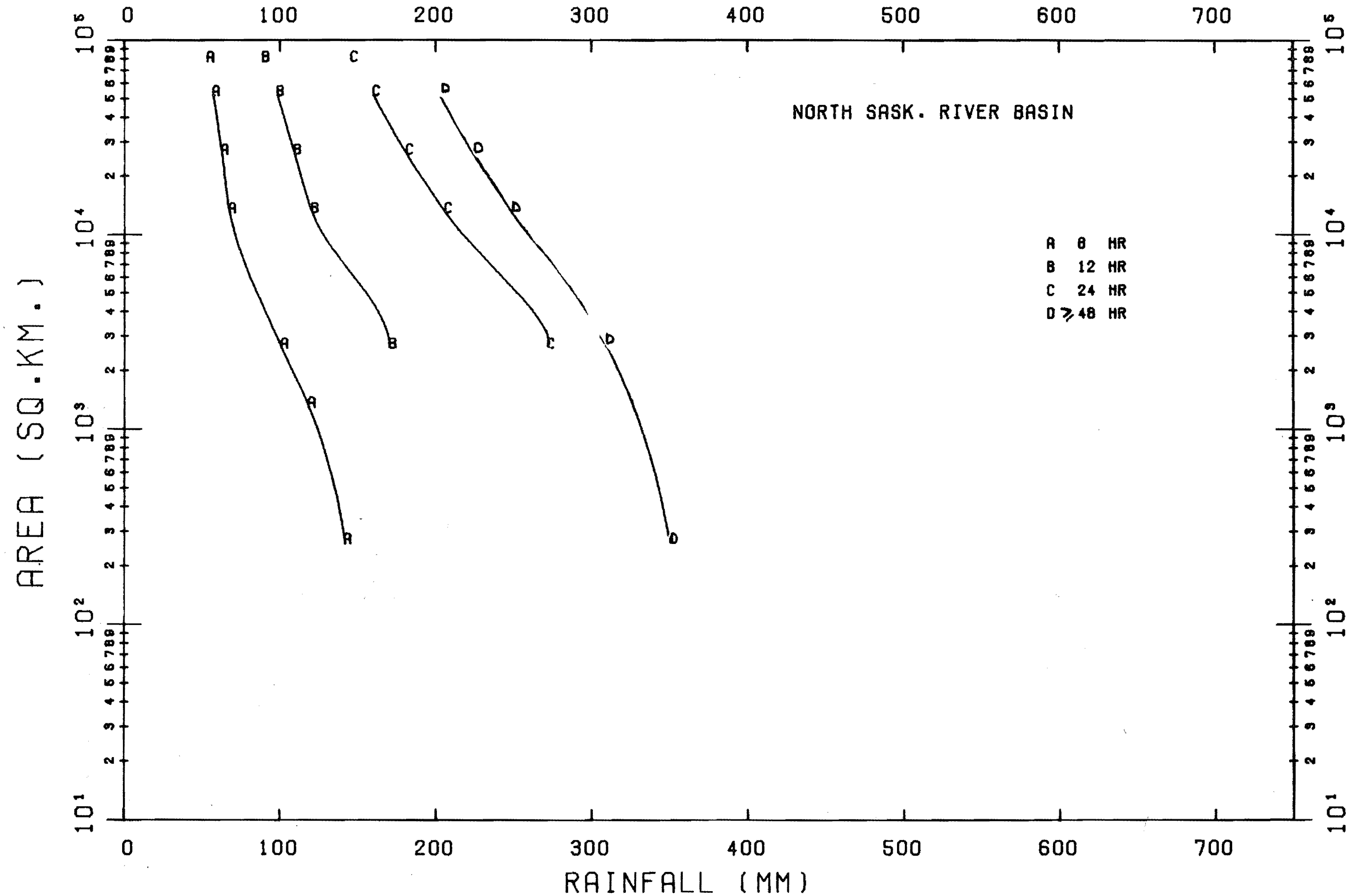

Figure 162 Envelope of the DAD curves for the North Saskatchewan River basin for June.

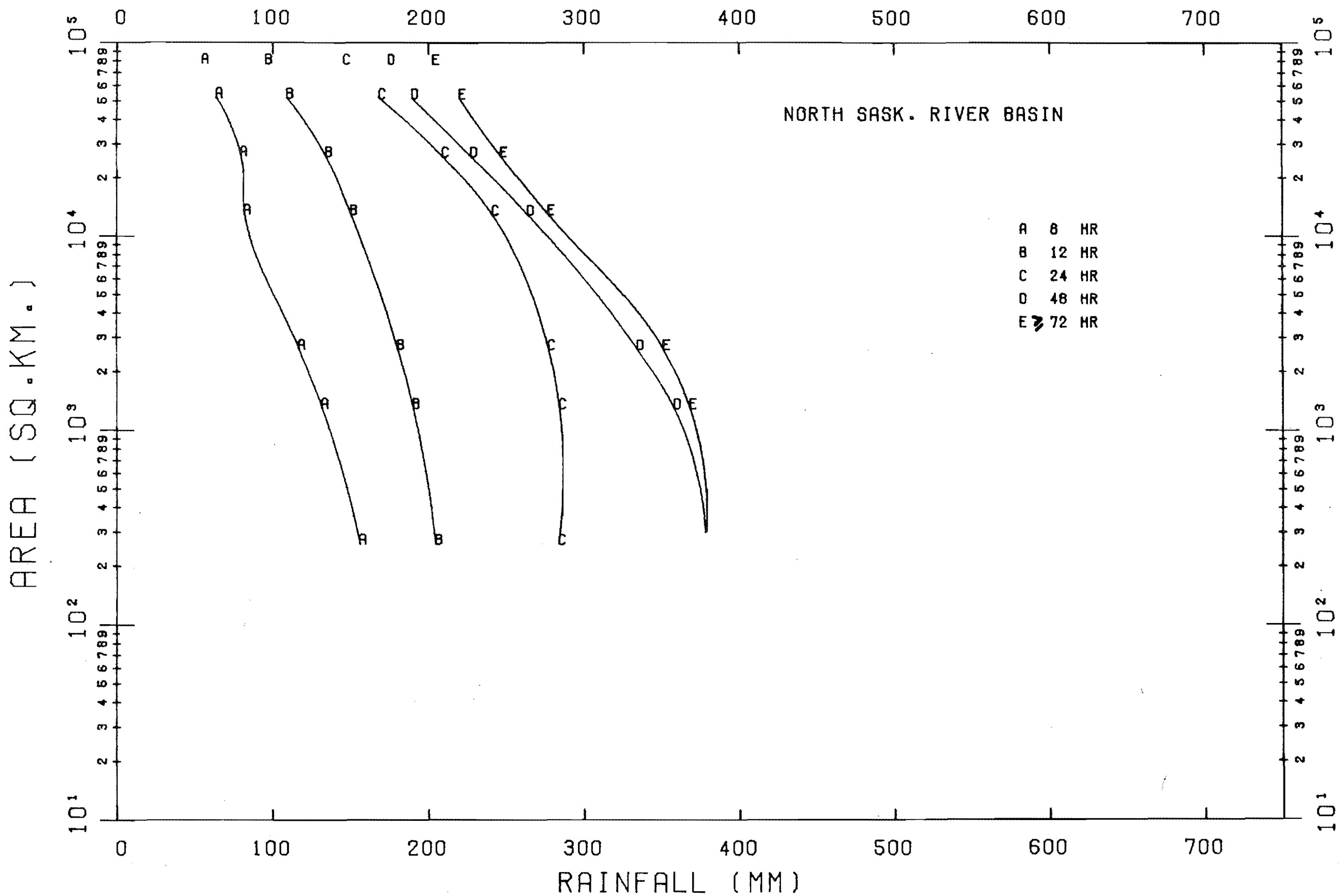

Figure 163 Envelope of the DAD curves for the North Saskatchewan River basin for July.

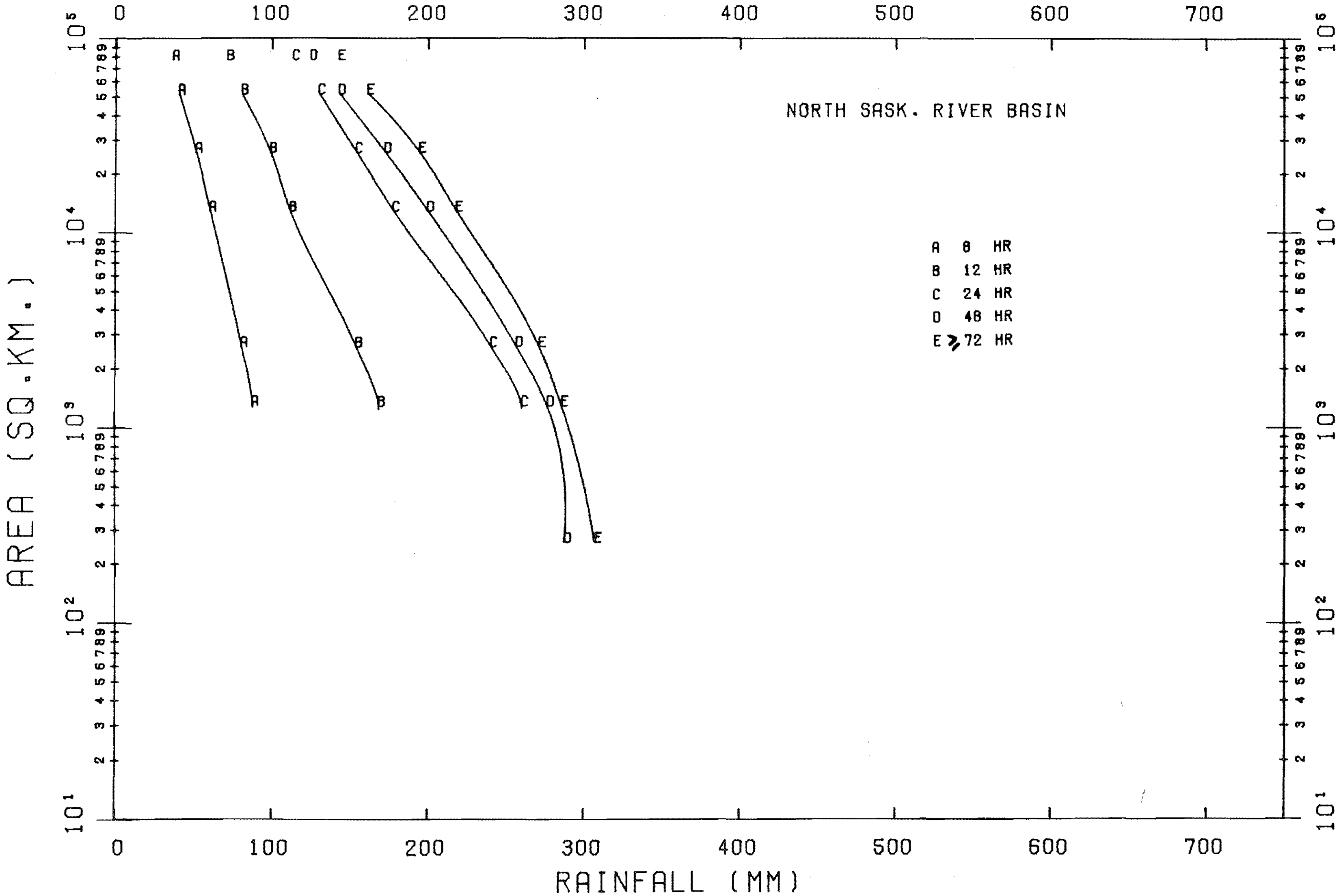

Figure 164 Envelope of the DAD curves for the North Saskatchewan River basin for August.

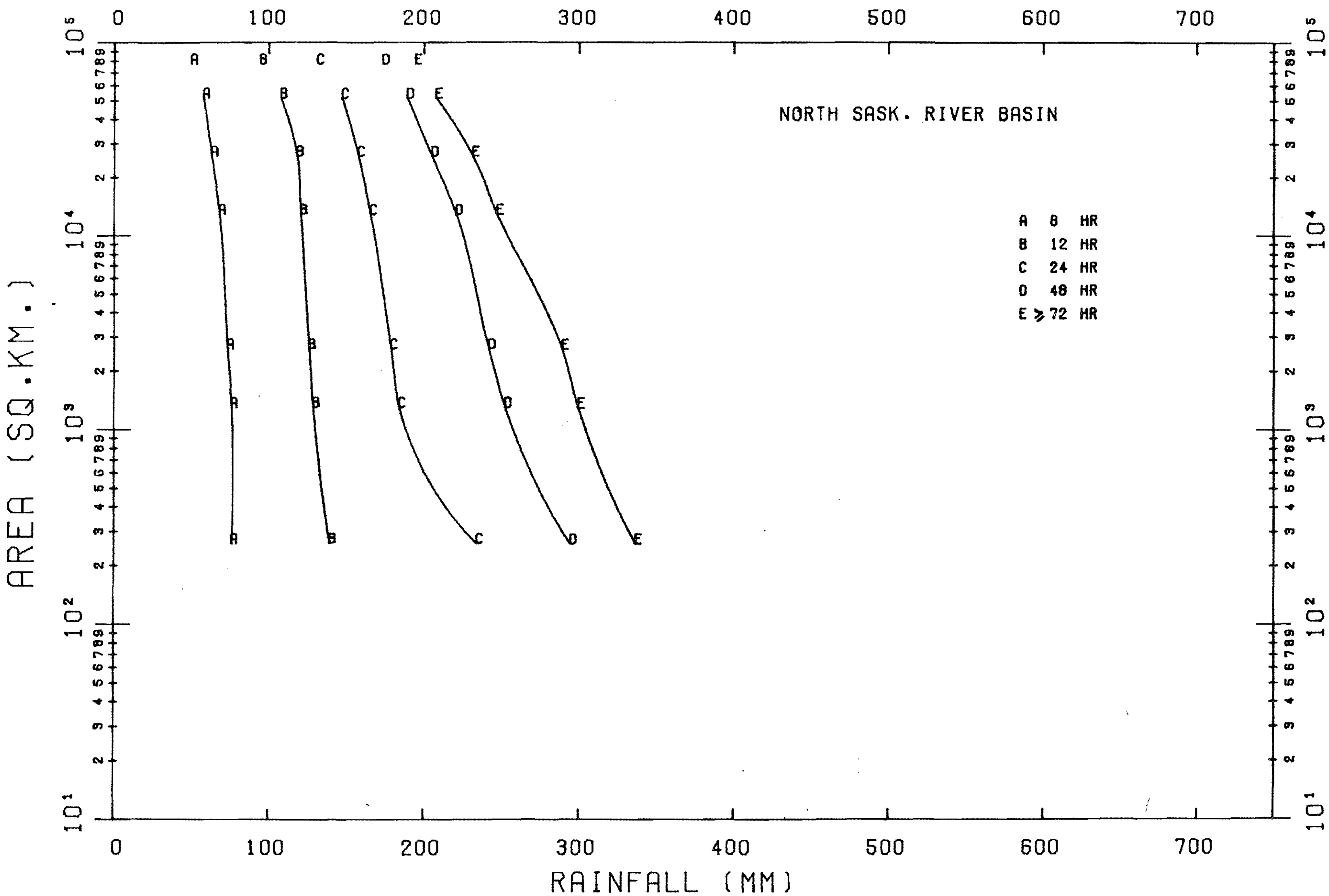

Figure 165 Envelope of the DAD curves for the North Saskatchewan River basin for September.

