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Hydrometeorological Report No. 22

AN ESTIMATE
OF
MAXIMUM POSSIBLE FLOOD-PRODUCING METEOROLOGICAL CONDITIONS
IN THE
MISSOURI RIVER BASIN
BETWEEN GARRISON AND FORT RANDALL

Prepared by

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1. Introduction

The Hydrometeorological Section has been requested by the U.S. Engineer Department, Corps of Engineers, to supplement the Garrison Report (1)* with a similar study for the Missouri River Basin between Garrison and Oahe and between Oahe and Fort Randall Dam sites (figure 1). Specific requests were made for estimates of:

a. Water equivalent of maximum possible accumulated snow

b. Water equivalent of maximum possible snowstorm

c. Average date of disappearance of snow cover

d. Maximum mid-May rainstorm

e. Seasonal variation of maximum storms, March through October

f. Minimum recurrence interval between maximum storms

Many of the problems of this study were also the problems of both the Columbia (2) and the Garrison Reports. Before the issuance of these reports there had been few, if any, attempts at their solution. The solutions that have been presented in the reports have been of necessity based on both data and theory which were insecure, although the best available at the time. Precedents were thus established, but it was felt that they should serve only as tentative guides to be followed in subsequent reports. The aim was, naturally, to improve the methods whenever possible.

* See list of references, section 11.

Basic to all three reports, for instance, are estimates of seasonal and even annual precipitation. Essentially, such an estimate cannot be made on a physical or theoretical basis, but renewed efforts are being made in each succeeding report to develop some physical checks on the estimate and to test the validity of previous methods. In the present study, refinements have also been added to the development of the seasonal variation of the maximum possible rainstorm, as well as to the development of the maximum possible snowstorm and its variation. These changes in technique are the result of the further study and investigation involved in the preparation of this report; they are not arbitrary changes. Any new technique which resulted in inconsistency with previous estimates was rejected unless it could be justified as unquestionably superior to previous methods.

2. Climate

Climatically the drainage area of the Missouri River between Garrison and Fort Randall belongs to the northern Great Plains. Only the extreme southwestern portions are subject to the steep orographic effects characterizing the eastern slopes of the Rockies.

Like the area above Garrison, this region is subject to high frequency of frontal passages, especially in winter. The frequency here is actually higher than above Garrison because the most frequent path of polar-air incursions is southeastward from northeastern Montana or northwestern North Dakota. Also, as in the Garrison, remoteness of the region from a moisture source and its position in the lee of the Rocky Mountains result in comparatively low precipitation totals despite the high storm frequency.

Farther east than the drainage area above Garrison, the Oahe-Ft.Randall basins are also more frequently subjected to invasions of tropical maritime air from the Gulf of Mexico. The general monsoon circulation characterizing the summer months leaves the region wide open to such invasions, with the result that more than 75% of the mean annual rainfall occurs from April to September, inclusive, and about 50% during May, June, and July. June is the month of heaviest mean monthly rainfall. Because the area is relatively free of rugged topography, there is rather uniform distribution of precipitation. The northwestward flow of the maritime tropical air in storm situations is indicated by the average decrease of mean annual rainfall from about 25 inches in southeastern South Dakota to about 15 inches in northwestern North Dakota. The Black Hills are an exception to this trend; their southeastward topographic aspect brings annual averages close to 25 inches here also.

In the colder months, however, between October and April, tropical air is almost never observed at the surface in this region. According to Willett (3), tropical air is never observed beyond northwestern Iowa in the winter months. During this period polar air overlies the region. The major precipitation at this time, mostly snow, occurs while the polar front is below the southern border of South Dakota. Some precipitation, however, is formed beneath the front by forced topographic lifting in the westward motion of the moistened air beneath the front. The average annual snowfall is between 31 and 35 inches, with March the peak snowfall month.

The midcontinental position of these basins subjects the air not only to an extreme range of temperature but also to an extreme range of dewpoint or moisture content. Studies made by the Hydrometeorological Section show that tropical air of high moisture content can reach the area in midsummer, when isotherms of maximum possible dewpoint characteristically bulge northward through the Mississippi and Missouri Valleys. In the winter months, however, the basins lie in a trough of the dewpoint isotherms. On either side, east and west, higher dewpoints (when reduced to a common standard level) are possible. Although data for northern sections of the United States are not complete, it is strongly indicated that in both North and South Dakota winter dewpoints (reduced) are the lowest for the latitude.

3. Storm Types

There are two important differences between the storm types characterizing the Missouri drainage area above Garrison and the types characterizing the drainage area immediately below (called in this report the Oahe-Ft.Randall basins, or area):

a. The steep orographic effect is minimized in the Oahe-Ft.Randall area, except in the Black Hills.

b. The Pacific source of moisture, responsible in the Garrison drainage area for important precipitation over the Absaroka Range and the portion of the basin just west of the Range, makes only minor contributions to the precipitation anywhere in the Oahe-Ft.Randall area.

Synoptically, the main storm types for either region bear a close resemblance.

In the Type I storm, in both areas, the basin is under the influence of modified polar air. The storm center crosses the Pacific Coast anywhere between Washington and southern California but in nearly all cases a secondary development follows in Colorado or New Mexico. The latter occludes and moves northeastward through or just east of the Dakotas. Deep cyclonic circulation aloft is associated with these storms. On the 10,000-foot chart it first appears as a trough over the northwestern states. As the trough approaches the Dakotas, the winds aloft become southwest and light precipitation - rain or snow - falls from the overrunning Pacific air. Accompanying the surface occlusion is the development of a closed cyclonic circulation aloft over the Dakotas. The flow of air from the south becomes intensified, bringing tropical maritime air aloft from the Gulf to the Dakotas. On the isentropic chart this flow is shown as a moist tongue flowing northeastward from the Gulf in advance of the Low aloft and then turning northwestward and cyclonically around the Low toward the Dakotas. This is the period of heavy precipitation, persisting as long as the region is under the influence of the moist tongue. During this stage of the storm, precipieation also falls from the lower polar air flowing from the east up the sloping terrain beneath the moist tongue and the frontal surface. As the tongue of overrunning air is displaced eastward or northeastward with the movement of the storm, the weather clears, but rather slowly since the moist tongue can curl completely about the Low aloft, precipitation occurring over the Dakotas on northeast and north winds behind the Low. The northwest winds in the surface polar air, however, preclude further orographic precipitation. During the winter months a cold wave is quite likely to follow in the wake of this storm type; however, the storm type can occur any time of the year. The storm of March 13-17, 1943, a major snowstorm in the Dakotas and a major rainstorm in the Ohio Valley, is of this type, and the sequence of circulations discussed is well illustrated in the maps accompanying the meteorological discussion of the rainstorm in a Hydrologic Storm Supplement (4).

Both above and below the Garrison, the Type II storm is what has been described in the Garrison Report as a persistent pressure pattern rather than a storm. It is most prevalent during the summer season. The principal features of a weather map of this type are a well-developed westward extenxion of the Bermuda High over the eastern half of the country and a trough of low pressure west of it. The mass of tropical Gulf air carried northward to the Dakotas by this circulation extends to high levels, the 10,000-foot chart showing circulation features almost identical with the surface chart. General showers fall over the Oahe-Ft.Randall basins, with precipitation occasionally intensified by the passage of a wave cyclone developing in the trough of low pressure. The storm ends when a lobe of the Pacific High pushes inland into the Great Basin, displacing the trough eastward. The displacement is reflected on the 10,000-foot chart, which indicates Pacific anticyclonic circulation extending to high levels over the Dakotas. The flow of tropical air is halted by the resulting wind shift aloft from south to northwest. The storm of September 5-14, 1938, is an example of Type II, as are many northern Minnesota and northern Wisconsin storms.