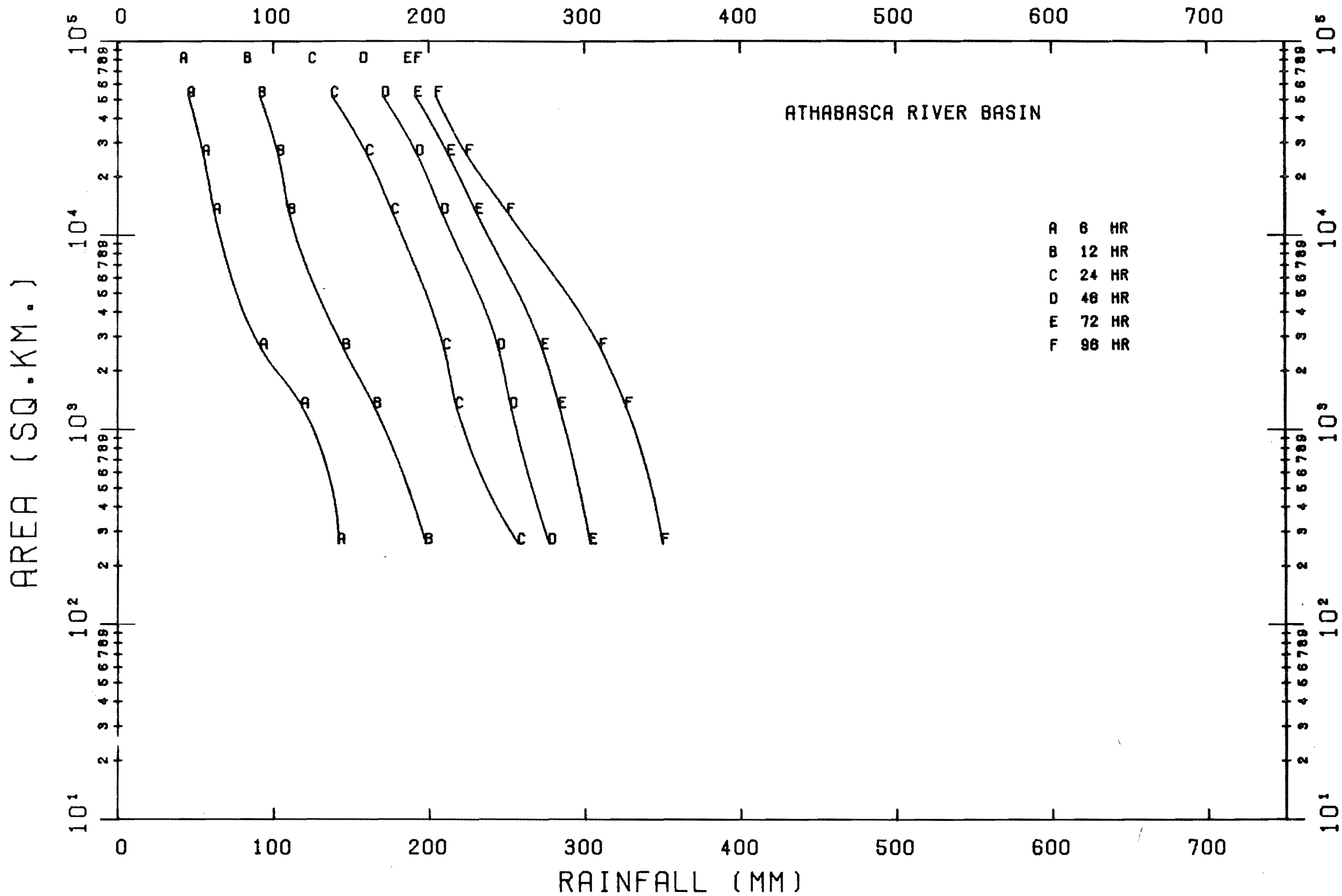

Figure 166 Envelope of the DAD curves for the Athabasca River basin for June.

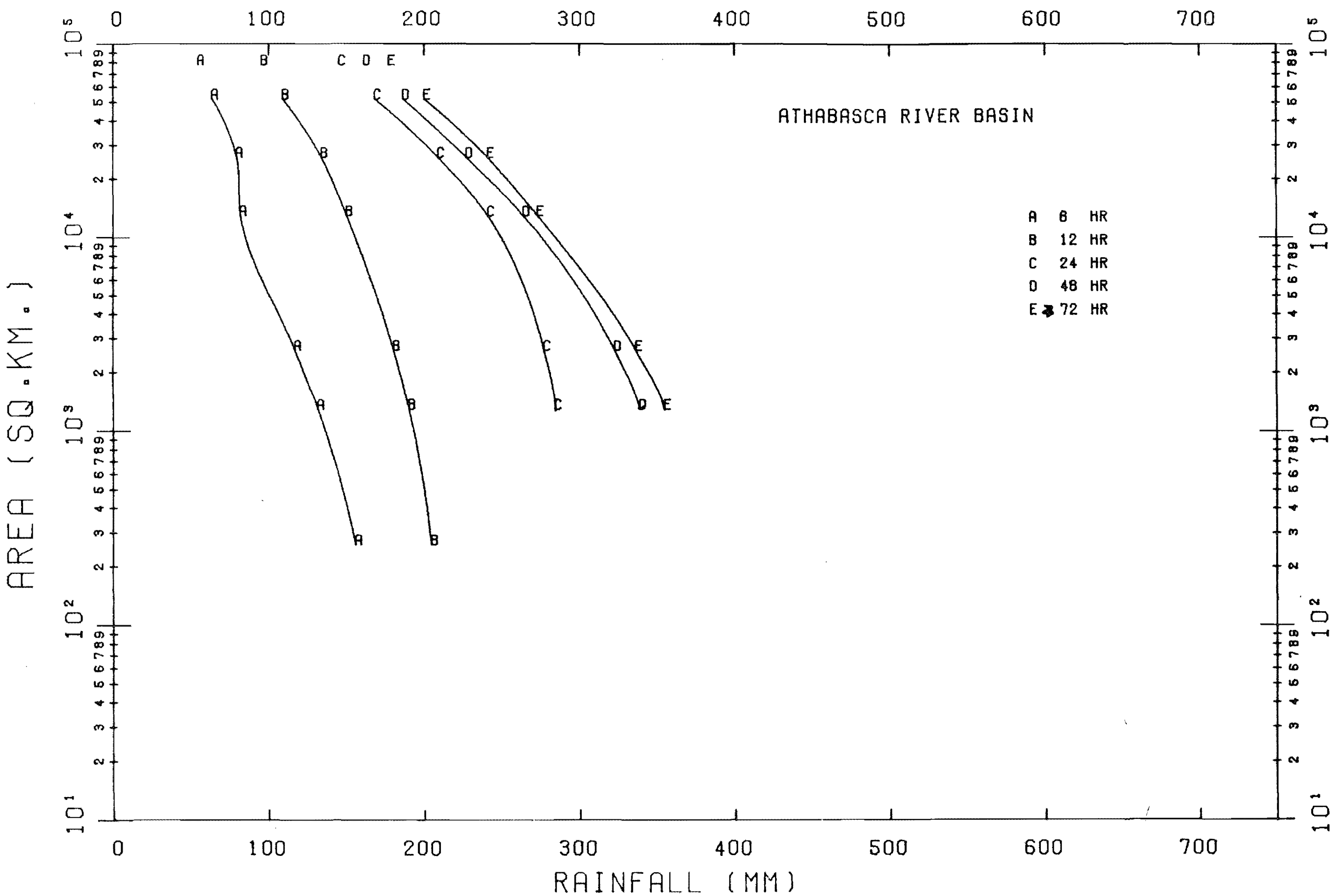

Figure 167 Envelope of the DAD curves for the Athabasca River basin for July.

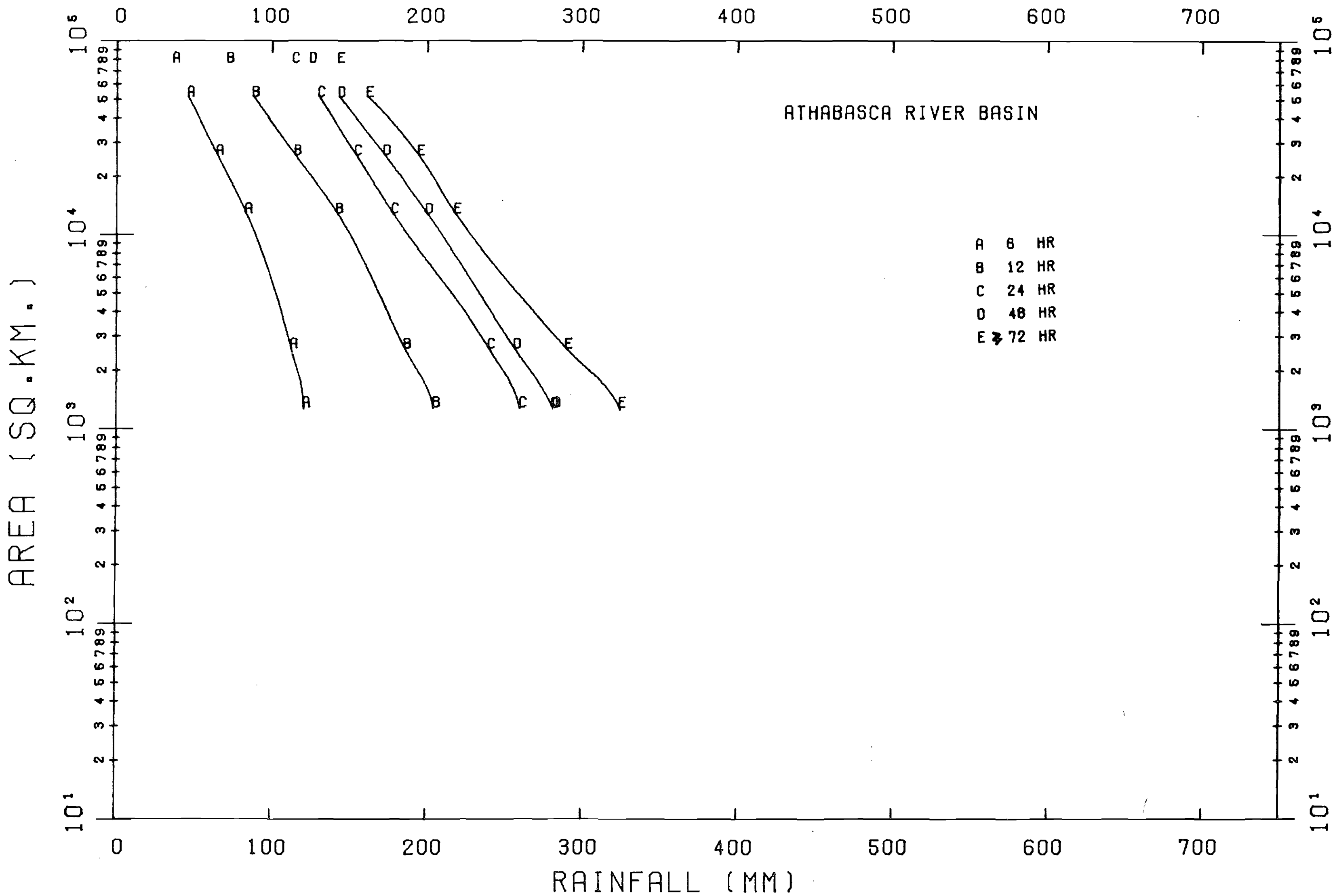

Figure 168 Envelope of the DAD curves for the Athabasca River basin for August.

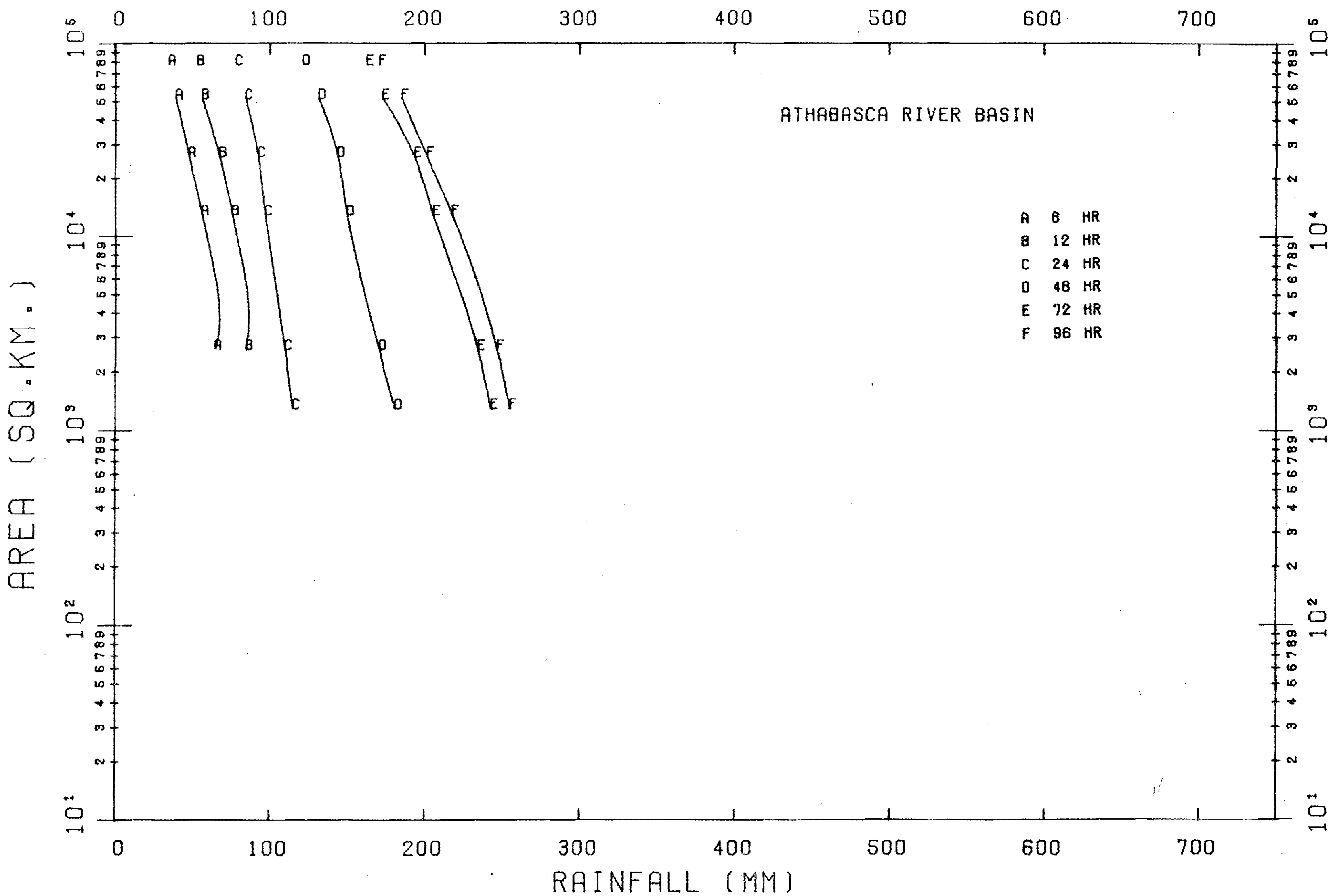

Figure 169 Envelope of the DAD curves for the Athabasca River basin for September.

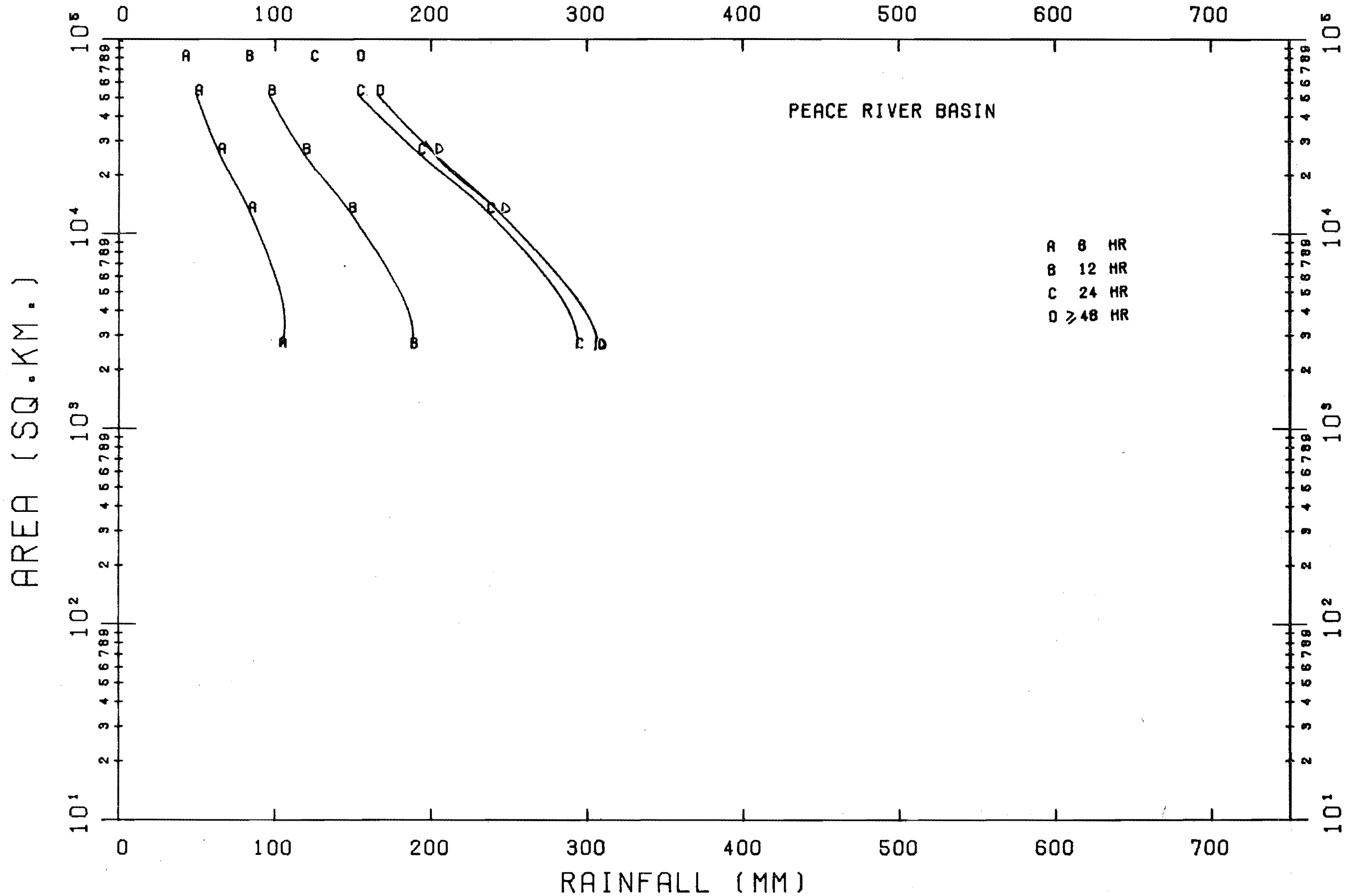

Figure 170 Envelope of the DAD curves for the Peace River basin for June.

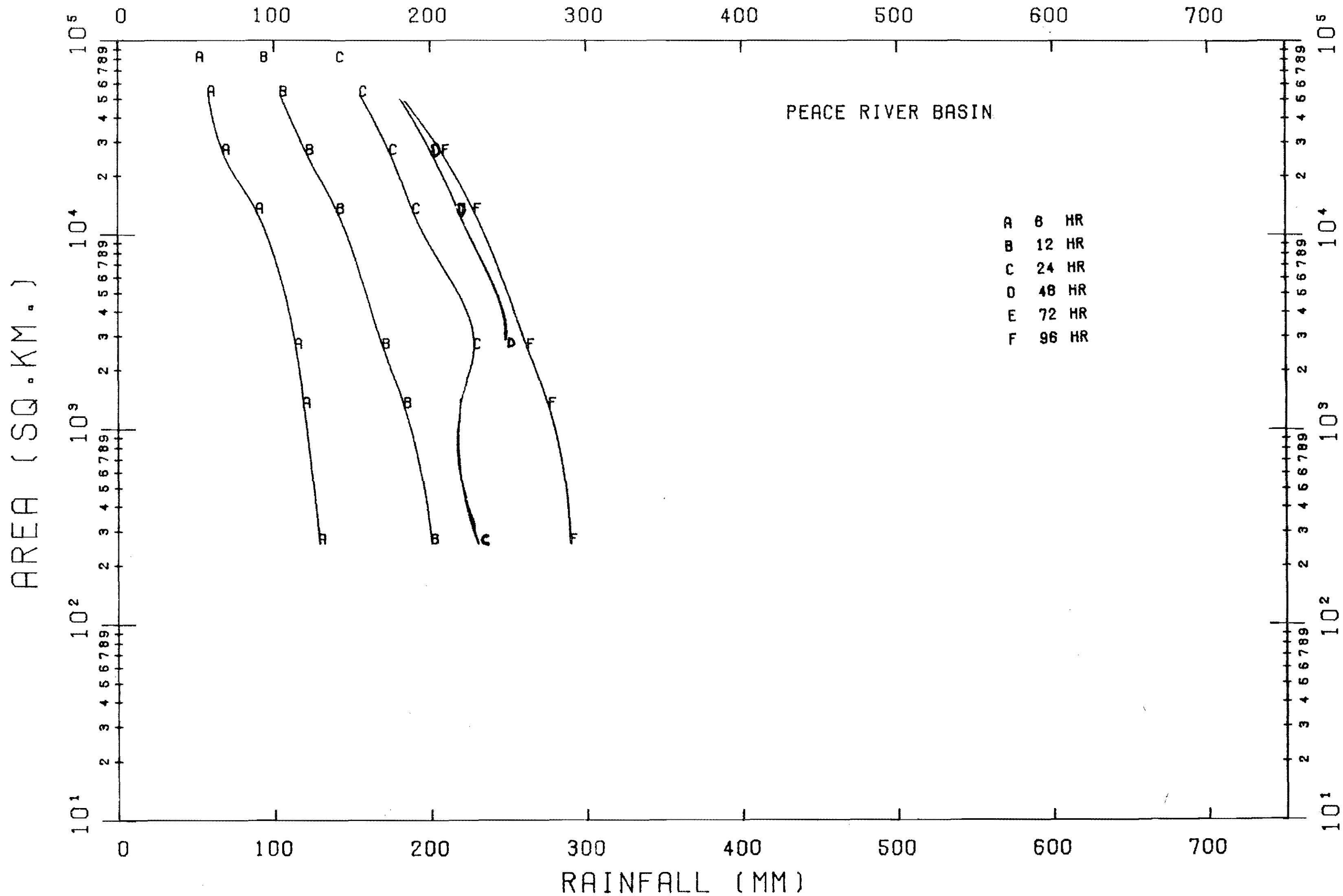

Figure 171 Envelope of the DAD curves for the Peace River basin for July.

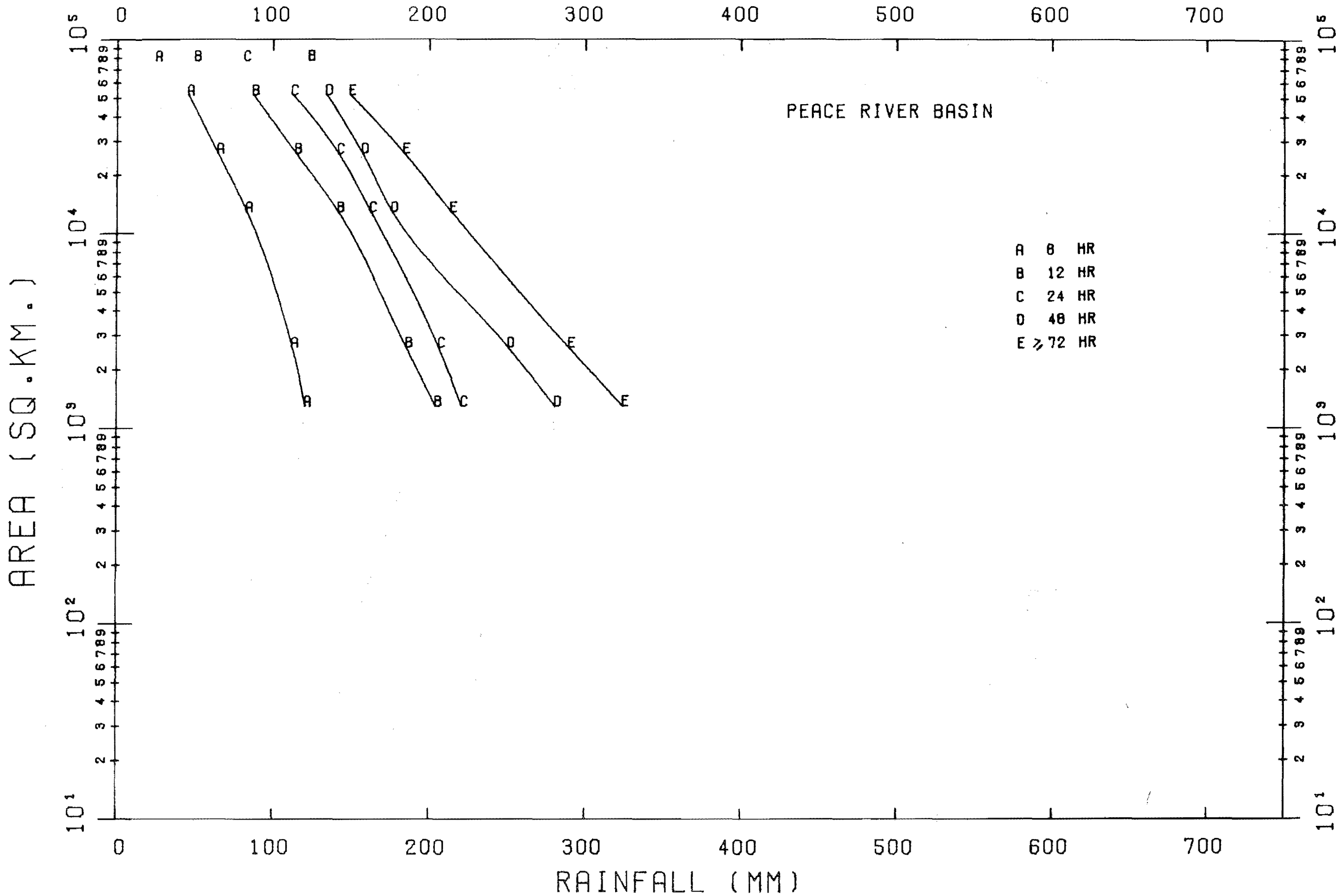

Figure 172 Envelope of the DAD curves for the Peace River basin for August.