The Type III storm over the Oahe-Ft.Randall area resembles Type III over the Garrison drainage basin in that it is also a non-occluding system within the longitudes considered. However, its path is south of the area of interest rather than north of it. The sources of moisture for this storm type are the same as for Type I. Very cold polar air and high pressure prevail over the basin, with the polar front far to the south. A Pacific front advancing eastward across the Southern Rockies deforms the polar front, the resulting perturbation then moving eastward as a stable wave. South and southwest winds in advance of the upper trough associated with the Pacific front bring tropical air over the polar air at the surface, and widespread rains or snows over the Dakotas follow, augmented by orographic precipitation in the east winds bringing polar air up slope across the Dakotas. In this storm type no closed cyclonic circultation aloft develops over the Dakotas but may develop over the eastern Lake region. Continued southward advance of the polar front and its associated area of overrunning ends the precipitation. The storm of January 16-17, 1936, belongs to Type III. Principally a winter-type storm, Type III can also occur at any other time of the year.

A minor type, labeled IV, is a local storm, restricted mostly to the Black Hills area and associated with the passage of an intense polar Canadian cold front southeastward across the basin. Heavy snowstorms of short duration may result in western South Dakota. The storm of January 20-21, 1915, is an example.

Although it is simpler to discover and specify the characteristic storm types of a region, it is worth while to determine what storm types can be excluded from the project area, even though they are known to be important rainfall-producers elsewhere. Since the determination of the maximum possible storm must be based at least in part on transposition of storms from other regions, such a knowledge serves as a definite restriction on certain transpositions. On the basis of a synoptic study of the 40-year record of Northern Hemisphere Historical Weather Maps (5), the following storm types were definitely excluded from consideration for the Oahe-Ft.Randall basins:

a. The topical storm or hurricane, or the storms associated with the topical storm either as forerunners in inverted V-shape troughs north of the tropical-storm center or as aftermaths in the form of decadent cyclonic systems. The line separating such occurrences from the region of their non-occurrence has been only roughly defined but it is definite that both North and South Dakota are considerably northwest of such a line.

b. The nonfrontal storm in the winter months. This follows from the characteristic position of the polar front south of the area during these months. Observance of this synoptic fact excludes from consideration for transposition many outstanding winter storms that have occurred at lower latitudes, notably the phenomenal Elba, Ala., storm of March 11-16, 1929.

c. Storms occurring outside of a region of meteorological homogeneity roughly comprising the plains area between the Rockies and the Appalachians but not including the Gulf States. In particular, many storms which both by proximity and synoptic pattern seem transposable to the region must nevertheless be excluded because their occurrence on the eastern slopes of the Rockies makes their rainfall primarily orographic.

4. The Maximum Possible General Rainstorm

In the Garrison Report a maximum possible mid-May storm was determined by transposition and moisture adjustment of a few available storms, consideration also being given to the enveloping values of maximum rainfall for the United States. For the variation of the maximum storm from March through October the mid-May storm was adjusted to occurrence in other months by use of moisture ratios, W_p-correction factors, and a wind-variation factor. The last two were derived from a study of mean monthly data, the assumption being that the relation between the mean values could be applied satisfactorily to the extreme or maximum cases. It was chiefly to avoid such a questionable assumption that a different method of determining the seasonal variation of the maximum rainstorm was used in the present report.

This method, essentially, is to derive the maximum storms for as many dates as possible independently. The pattern of the seasonal variation of the maximum storm is implicit in the results, independent of assumptions concerning the nature of the phenomena governing the variation and, moreover, independent of the data chosen as the best available indication of the variation. A sufficient number of analyzed storm instances, occurring in or transposable to the area, are required, to give assurance that a maximum determination can be made within practically every month. A combing of the available storm data indicated that for most months sufficient storms were available, allowing a reasonable interpolation of the values within the months with scantier data. In all, 102 storms were used, the number within a calendar month varying from 20 in June to 3 in February. These storms are listed below, by date and U. S. Engineer storm assignment designation; for those marked with an asterisk only preliminary depth-area data were available. Storms discarded for synoptic reasons are not included.

Storm Date	Assignment Number
Jan. 1-3, 1907	LMV 1-15
Jan. 4-5, 1917	LMV 3-3
Jan. 6-11, 1930	LMV 2-22
Jan. 18-21, 1935	LMV 1-19
Jan. 21-24, 1920	OR 6-23
Feb. 9-14, 1938	GL 2-27
Feb. 14-19, 1938	SW 2-17
Feb. 19-23, 1922	GL 4-17
Mar. 9-12, 1939	UMV 4-16
Mar. 13-14, 1918	GL 2-17
Mar. 23-27, 1913	OR 1-15
Mar. 31-Apr. 2, 1917	UMV 3-4

Storm Date	Assignment Number
Apr. 5-9, 1938	GM 2-25
Apr. 5-11, 1919	GL 2-19
Apr. 12-15, 1911	LMV 1-8
Apr. 17-21, 1927	SW 2-4
May 2-6, 1898	SW 1-2
* May 6-9, 1927	MR 4-25
* May 6-11, 1943	SW 2-20
May 10-12, 1914	GL 2-15
* May 10-12, 1920	MR 4-17
May 15-19, 1930	LMV 2-24
May 17-19, 1927	UMV 4-12
May 19-22, 1912	GL 3-1
May 25-29, 1915	MR 2-7
* May 25-29, 1929	MR 4-27
May 27-June 2, 1935	MR 3-28B
May 29-June 3, 1929	MR 3-25
May 30-31, 1938	MR 3-29
June 2-6, 1898	UMV 1-3
June 2-6, 1932	SW 2-7
* June 2-7, 1908	MR 1-24
* June 3-4, 1940	MR 4-5
* June 3-5, 1904	MR 4-8
June 3-8, 1905	GL 2-12
June 6-8, 1906	MR 5-13
June 6-12, 1913	SW 1-14
June 8-11, 1922	GL 2-21
June 9-10, 1905	UMV 2-5
June 10-11, 1938	UMV 3-17
* June 10-13, 1944	MR 6-15
* June 11-12, 1915	MR 4-15
June 12-15, 1930	UMV 2-14
June 12-18, 1935	SW 2-13
* June 17-21, 1921	MR 4-21
June 23-26, 1942	MR 6-1
June 25-26, 1935	UMV 3-14
June 28-29, 1933	UMV 2-15
June 29-July 1, 1938	GL 3-11
Jul. 1-6, 1901	UMV 1-8
Jul. 4-7, 1909	UMV 2-8
Jul. 5-8, 1928	UMV 1-18
Jul. 9-12, 1922	MR 2-29
Jul. 11-16, 1937	UMV 1-20
Jul. 13-15, 1927	SW 2-5
Jul. 13-16, 1907	MR 1-23
Jul. 13-17, 1916	UMV 1-16
Jul. 18-21, 1905	SW 1-7

Storm Date	Assignment Number
Jul. 18-22, 1897	UMV 1-2
Jul. 18-23, 1909	UMV 1-11
Jul. 19-24, 1912	GL 2-29
Jul. 21-23, 1917	GL 2-30
Jul. 24-28, 1892	UMV 1-1
Jul. 25-27, 1897	GL 4-5
Aug. 1-2, 1929	UMV 2-17
Aug. 3-6, 1924	GL 2-22
Aug. 15-17, 1932	SW 2-8
Aug. 18-20, 1924	UMV 4-11
* Aug. 19-22, 1918	MR 4-16
Aug. 24-28, 1903	MR 1-10
Aug. 28-31, 1941	UMV 1-22
Aug. 31-Sept. 3, 1937	GL 3-5
Aug. 31-Sept. 5, 1926	MR 3-8
Sept. 2-5, 1926	SW 1-30
Sept. 2-6, 1940	SW 2-18
Sept. 6-9, 1915	MR 2-11
Sept. 6-10, 1937	SW 2-15
Sept. 8-9, 1926	OR 4-22
Sept. 11-16, 1915	UMV 1-15
Sept. 11-16, 1926	SW 2-1
Sept. 12-19, 1905	UMV 2-18
Sept. 13-20, 1923	SW 1-26
Sept. 15-19, 1942	UMV 1-25
Sept. 16-19, 1919	MR 2-23
Sept. 23-26, 1925	SW 1-29
* Sept. 27-Oct. 1, 1923	MR 4-23
Sept. 28-Oct. 2, 1927	MR 3-14
Oct. 3-6, 1910	OR 4-8
Oct. 18-22, 1941	MR 6-2
Oct. 19-24, 1908	SW 1-11
Oct. 25-28, 1919	LMV 1-13A
Oct. 27-30, 1900	UMV 1-7A
Oct. 30-Nov. 1, 1900	UMV 1-7B
Oct. 30-Nov. 1, 1919	LMV 1-13B
Nov. 10-16, 1909	MR 1-29
Nov. 15-17, 1928	MR 3-20
Nov. 16-19, 1921	SW 1-24
Nov. 17-21, 1906	LMV 1-4
Dec. 8-14, 1932	GM 2-11
Dec. 16-20, 1895	MR 1-1
Dec. 26-28, 1942	UMV 3-22
Dec. 27, 1922	UMV 3-10

Each storm in the list was adjusted for moisture content on the basis of a comparison of the dewpoints characterizing the inflow into the storm with the maximum possible dewpoints that would characterize inflow into the storm if it occurred over the Oahe-Ft.Randall area. An excessive transposition in time was avoided by confining the adjustment to those maximum dewpoints possible within 15 days on either side of the acutal storm date.

Two types of dewpoint adjustment were used. One, based on a thunderstorm-type flow model, was used for the months May to October, inclusive. For the months November to April, inclusive, the adjustment was based on a cyclonic flow model suggested by the Section's experiments in reproducing storm rainfall in the region of the Osage River. While the mechanisms or flow models are hypothetical and subject to revision as more data become available, the moisture adjustments nevertheless remain secure because model changes have relatively little effect on the ratio of adjustment from one dewpoint to another. Fuller discussion of fundamental models must, however, be left to a later report.

All adjusted storm values were plotted, at month and day of occurrence, on a one-year time scale and curves drawn enveloping all values, with some exceptions, for specified areas and durations. The values not enveloped belonged to two types. In one case these values were considered excessively high because they came from storms that were intensely orographic - an intensity, which, it was decided, could not be duplicated by the non-orographic features of a storm over the Oahe-Ft. Randall area. These were storms which should have been excluded from transposition because they occurred outside the region of meteorological homogeneity, as defined in the last section, but were nevertheless experimentally transposed and adjusted because of doubts arising in the initial selection. The storm of September 27-October 1, 1923, which had an important use in the Garrison study, was of this type. The other type of value not enveloped came definitely from a more local, short-duration type of storm than can be considered critical for the project basins. In general, this was a 12-hour value which was about equal to the 24-hour value in the same storm and usually close to the 24-hour enveloping value derived in this study. The Bonaparte, Iowa, storm of June 9-10, 1905, is such a storm. Values derived from such storms could not occur in the maximum storms over areas like 20,000 and 60,000 square miles and so were excluded from the envelopment.

The maximum depth-area values, so derived, for the middle of May are as follows:

MAXIMUM POSSIBLE MID-MAY GENERAL RAINSTORM
OVER THE MISSOURI RIVER BASIN BETWEEN
GARRISON AND FORT RANDALL
(INCHES)

Area (square miles)	Duration (hours)				
	12	24	48	72	96
2000	6.1	8.4	11.0	12.4	13.0
5000	5.4	7.4	10.0	11.2	11.9
10,000	4.7	6.6	9.1	10.2	10.8
20,000	4.0	5.7	7.8	8.9	9.5
50,000	2.9	4.3	5.7	6.7	7.2
60,000	2.6	4.0	5.2	6.1	6.6

The depth area curves from 2000 to 60,000 square miles are given in figure 2.

It is encouraging that most of the enveloping values throughout the year were determined by storms occurring in Minnesota, Wisconsin, the Dakotas, and Iowa rather than by storms transposed from states farther south. The seasonal variation from March through October shown by this envelopment is presented in figure 3 as a function of the mid-May values. The figure shows that this seasonal variation has itself an important variation with area, although only for a portion of the year. Meteorologically, the variation with area is to be expected. Even the widespread storm of midsummer is essentially composed of thunderstorms or local storms, many of which can produce high peaks of rainfall over smaller areas like 2000 square miles. However, when the precipitation is averaged over fully 60,000 square miles, the localized nature of the peaks reduces their effect on the 60,000-square-mile average depth. The spring storm, however, is a more uniform type of storm in which, although the peaks are individually lower than in midsummer, each controls a greater area and so these peaks have a greater effect on the average depth over the larger areas. Thus the variation between the May and the midsummer depths is largest for the 2000-square-mile area and smallest for 60,000 square miles. Area is apparently not significant in the variation between fall and spring. Tests were also made for a variation with duration, but that was found neither large enough nor systematic enough for further investigation.

5. The Maximum Possible Snowstorm

The major snowstorm of the region is the Type I storm previously described. Important examples are the storms of March 13-17, 1943, and November 9-11, 1940. In such a storm, for computation purposes, two important precipitation mechanisms are present. There is frontal lifting of the warm moist air flowing from the south, and there is orographic lifting of the cold moist air flowing from the east below the frontal surface.

The storm of March 1943 is of special interest because it occurred over the project basins and was also one of the greatest of record for the region. Only preliminary depth-area data were available, based on the total isohyetal map accompanying Part I of the storm study; a 24-hour breakdown over the total area of primary interest (93,000 square miles) was based on the automatic records within the storm.

By using all available meteorological data, including the radiosondes at Bismarck, International Falls, and St. Paul, it was possible to make satisfactory estimates of moisture content in the air flowing above the front and in the air flowing below the front, as well as an estimate of the frontal slope itself. The latter is constant neither in time nor in space, but for purposes of simplifying the computations a mean slope was assigned to the frontal surface over the area for each period, the magnitude of the slope being an inverse function of the distance of the surface position of the front from the area. The slope was found to vary linearly from 1/100 when the surface front was at the basin boundary to 1/250 when the surface front was

300 miles away, usually measured in an approximately north-south direction. This is the frontal slope measured in the same direction, i.e., normal to the surface position of the front. Considered in an east-west direction, for purposes of orographic computation, the frontal slope was assumed to be constant and parallel to the topographic slope, which runs from an elevation of 1500 feet on the east side of the basins to about 4000 feet on the west side.