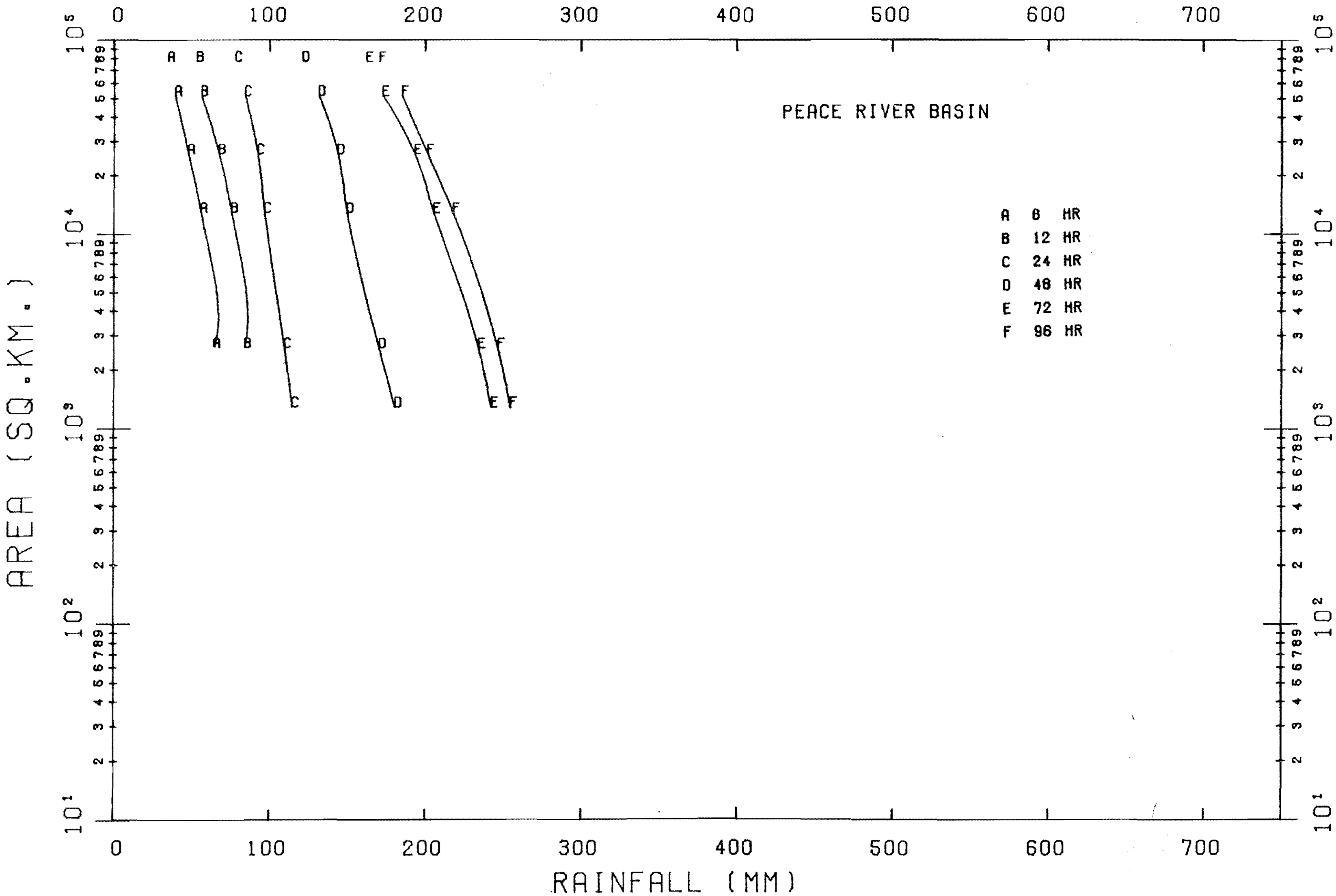

Figure 173 Envelope of the DAD curves for the Peace River basin for September.

8.4 GRAPHS OF ESTIMATED PMP FROM STATISTICAL APPROACH

Figures 174 to 176 show K_m as a function of the mean of annual series of 48-, 72-, and 96-hour rainfalls for first-order weather stations in Alberta. Figures 177 to 194 contain the estimated PMP using the statistical approach for the six basins.

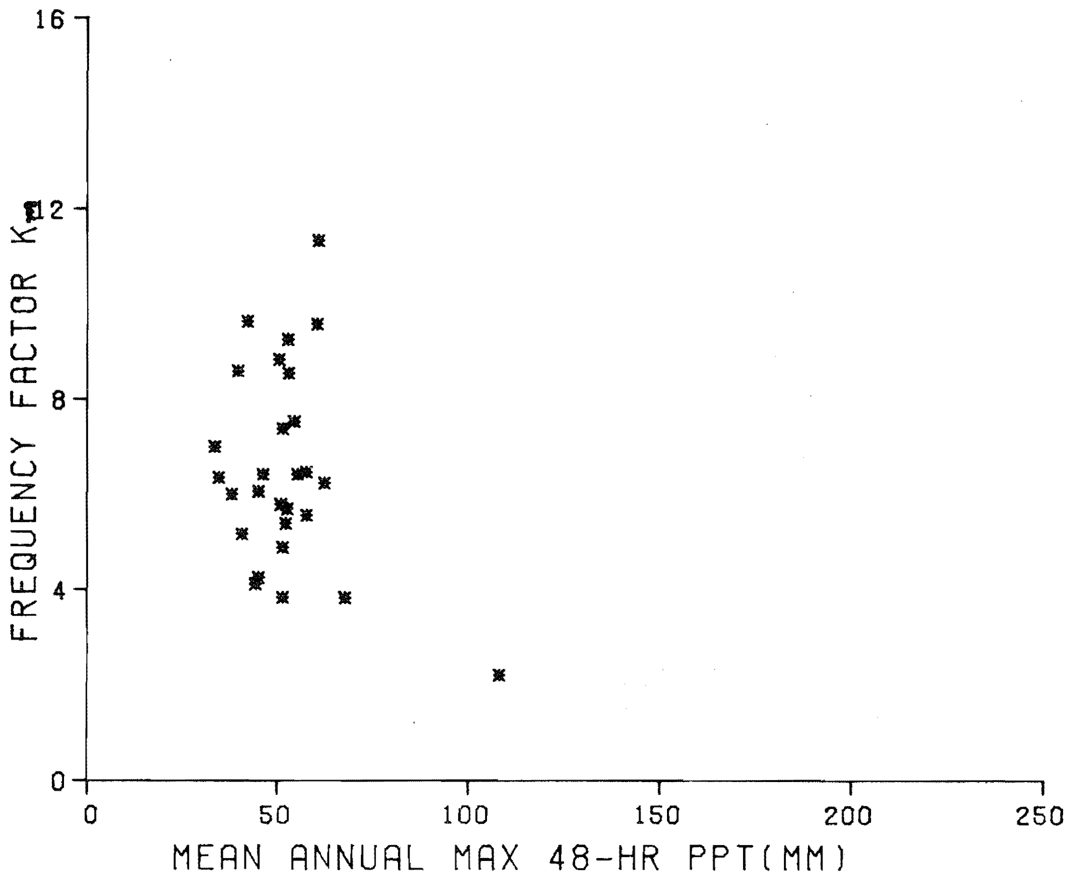

Figure 174 K_m as a function of the mean of annual series for 48-hour rainfall for Alberta weather stations.

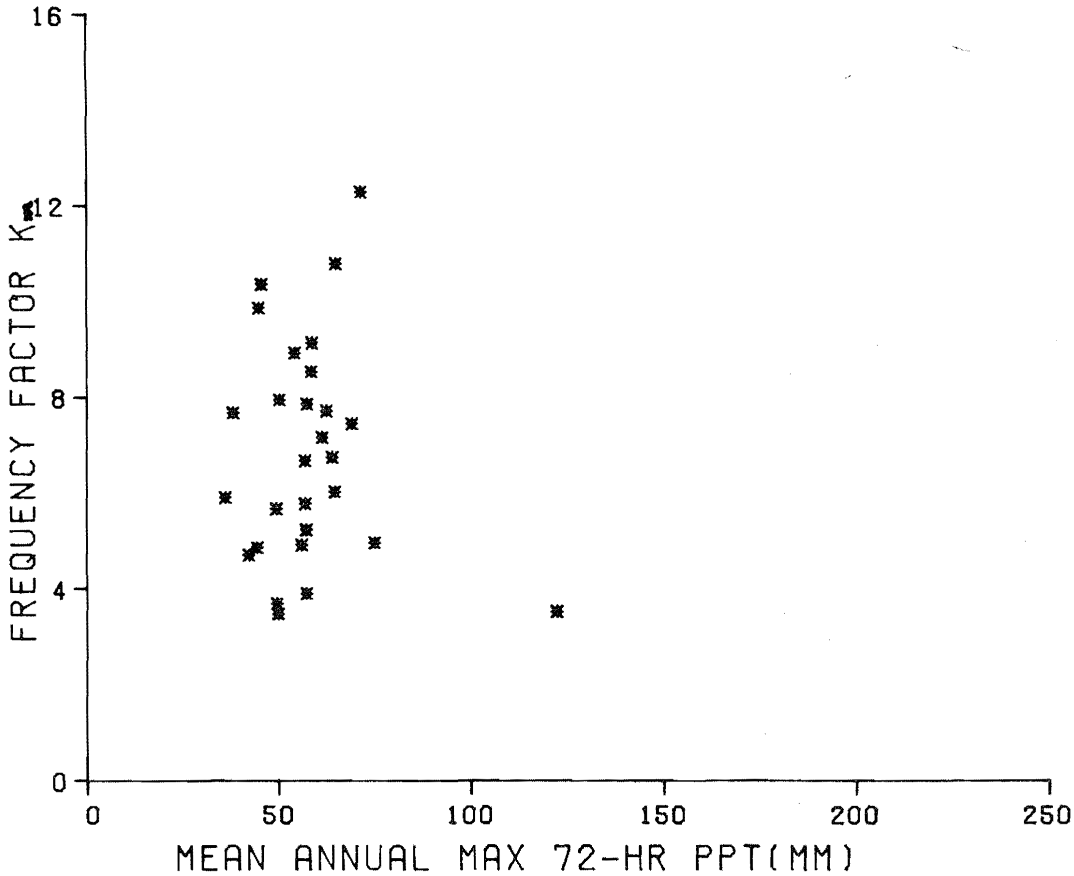

Figure 175 K_m as a function of the mean of annual series for 72-hour rainfall for Alberta weather stations.

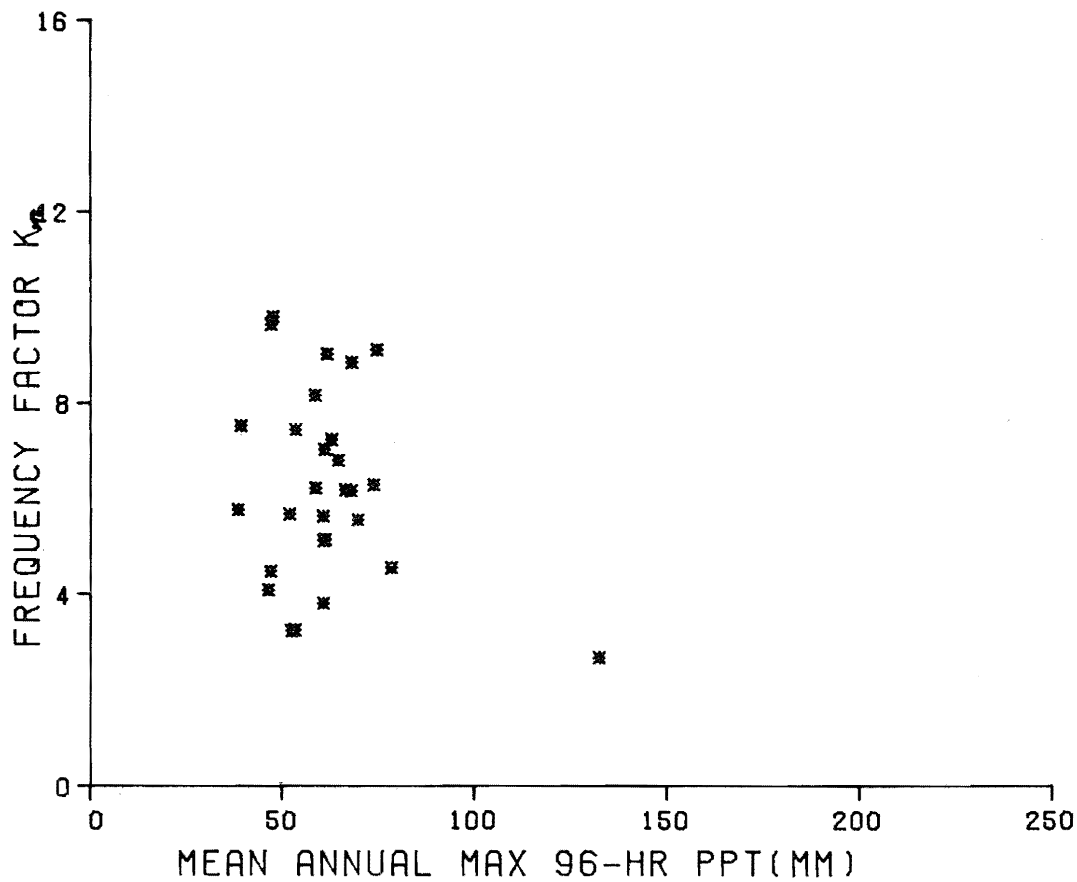

Figure 176 K_m as a function of the mean of annual series for 96-hour rainfall for Alberta weather stations.