Given the data described above it was possible to compute, for each 24-hour period, the effective precipitable water W_E produced by frontal lifting and also the W_E orographically produced. These can be called the observed frontal W_E and the observed orographic W_E. By substituting for the moisture content in the air above the front the highest possible moisture content consistent with a pseudo-adiabatic lapse rate in saturated air and temperatures no higher than 32°F at all elevations over the area of interest, it was then possible to compute for each 24-hour period a maximum possible frontal W_E. A maximum possible orographic W_E was also computed, this based on the assumption of saturation and an isothermal lapse rate at 32°F in the air below the front. Such layers, isothermal and saturated, with temperatures close to 32°F, were observed in the region. In the frontal case the air flow was restricted to the space between the frontal surface and the 300-mb surface; in the orographic case the flow was restricted to the space between the ground and the frontal surface, both having the same slope.

Before adjustment of the observed storm to its maximum value for increased moisture content, it was necessary to separate the frontal from the orographic precipitation. This was done by assuming that they bore the same ratio to each other as the observed frontal and orographic W_E values. For every 24-hour period each of these two precipitation components (frontal and orographic) was then increased to its maximum by multiplying it by the appropriate ratio of the maximum to the observed W_E. The results, in inches of water equivalent over 93,000 square miles, are tabulated below:

Date	Observed Precip.	Adjusted Precip.
13	0.07	0.12
14	0.14	0.28
15	0.30	0.48
16	0.34	0.49
17	0.12	0.39
Total	0.97	1.76

The adjusted storm is thus 180% of the observed. Adjusted by the same percentage, the value over 60,000 square miles is 2.2 inches, over 20,000 square miles 3.1 inches, and over 2000 square miles 4.3 inches.

However, this is not necessarily the maximum possible snowstorm. It would be if it could be assumed that the dynamic structure of the March 1943 storm was at a maximum, that is, if the moist air had been processed at the greatest possible rate. Because no theoretical method of extrapolating wind structures to their upper limits is available, the best security is in a moisture adjustment of a large number of major storms and envelopment of the values obtained. For this purpose seven storms in all were subjected to the analysis and adjustment described above. They were:

Dates	Assignment numbers
March 23-27, 1913	OR 1-15
March 10-12, 1939	UMV 4-16
* March 13-17, 1943	MR 6-11
April 17-21, 1927	SW 2-4
April 12-15, 1911	LMV 1-8
Feb. 14-19, 1938	GL 2-27
* Nov. 9-11, 1940	(to be assigned)

Only preliminary depth-area data were available for those storms marked with an asterisk.

All but the 1943 storm required transposition to the area, and these were examined meteorologically to determine the propriety of such transposition. Some were originally rainstorms; some were reduced in the transposition and adjustment. The final enveloping depth-area values for a duration of 96 hours are shown in figure 4. This curve is dominated by values from the March 1913 storm. In that storm the adjustment was on the basis of a 60,000-square-mile area. To obtain the values for smaller areas the observed values for all areas in the 1943 storm were increased by the ratio of the adjusted depth over 60,000 square miles in the 1913 storm to the observed depth over 60,000 square miles in the 1943 storm. The final values are considered to be the maximum for a snowstorm occurrence in mid-March and the curve is so designated in figure 4. To obtain the mid-May maximum snowstorm values, also shown in figure 4, it was necessary to consider the seasonal variation of the maximum snowstorm.

Figure 3 shows the seasonal variation of the maximum general rainstorm. Essentially such a variation is compounded of two separate variations - one of moisture content and the other of storm dynamics. The latter is only roughly a variation in wind speed; it involves a change in wind structure which results in a change of storm intnsity even when the air-mass moisture content is constant. The variation of moisture content is available as data basic to the report in the seasonal march of the maximum possible dewpoint temperatures in the region. The dewpoint variation can also be stated as a variation in intensity of precipitation per unit net-inflow wind if a definite rainfall mechanism is postulated. Such a mechanism has been postulated in estimating the maximum mid-March snowstorm, and also in the determination of the maximum possible rainstorm by transposition and adjustment of storms to the project area. The seasonal variation of the dynamic or wind factor is qualitatively evident in all hydrometeorological studies but hitherto it has been impossible to express it quantitatively in any satisfactory manner.

Within the limits of the accuracy of the data and assumptions used in this report, it now becomes possible to make such a quantitative statement. The seasonal march of maximum possible dewpoint can, as has been said, be expressed as a curve of seasonal variation of storm intensity or W_E; that is, the curve also states the seasonal changes in a theoretical maximum storm if such a storm were solely a function of the dewpoint or W_E. The maximum storm would be solely such a function if the wind factor were constant. That the wind factor is not constant is evidenced by the fact that the curve of actual maximum storm variation (figure 3) differs from the curve of the dewpoint function. However, since two of the three seasonal variations are available, it is possible to derive the third, or the variation of the wind factor.

The facts can be stated as follows: The ratio of the maximum July storm (S_J) to the maximum May storm (S_M) is equal to the product of the ratio of the maximum July moisture content (M_J) to the maximum May moisture content (M_M) times the ratio of the maximum July wind factor (W_J) to the maximum May wind factor (W_M), or

$$S_J/S_M = (M_J/M_M)\ (W_J/W_M)$$

and, therefore, $$W_J/W_M = (S_J/S_M)/(M_J/M_M)$$

Since all terms on the right-hand side of the last equation are known, the variation of the wind factor can be derived. For example, suppose the dewpoint curve indicates that the July storm can be 150% of the maximum mid-May storm while the maximum-storm curve shows the percentage to be 135. Then the ratio of the July wind factor to the mid-May wind factor is 135/150 or 90%.

The maximum snowstorm differs from the maximum rainstorm in that it occurs at what is for all practical purposes a constant dewpoint or a constant set of dewpoints. Assuming saturated conditions (in the maximum case), the storm must occur at dewpoints such that no temperatures above 32°F occur over the storm area. If such dewpoints can be achieved over the area throughout the season, the maximum snowstorm over the region can have no seasonal variation due to moisture content, because higher moisture content - and hence higher dewpoints - will change the precipitation from snow to rain. Except in the air below the frontal surface in January and February, the maximum dewpoints required for the maximum snowstorm conditions can be achieved in the Oahe-Ft. Randall area. Even in the months mentioned the dewpoint deficiency is small enough to be neglected.

However, the maximum snowstorm will vary with the wind factor. The wind variation, derived as described above from the independent variations of the maximum dewpoint and the maximum rainstorm, has been applied to the maximum mid-March snowstorm in order to obtain most of the variation of the maximum snowstorm as shown by the curves in figure 5, where the values have been converted into terms of the mid-May snowstorm. As in figure 3, for the maximum rainstorm, the variation itself varies with area. Only the 2000- and the 60,000-square-mile variations are shown, and linear interpolation is suggested for obtaining the percentages applicable to intermediate areas. The absolute values of the mid-May snowstorm, derived from this figure, are shown in figure 4.