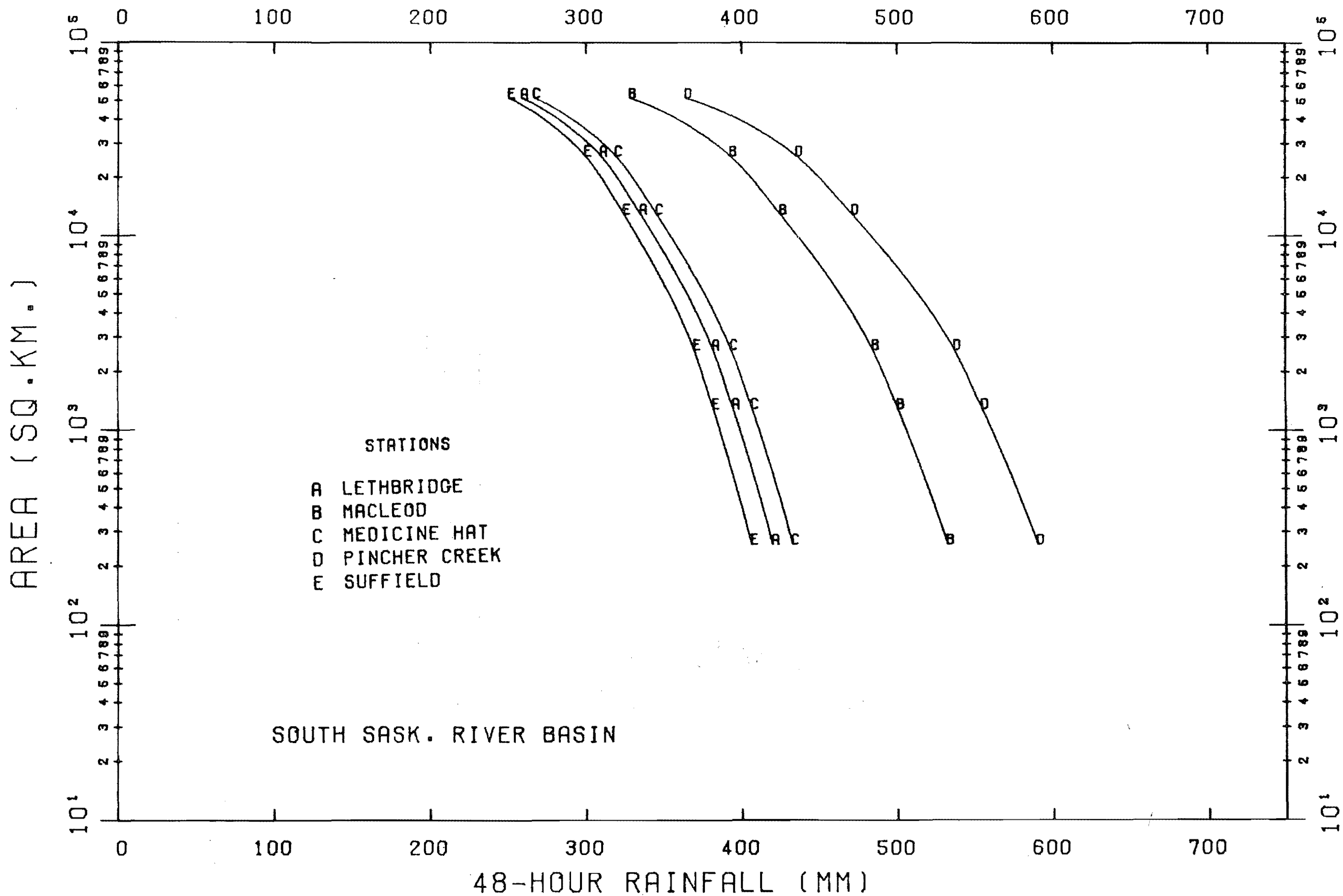

Figure 177 Enveloping depth-area 48-hour curves of estimated PMP for the Oldman River basin.

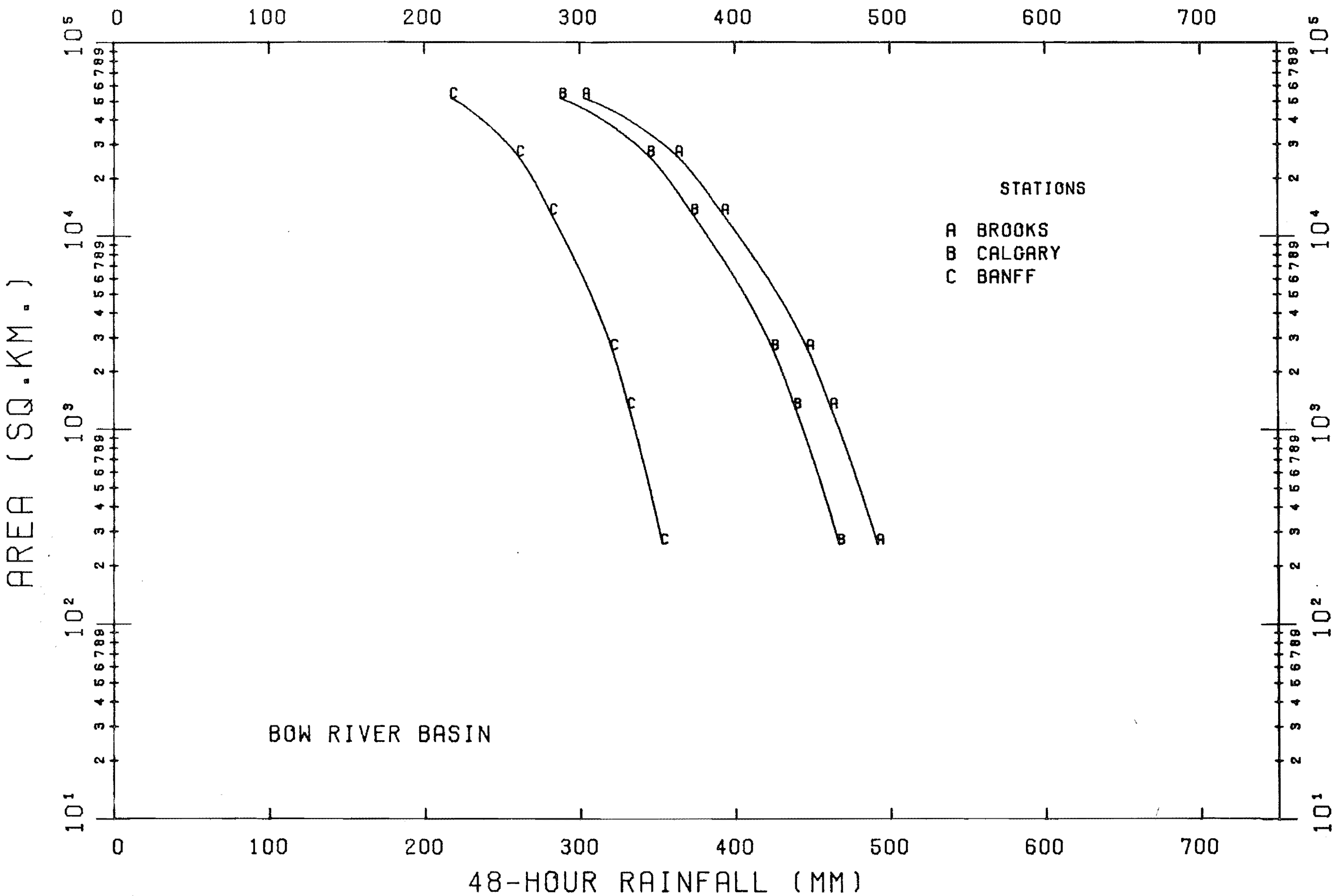

Figure 178 Enveloping depth-area 48-hour curves of estimated PMP for the Bow River basin.

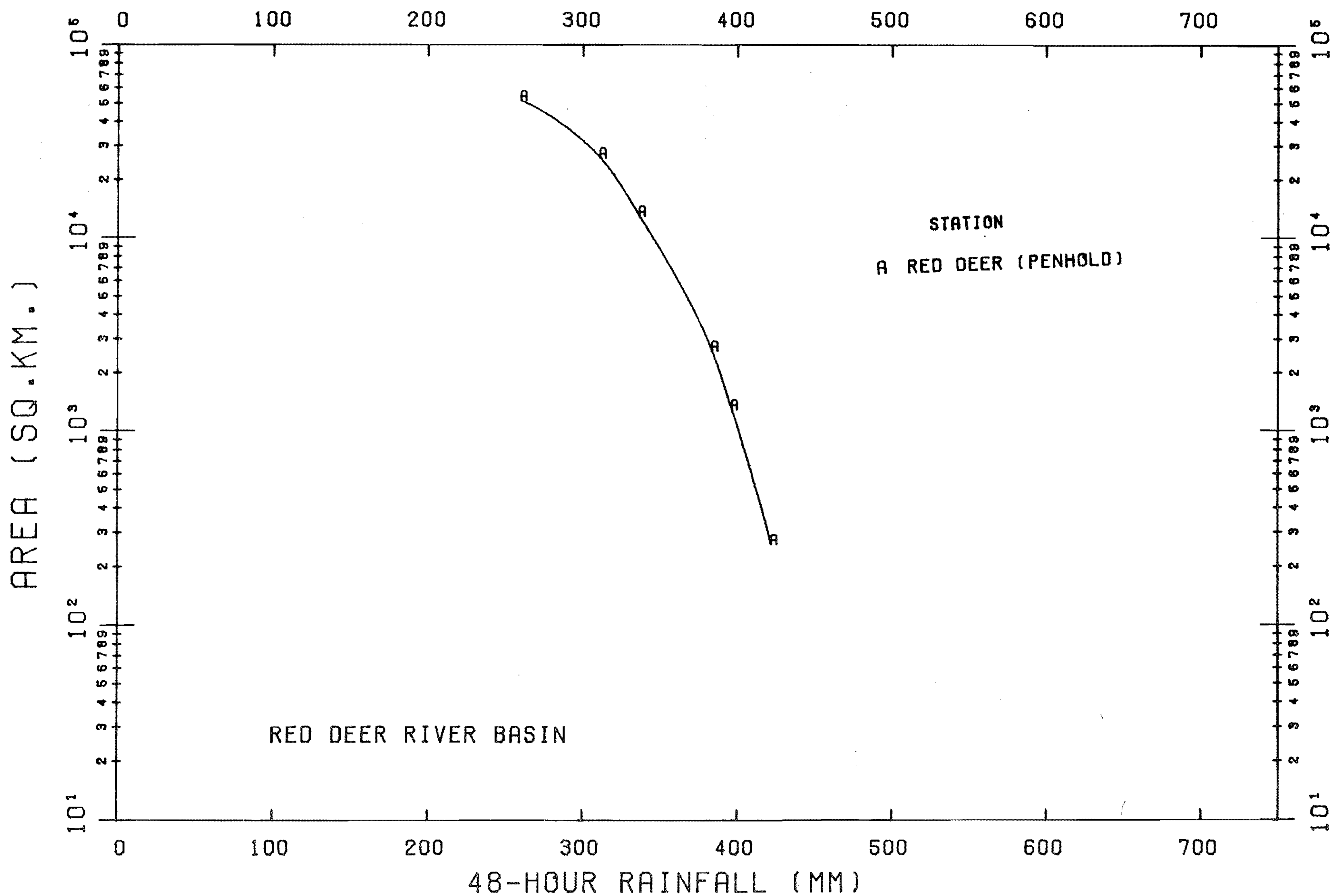

Figure 179 Enveloping depth-area 48-hour curves of estimated PMP for the Red Deer River basin.