One other important factor was considered in developing the seasonal variation of the snowstorm. Even if dewpoints higher than 32°F can be achieved almost all the time, it does not follow that dewpoints or temperatures as low as 32 can be achieved or, if achieved, can last the total duration of the maximum snowstorm, which is 96 hours. An examination of the temperature records in the region, consisting mostly of maximum and minimum values, did not provide a satisfactory criterion for determining the possible duration of snowstorm conditions. The occurrence of consecutive days with snow was finally used as the criterion for the snowstorm duration. A study was made of cooperative-station records in the region to determine the seasonal variation of the number of consecutive days on which snow could fall. For the times of year at which it was decided that less than four consecutive days of snowfall could occur, the percentage indicated by the wind-factor variation curve was applied to a less-than-four-day total, but the less-than-total amount was always the maximum for the duration. For a one-day storm, for instance, the maximum 24-hour amount was used. The four-day duration was reduced linearly to zero from May 15 to July 15 on the spring-summer side and from October 15 to August 15 on the fall-summer side. The curves as given in figure 5 have incorporated these trends.

6. Storm Recurrence

The 40 years of published Northern Hemisphere surface synoptic charts (5), and also the U.S. Engineer Department's storm-assignment lists, were studied to evaluate storm frequencies and minimum storm-recurrence intervals over the Oahe-Ft. Randall area. It was qualitatively determined that the minimum recurrence interval between maximum possible storms is also subject to a seasonal variation. In terms of the length of interval, the seasonal variation is the reverse of the variation of the maximum possible rainstorm.

The shortest recurrence interval is at the time of the maximum rainstorm, approximately August 1. Its length is five days, measured as the lapse of time between the ending of the maximum 24 hours of rainfall of the first storm and the beginning of the maximum 24 hours of rainfall of the second storm. Illustrating such a recurrence interval are the major storms, July 18-22, 1897 (UMV 1-2) and July 25-27, 1897 (GL 4-5), the first occurring over northern Minnesota and the second over northern Wisconsin. This minimum time interval is longer than the minimum interval in more southern latitudes and along the Atlantic Coast because, Minnesota and Wisconsin being at a greater distance from the oceanic and Gulf sources of moisture, a longer period is required to reestablish a strong current of moist air after each storm occurrence.

The interval increases as the season becomes cooler. The polar-air thrusts which end the storms reach lower and lower latitudes and the period required to reestablish strong currents of tropical maritime air is increased. Furthermore, the relation between cold air temperatures aloft and heavy precipitation becomes more definite in the cooler months. The relation is such that excessively cold air is accompanied by a strong south or southeast current east and northeast of the low pressure in the cold air aloft. The strength of the moisture-bearing south or southeast current depends on the potential energy manifest in the temperature gradient from the warm to the cold air. Examination of intense cold Lows such as the one accompanying the Dakota snowstorm of March 1943 indicates that, while a succession of cold Lows can advance from the west or northwest with about the same periodicity as indicated by the minimum summer-storm interval, the succeeding cold Low is not as intense as its predecessor. The temperatures in the new invasion of cold air may be as low or lower but the older cold air, although modified, still persists in advance to weaken the temperature gradient. In general, the more intense the first storm the weaker the following temperature gradient and therefore the weaker the following storm. On this basis, necessarily qualitative and derived from limited study of limited upper-air data, the midwinter maximum storm of February is given a minimum recurrence interval of 12 days, defined as the interval between maximum 24-hour precipitation periods, as before. Figure 6 graphs the seasonal variation throughout the year between the midwinter and midsummer values of 12 and 5 days, respectively. The same recurrence interval can be applied to maximum snowstorms. It is also the interval between the maximum snowstorm followed by the maximum rainstorm and vice versa.

The possibility of coincidence of runoff from severe storms between Garrison and Fort Randall with the peak outflow from the flood above Garrison is thus definitely indicated. However, in using the minimum recurrence intervals for such a purpose, the maximum rainstorm postulated below Garrison Dam site must be considered as occurring on ground covered by less than the maximum possible accumulation of snow (discussed in section 7). The previous occurrence of the maximum rainstorm above Garrison will have been accompanied by sufficient warmth to melt a substantial portion of the snow cover below Garrison. Although, during the occurrence of the maximum rainstorm above Garrison, the area below Garrison may very well be beneath the frontal surface and not within the moist tropical air producing the rainfall above Garrison, the lower layer of air will always be a greatly modified polar air mass, modified sufficiently to cause substantial melt. The determination of the minimum possible melting in such a situation would require a great deal more research than is practicable before the promised completion date of this preliminary report.

Although some of the snowpack is lost in the combination of events outlined above, it is meteorologically sound to have a maximum snowstorm over the Oahe-Ft. Randall Basins intervene between the maximum rainstorms above and below Garrison. Since the same recurrence interval applies to the maximum snowstorm as to the maximum rainstorm, the use of an intervening snowstorm would, however, double the minimum time interval between the maximum rainstorms above and below Garrison.

Another possibility in the trial sequence of floods and storms below and above Garrison is suggested. The snow cover (that is, maximum snow accumulation plus late spring snowstorm) above Garrison can be melted while still retaining the maximum snow accumulation below Garrison, if the maximum rainstorm is omitted from the Garrison flood sequence. It is the surge of tropical air from the southeast, necessary to produce the maximum Garrison rainstorm, which helps to melt the snow cover below Garrison. If the storm is omitted, a snow-melt flood above Garrison just preceding a critical sequence of events below Garrison can be combined with the flood resulting from any combination of events below Garrison consistent with the restrictions imposed by the minimum recurrence interval.

7. Maximum Seasonal Accumulation of Snow

By computations independently made, the average snowfall over the basin between Garrison and Oahe Dam sites, and also over the basin between Oahe and Fort Randall Dam sites is 3.6 inches of water equivalent. The value for each basin was obtained from a statistical regression relating mean monthly temperature, mean monthly precipitation, and mean monthly snowfall at all stations where these data were available, as was done in the Garrison Report. The identity of the snowfall values for both basins is an indication of the comparative homogeneity of the whole basin between Garrison and Fort Randall. Unlike the area above Garrison, where it was indicated that the area-elevation distribution makes the computed average snowfall of 4.9 inches only an index to a true value of about 10 inches, the area between Garrison and Fort Randall contains a satisfactory density of high-altitude stations. Hence the average snowfall values given above may be taken as truly representative of the average situation over the basin below Garrison.

An exact physical basis for computing the upper limit of the possible annual snowfall or of the possible snow accumulation is not yet known. The estimate of practical upper limits must therefore be empirical, based on a more or less subjective extrapolation of a comparatively short period of record. Three methods for arriving at this estimate have been used.

In the first method a maximum percentage of normal is applied to the normal or mean annual snowfall. The percentage to be applied can be selected from several possible values ranging from one based on the actual record of one maximum season to a percentage computed from a synthetic snow season obtained by combining maximum short-period precipitation values. The following table demonstrates the range of the possible percentages of normal:

Wettest calendar year for sections of North and South Dakota in subject basin	143% of Normal
Synthetic year composed of wettest 3-month periods of record	183% " "

Synthetic year composed of wettest months of record	229% of Normal
Synthetic snow season composed of wettest months, September through May, over the basin	258% " "
Synthetic year composed of wettest weeks of record	363% " "

The percentage determined for the synthetic snow season, 258, was selected as the most reasonable, since it excludes the effect of the non-snow-contributing months. Application of this selected percentage, 258, to the mean annual water equivalent of snowfall, 3.6 inches, yielded a maximum accumulation of 9.3 inches for the basin as a whole.

All the states which extend into the basin have experienced state-wide seasonal precipitation greater than 200% of normal. Furthermore, there is no known physical reason why wettest periods as long as a month could not occur in sequence. Examination of the synoptic features of the particular months combined in the synthesis reveals no meteorological discontinuity to be bridged. Even the combination of wettest months includes dry periods of recurrence intervals sufficiently long to permit reestablishing the moisture inflow. It is not necessary that a comparatively dry month follow a wet month; it is only the operation of random chance which makes this the usual case, since the months with far less than maximum recorded rainfall have the much higher frequency. This argument cannot be extended to the combination of wettest weeks and days because of the necessity for periods of moisture replenishment.