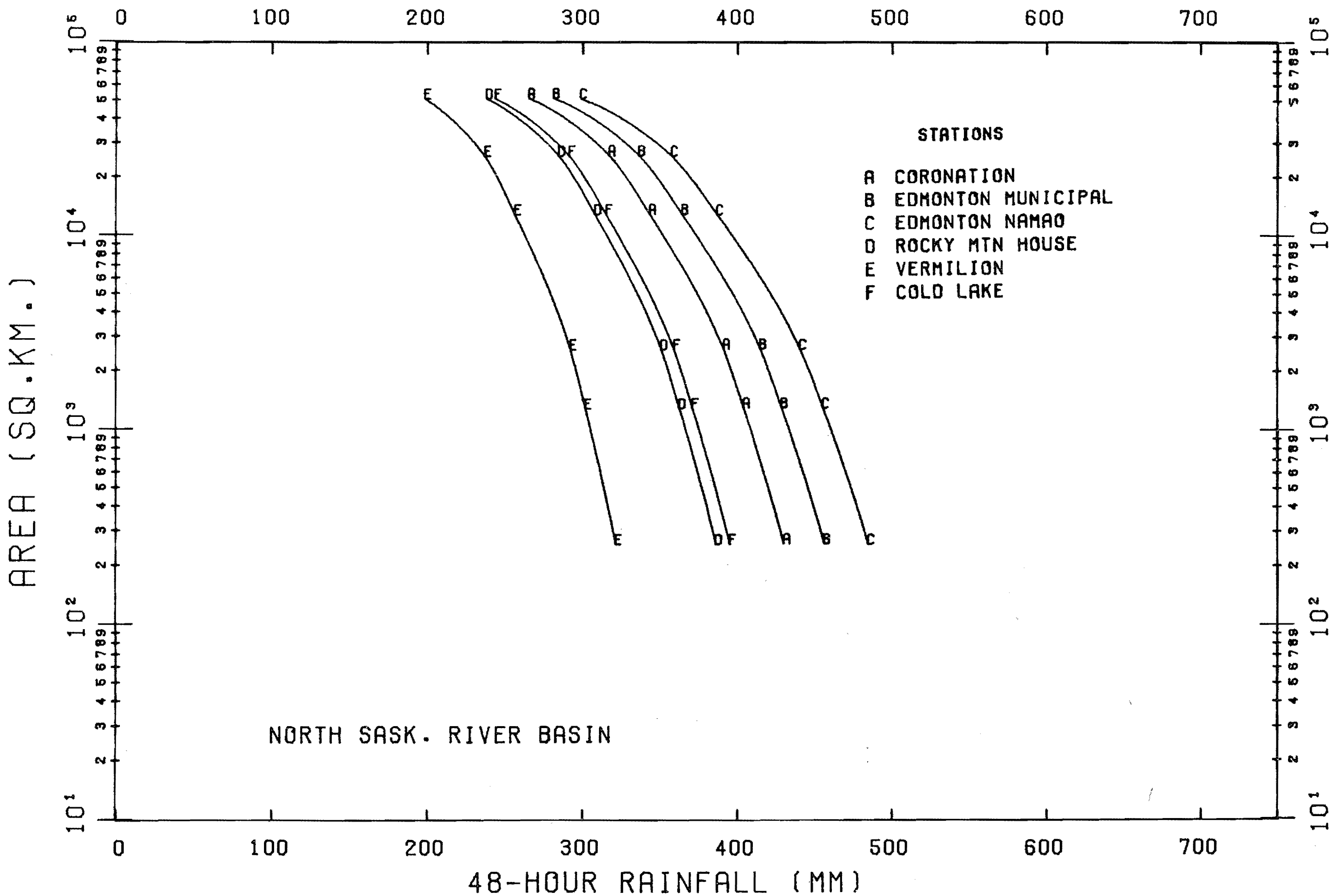

Figure 180 Enveloping depth-area 48-hour curves of estimated PMP for the North Saskatchewan River basin.

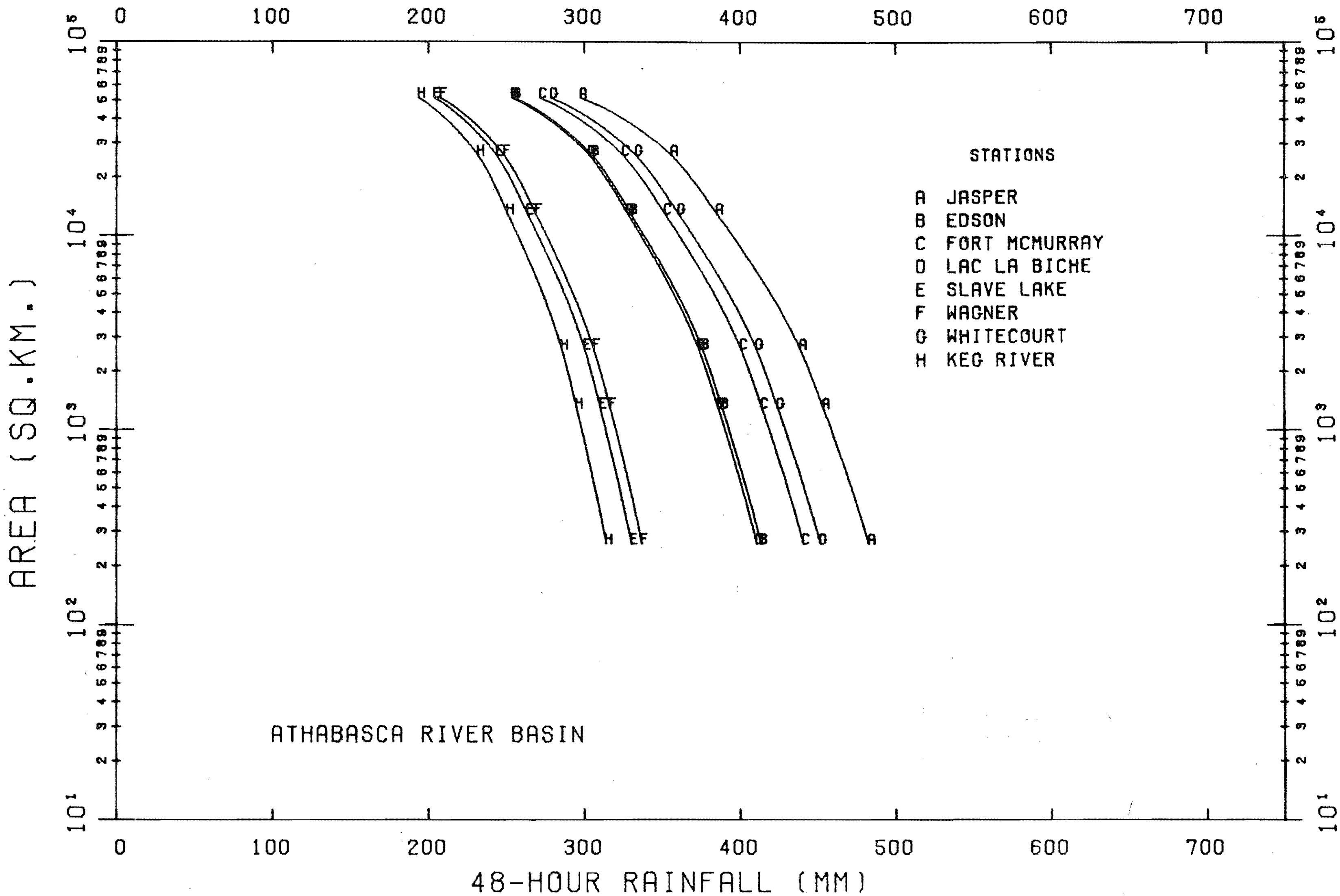

Figure 181 Enveloping depth-area 48-hour curves of estimated PMP for the Athabasca River basin.

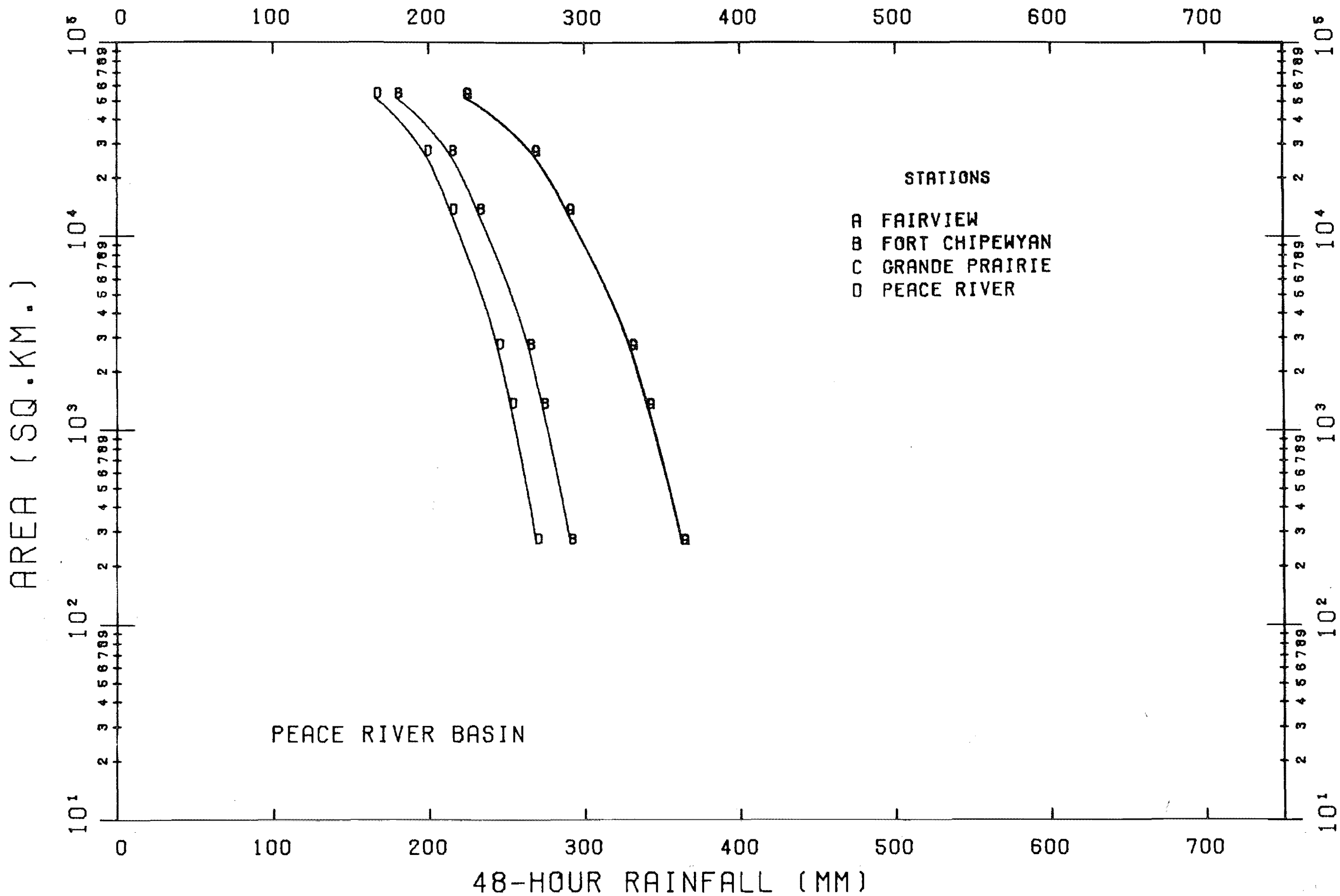

Figure 182 Enveloping depth-area 48-hour curves of estimated PMP for the Peace River basin.

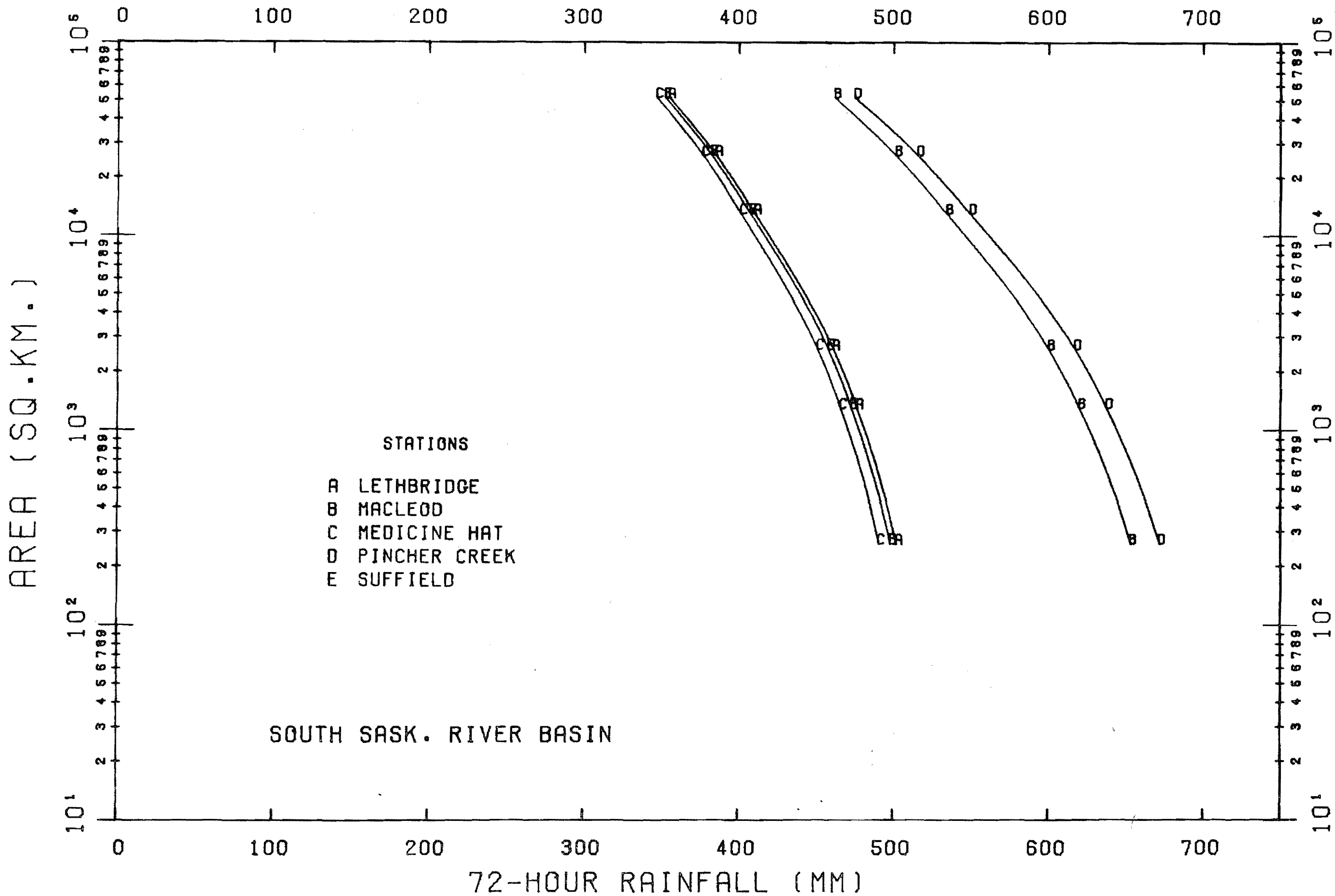

Figure 183 Enveloping depth-area 72-hour curves of estimated PMP for the Oldman River basin.