Consideration of the temperature regime, a matter closely related to the snowfall problem, also indicates that such a synthetic season is well within the realm of possibility. Some of the wettest months were also the coldest months of record, and those which were not the coldest months of record experienced total precipitation amounts not materially different from the coldest months of the same name. A study showed that the synthetic season composed of the coldest months of record since 1892 was only slightly colder than the severe winter of 1880-81, historically the winter of the greatest recorded snowfall and snowpack. This comparison is shown graphically in figure 7.

Another physical check was made on the reliability of using a year or season synthesized from the wettest months of record. The average weekly precipitation amounts for the calendar year 1915 for the combined area of Middle North Dakota and Middle and Western South Dakota (a combination approximating the basin area and characteristics) were used as storm amounts and adjusted upward on the basis of maximum possible moisture content, in approximately the same way as storms were adjusted upward for the determination of the maximum possible storm. The weekly amounts were obtained from the WPA weekly rainfall tabulations for state sections and 1915 was used because it was the calendar year of maximum precipitation for the period of WPA tabulation, 1906-35. The annual rainfall adjusted in this manner was 228% of normal, a percentage practically identical with that of the synthetic year composed of the wettest months of record. This value, incidentally, is considered to be a reasonable estimate of the maximum possible annual precipitation over the basin area between Garrison and Fort Randall.

The synthetic season of wettest months of record from September through May was also used in making the second estimate, which served as a check on the first. In this second estimate the maximum possible accumulation of snow was obtained by applying to the monthly precipitation amounts from the wettest months the following statistically derived equation:

$$P_s = P_t \frac{(53 - T)}{32}$$

where P_s is the precipitation in the form of snow, P_t is the monthly total precipitation, and T is the mean monthly temperature in degrees Fahrenheit for the states of North and South Dakota, the equation being the same as that derived for the computation of the mean annual snowfall used in the first estimate above. Combination of the monthly snowfalls so computed into a September-to-May snow season gave a water equivalent of 10.6 inches.

A third estimate of the maximum possible accumulation of snowfall was obtained by tabulating the snowfall occurring at selected stations in the basin during the particular months of available record which gave South Dakota its greatest snowfalls of record. An average for the basin of 10.1 inches of water equivalent was obtained by this approach.

The estimates derived by the several methods are of the same order of magnitude. Because the last approach, however, permits the best isochional analysis, it was used and extended to estimates of the maximum snow accumulation for areas of all sizes. While for the basin as a whole, 80,000 square miles, 10.1 inches of water equivalent was obtained, for 25,000 square miles the value is 14.0 inches, for 5000 square miles 17.4 inches, and for 2000 square miles 17.8 inches. These areal relationships, expressed in percent of a mean annual value of 17.34 inches, are shown in figure 8. The accumulations are to the end of June.

For continuity with the Garrison report, figure 8 has been labeled maximum possible snow accumulation. However, just as in the Garrison report, the values represent accumulations of snowfall in the same sense as accumulation of precipitation, rather than depth of snowpack. The probable losses from the snowpack previous to the critical sequence of meteorological events accompanying the flood are beyond the scope of this preliminary report.

8. Snow-Melting Rates

In order that the foregoing estimates of maximum possible snow accumulation may be translated into estimates of the volume of snow melt, temperature information similar to that provided in the Garrison report has been included. Figures 9 and 10 give the mean monthly temperature variation with station elevation for the areas between Garrison and Oahe Dam sites and between Oahe and Fort Randall Dam sites, respectively. Figure 11 shows the maximum deviations from normal which may be applied to mean monthly temperatures in order to synthesize a critical snow-melt year. The double mass curves of percent of total snow melt versus degree-day accumulation shown in figure 14 are envelopments of the curves of figures 12 and 13, which were based on the ten years of record which experienced the greatest snow-melt volume. Figure 15 shows the average degree-day accumulations at the temperature index stations based on the same data as figures 12 and 13. All of the foregoing figures parallel similar figures in the Garrison Report and are presented here as a continuation of that report.

9. Average Date of Disappearance of Snow on the Ground

It is difficult in an area such as the Missouri River Basin between Garrison and Fort Randall Dam sites to fix the exact date of disappearance of snow on the ground. Usually there are as many dates of disappearance as there are snowstorms. The typical situation is one in which a thaw melts the snow from the latest snowstorm before the next snowstorm begins. Occasionally, in the higher elevations, snow from several storms does accumulate and remain on the ground for a period of weeks or even months, but a general seasonal snowpack of the type that begins to accumulate in the fall and continues to grow until the spring thaw is the exception rather than the rule. The winter of 1880-1881 is such an exception. Then, according to newspaper accounts, snow which fell in October lay on the ground the following spring and four feet of snow blanketed the entire Missouri Valley. The date of disappearance of a snowpack of that magnitude can be fixed with some reliability. Fixing the date of disappearance of snow during a period of recurring snowstorms is a more arbitrary matter. Figure 16 shows the variation with station elevation of the average date of disappearance of snow on the ground and also the variation with elevation of the latest date of disappearance of snow on the ground. The date of disappearance was arbitrarily taken as the first date following January 1 on which there was no snow on the ground, and after which there was no two-week period of snow on the ground. In other words, the selected date marked the end of the last period of snow on the ground which was two weeks or more in duration. In dry, warm years the snow may disappear as early as a month before the average date given. In wet, cold years disappearance of the snow over the basin as a whole may be delayed as much as two months. At individual stations the possible range is even broader, varying from 65 days before average date of disappearance to 96 days after the average date of disappearance. These values are of slight import over the total basin however.

10. Qualifications and Restrictions

The hydrologic trials of combinations of events involving melt of seasonal snow accumulation, late snowstorms, and maximum rainstorms are subject to a few restrictions and qualifications, some of which have already been stated:

a. The minimum recurrence interval between rainstorms or snowstorms is applicable to the area above Garrison as well as to the area below Garrison.

b. The non-melting temperatures accompanying the snowstorm should be given a minimum duration varying from four days, before May 15, to zero on July 15, the decrease during that period being linear with time.

c. Peak outflow from a flood above Garrison can be synchronized, subject to the restrictions of the storm-recurrence interval, with the flood resulting from a combination of maximum seasonal accumulation of snow, maximum snowstorm, and maximum rainstorm in the basins below Garrison only if the combination of events contributing to the flood above Garrison does not include a maximum rainstorm. The occurrence of the latter implies the disappearance of a portion of the snowpack below Garrison.

d. If the combination of events contributing to the flood above Garrison includes the maximum rainstorm, then the snow cover contributing to the ensuing flood below Garrison must be reduced.

e. As in the Garrison Report, the maximum snowstorm can be added to the maximum snow accumulation. This addition can be thought of as a type of snowfall which (because it occurs at low as well as at high elevations) must be utilized for almost immediate snow melt because it cannot be expected to remain as an addition to a long-accumulated snowpack.

f. There is no known physical restriction on the addition of two or more maximum snowstorms to the maximum seasonal accumulation any more than there is on the addition of one maximum snowstorm to the seasonal accumulation. However, the procedure is not recommended. If a preliminary snowstorm is used in the hydrologic trials, it is recommended that it be used only as a fresh-snow substitute for its water equivalent in the accumulated snowpack. For example: If an April 1 snowstorm be allowed to occur before a May 1 snowstorm, then the water equivalent of the April 1 storm should be subtracted from the snow accumulation that would otherwise have been used as of May 1, the date of the final snowstorm. Within the limits of the given maximum snowstorm values and minimum intervals of recurrence, it is permissible to compress the snow accumulation into the latter part of the season instead of adhering to the mass curve of snow accumulation.

g. In entering for a value of given date in the curves of seasonal variation a leeway of 15 days from date is allowable.

h. The period of record available for study of snow-melt runoff was necessarily limited to those years for which stream-gage readings were available for the principal sub-basins. Although in each sub-basin the ten years having the largest snow melt were selected, no season of exceptional snow accumulation was available for study. In using the curves which relate percent of total snow-melt runoff to degree days it should therefore be remembered that the number of degree days which account for the melting of, for example, 90% of the largest snowpack studied will very likely not account for the same percentage melting of the maximum possible snowpack.