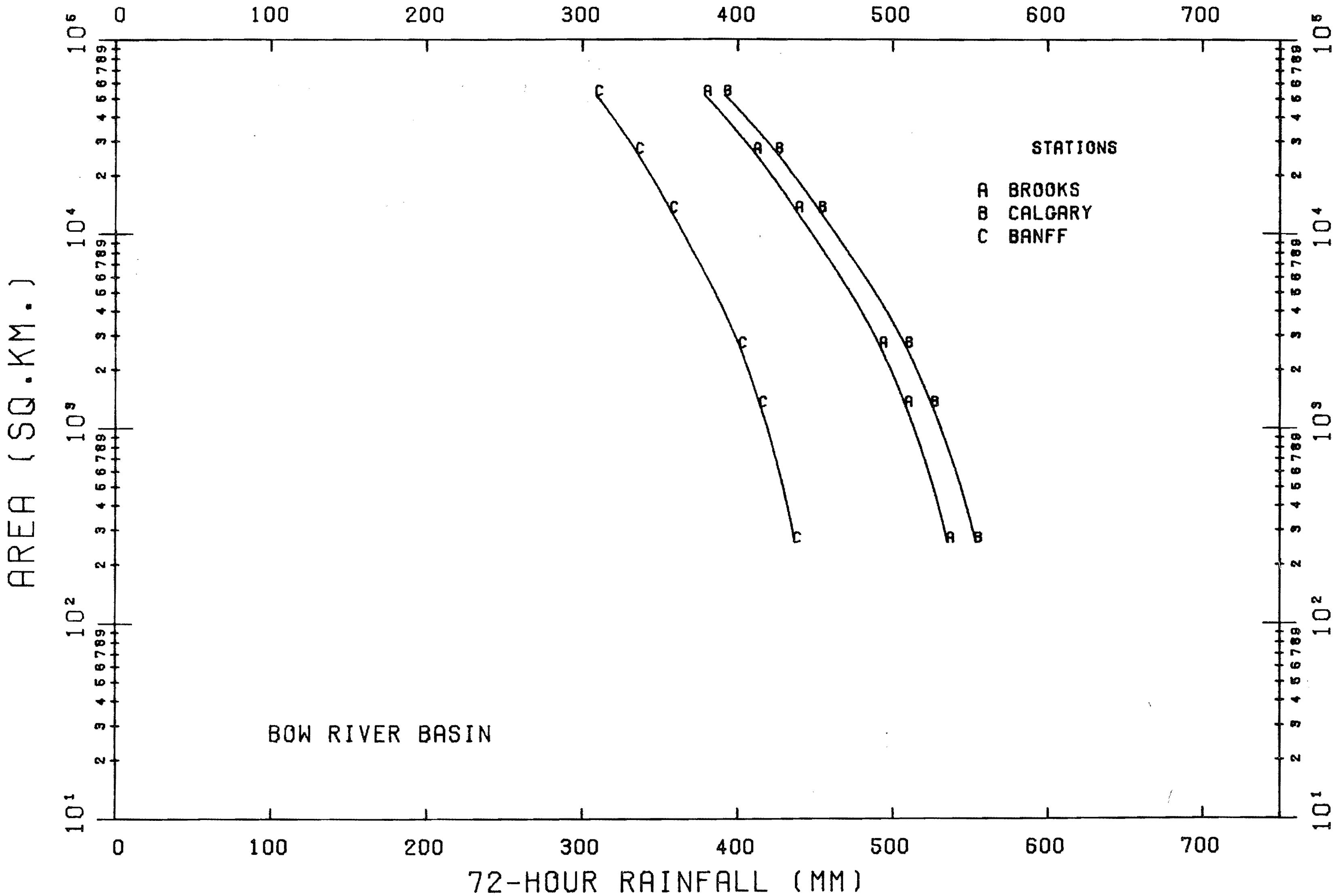

Figure 184 Enveloping depth-area 72-hour curves of estimated PMP for the Bow River basin.

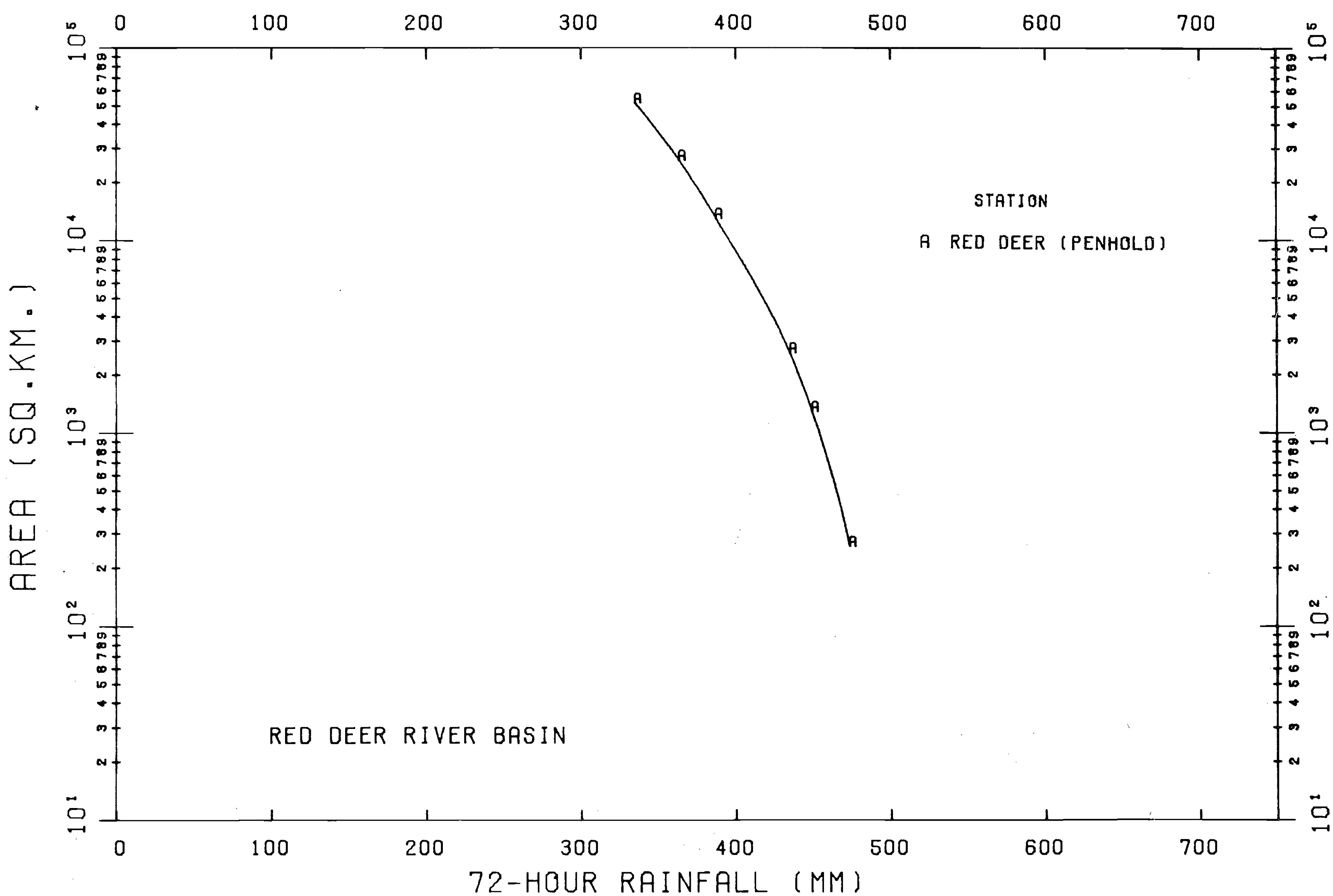

Figure 185 Enveloping depth-area 72-hour curves of estimated PMP for the Red Deer River basin.

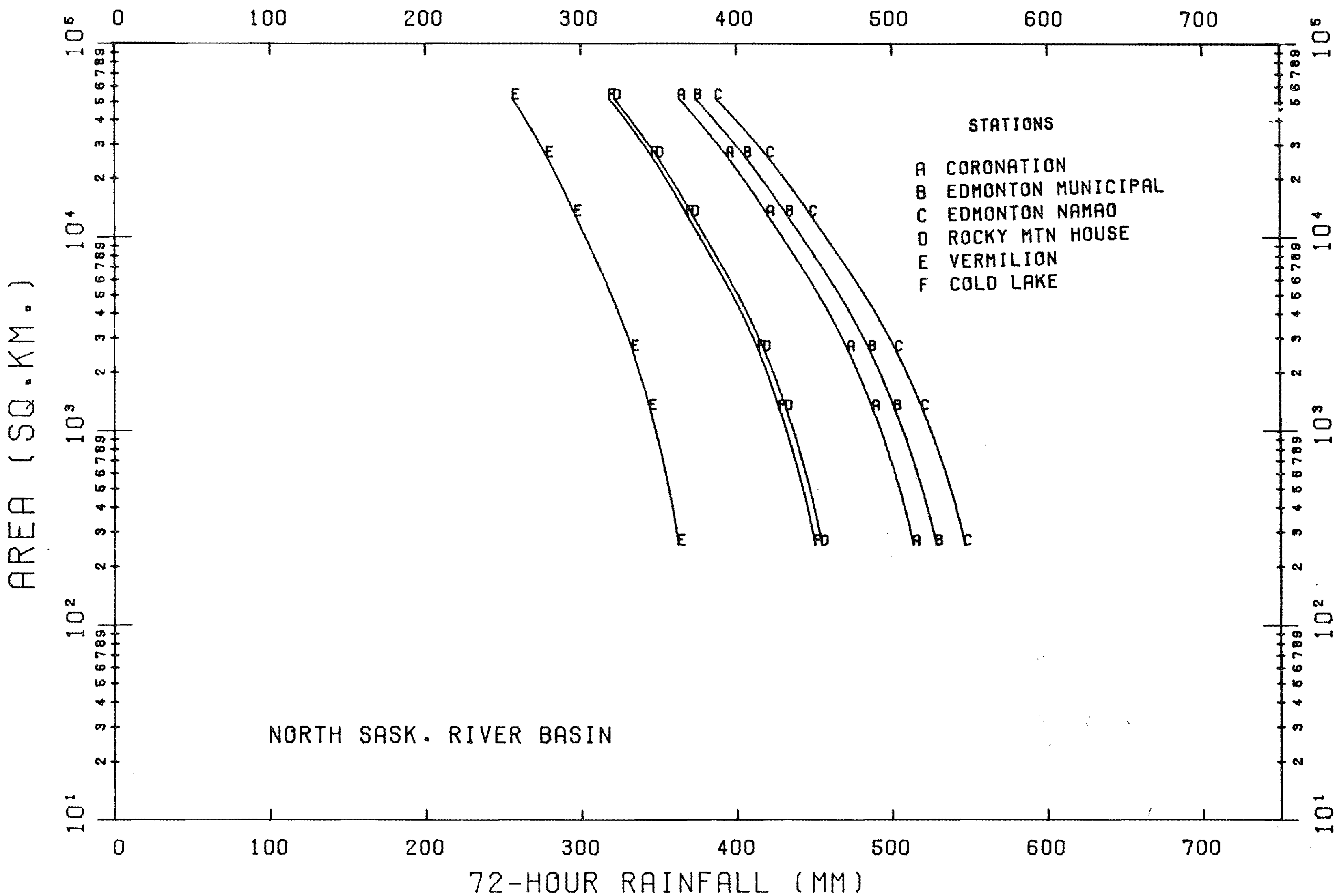

Figure 186 Enveloping depth-area 72-hour curves of estimated PMP for the North Saskatchewan River basin.

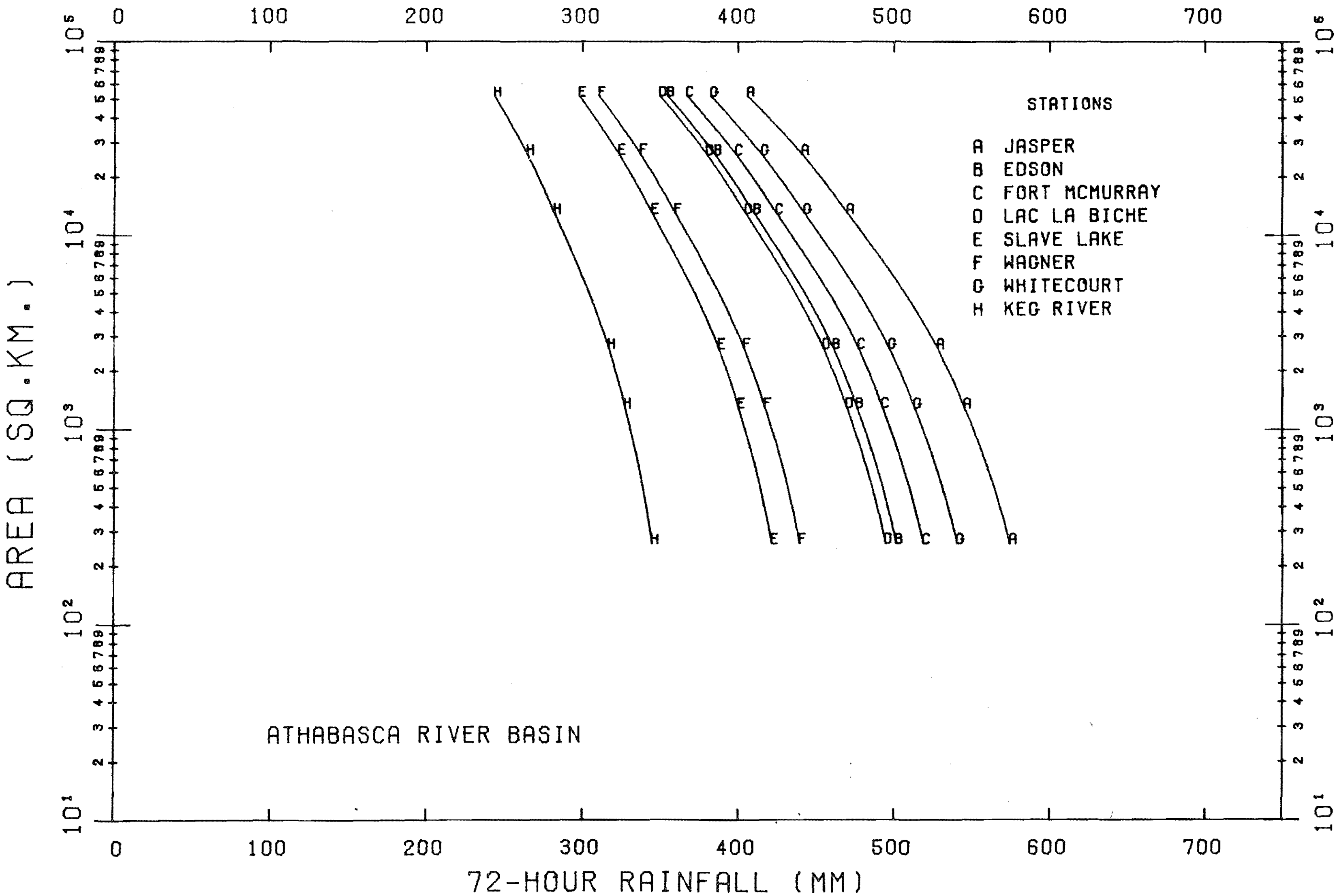

Figure 187 Enveloping depth-area 72-hour curves of estimated PMP for the Athabasca River basin.

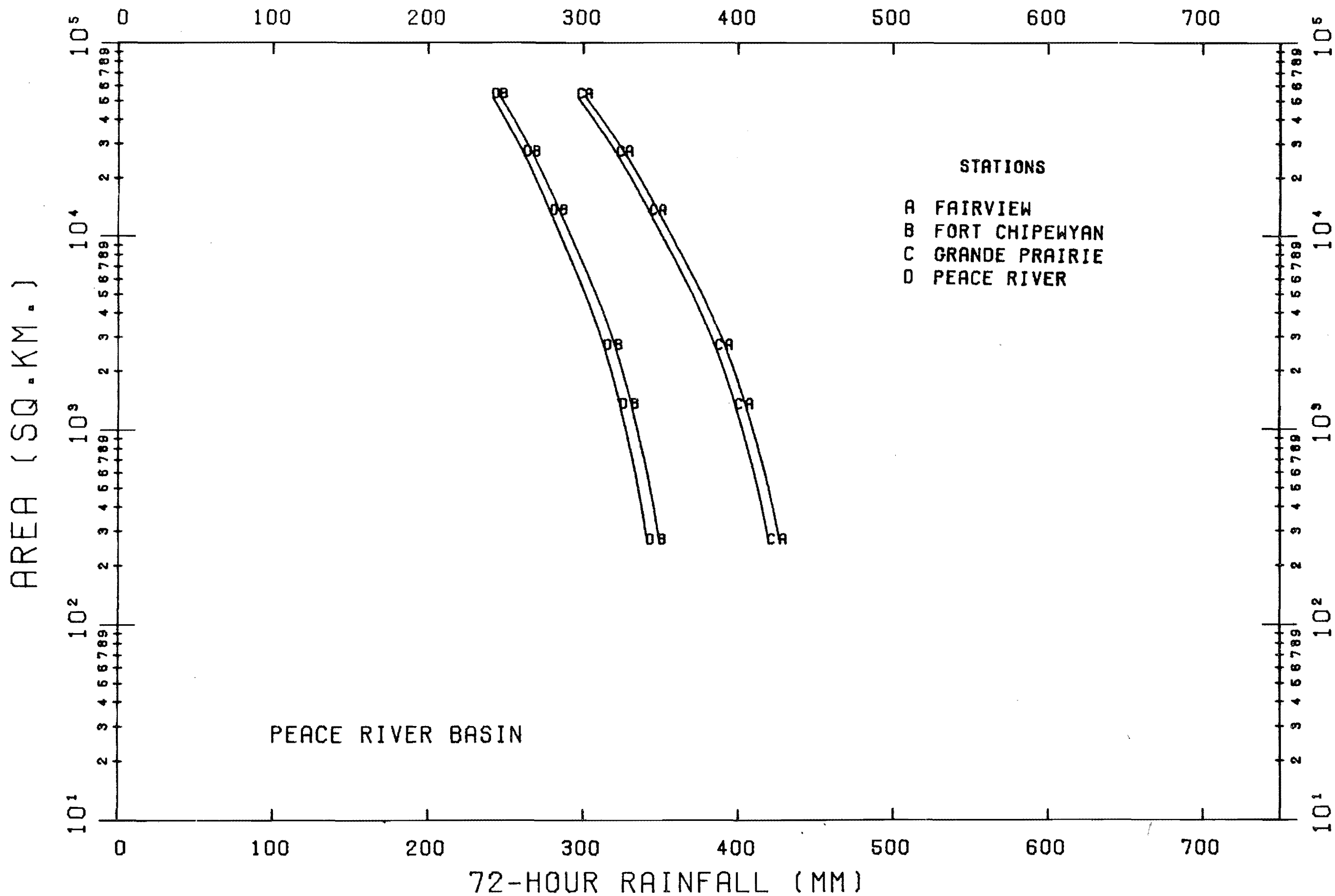

Figure 188 Enveloping depth-area 72-hour curves of estimated PMP for the Peace River basin.

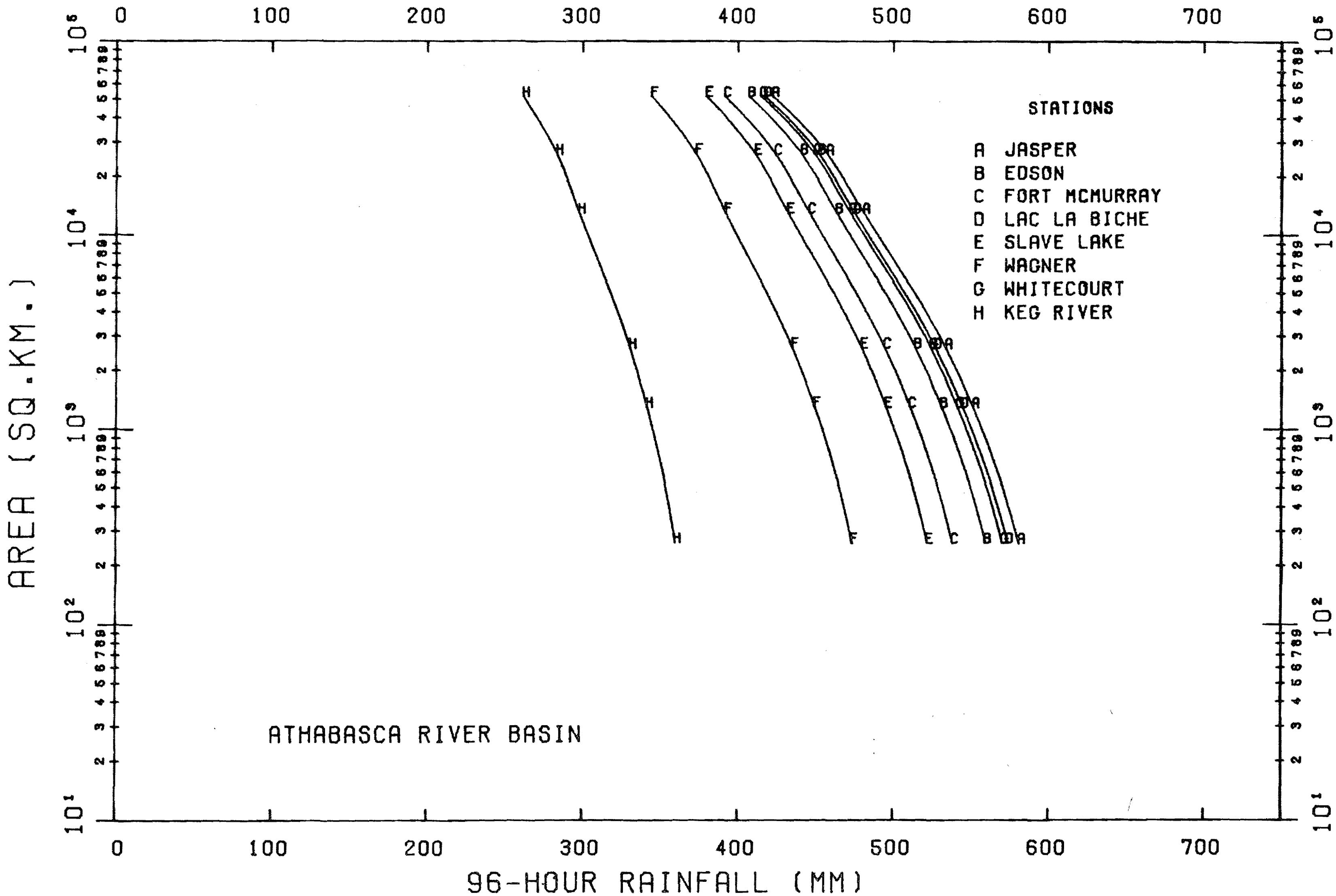

Figure 193 Enveloping depth-area 96-hour curves of estimated PMP for the Athabasca River basin.

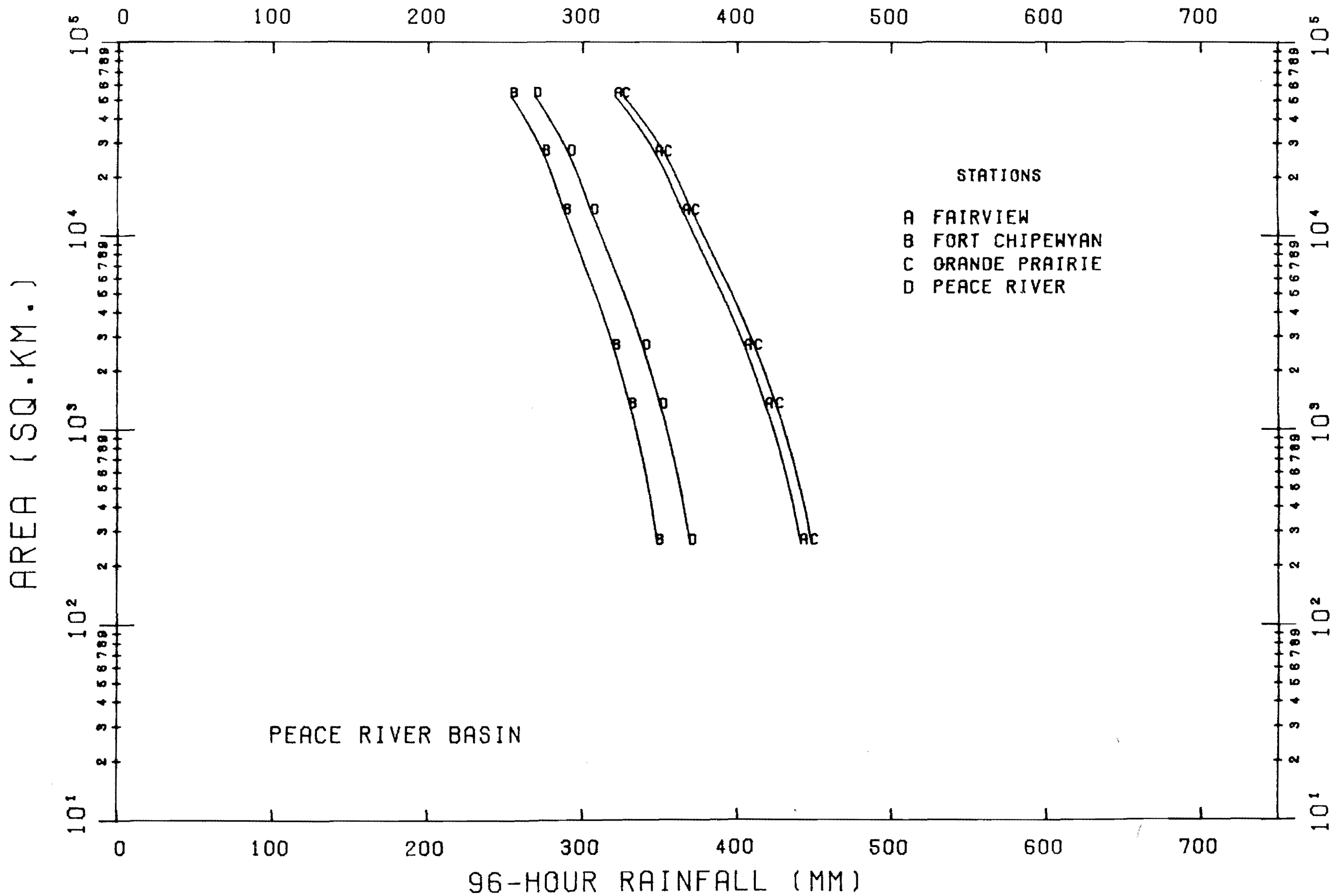

Figure 194 Enveloping depth-area 96-hour curves of estimated PMP for the Peace River basin.