Such an assumption, however, would certainly be on the safe side.

i. Because some rise of temperature must intervene between the subfreezing temperatures that accompany the snowstorm, or serve to maintain the accumulated snowpack, and the onset of the maximum rainstorm, some snow melt is to be expected before the rainstorm. However, consideration of the delays in runoff arising from the snow-ripening process and the lag between melt and runoff to streamflow, permits the synchronization of runoff from melt and runoff from rainfall into a critical combination. Except for the necessary short period of preliminary warning considered above, it is meteorologically possible for the maximum rainstorm of the season to occur on the maximum snow accumulation for the same date. However, where the sequence of events consists of snowstorm followed by rainstorm the minimum recurrence interval must elapse.

11. References

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3. H. C. Willett, Descriptive meteorology, New York, Academic Press, 1944, p. 221.

4. U.S. Weather Bureau, Hydrologic Supplement for the storm of March 10-22, 1943, Ohio River drainage area, in cooperation with the Engineer Department, Corps of Engineers, U.S. War Department. (Compiled at Hydroclimatic Unit, Cincinnati, Ohio)

5. U.S. Weather Bureau, Historical Weather Maps, Northern Hemisphere Sea Level, Daily Synoptic Series, in cooperation with U.S. War and Navy Departments. (Map analysis by New York University, University of Chicago, and University of California at Los Angeles, in cooperation with the U.S. Weather Bureau)

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Weather Bureau

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Hydrometeorological Section

MISSOURI RIVER BASIN BETWEEN GARRISON AND FORT RANDALL DAM SITES

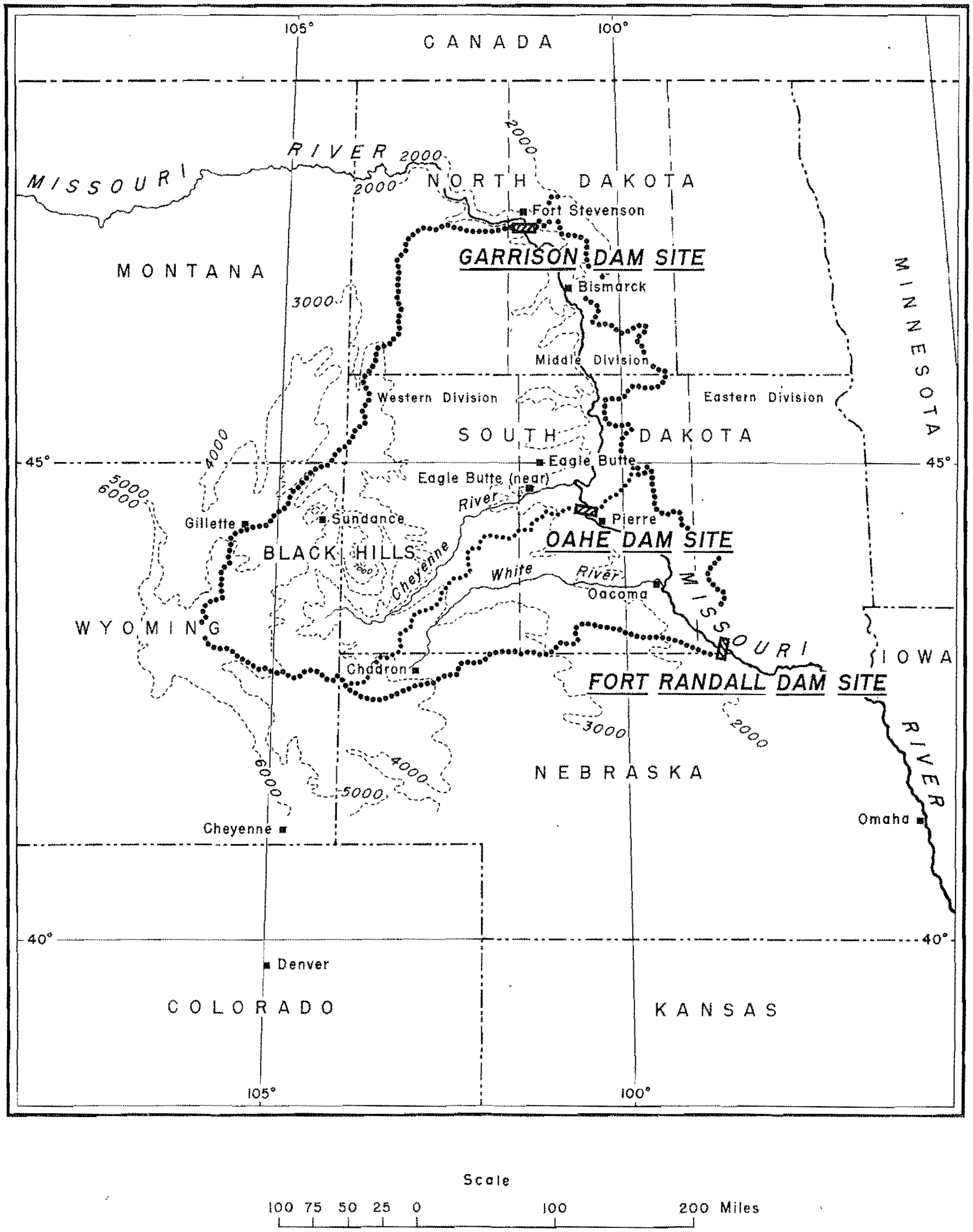

Figure 1

MAXIMUM POSSIBLE MID-MAY GENERAL RAINSTORM

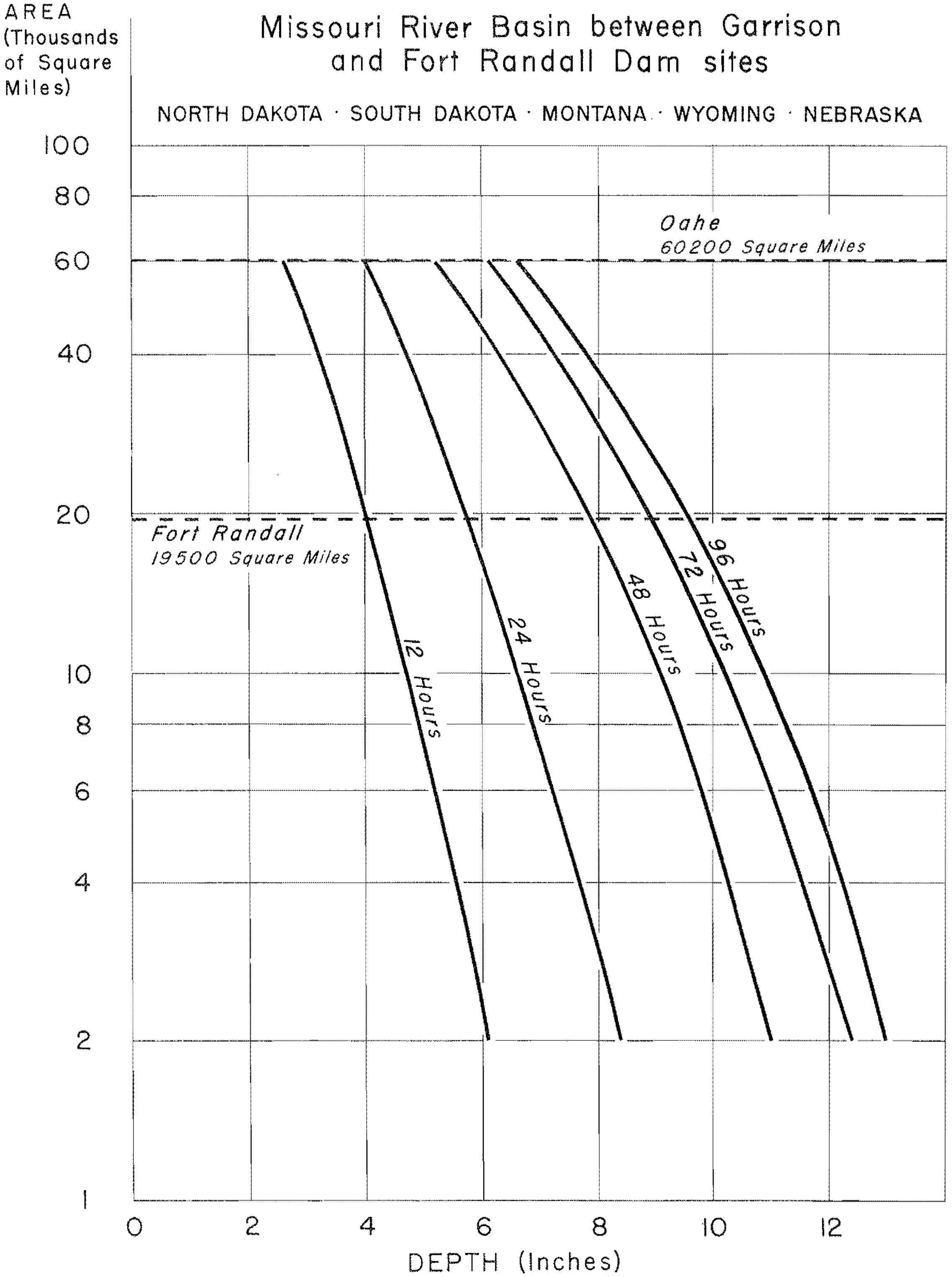

Figure 2

SEASONAL VARIATION (March thru October) OF MAXIMUM POSSIBLE GENERAL RAINSTORM

Missouri River Basin between Garrison and Fort Randall Dam sites

NORTH DAKOTA · SOUTH DAKOTA · MONTANA · WYOMING · NEBRASKA

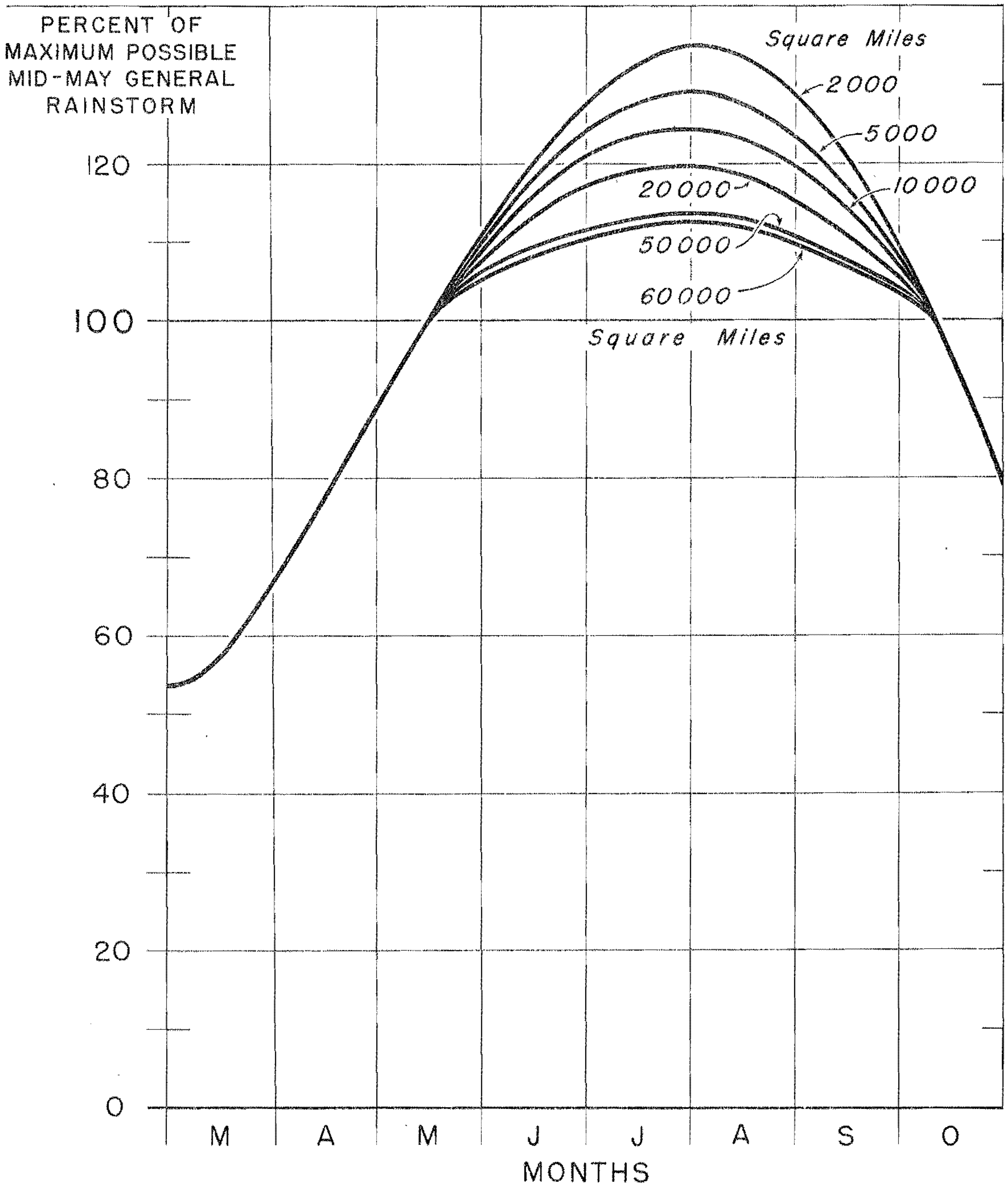

Figure 3

MAXIMUM POSSIBLE MID-MARCH AND MID-MAY GENERAL SNOWSTORMS

Missouri River Basin between Garrison and Fort Randall Dam sites

NORTH DAKOTA · SOUTH DAKOTA · MONTANA · WYOMING · NEBRASKA

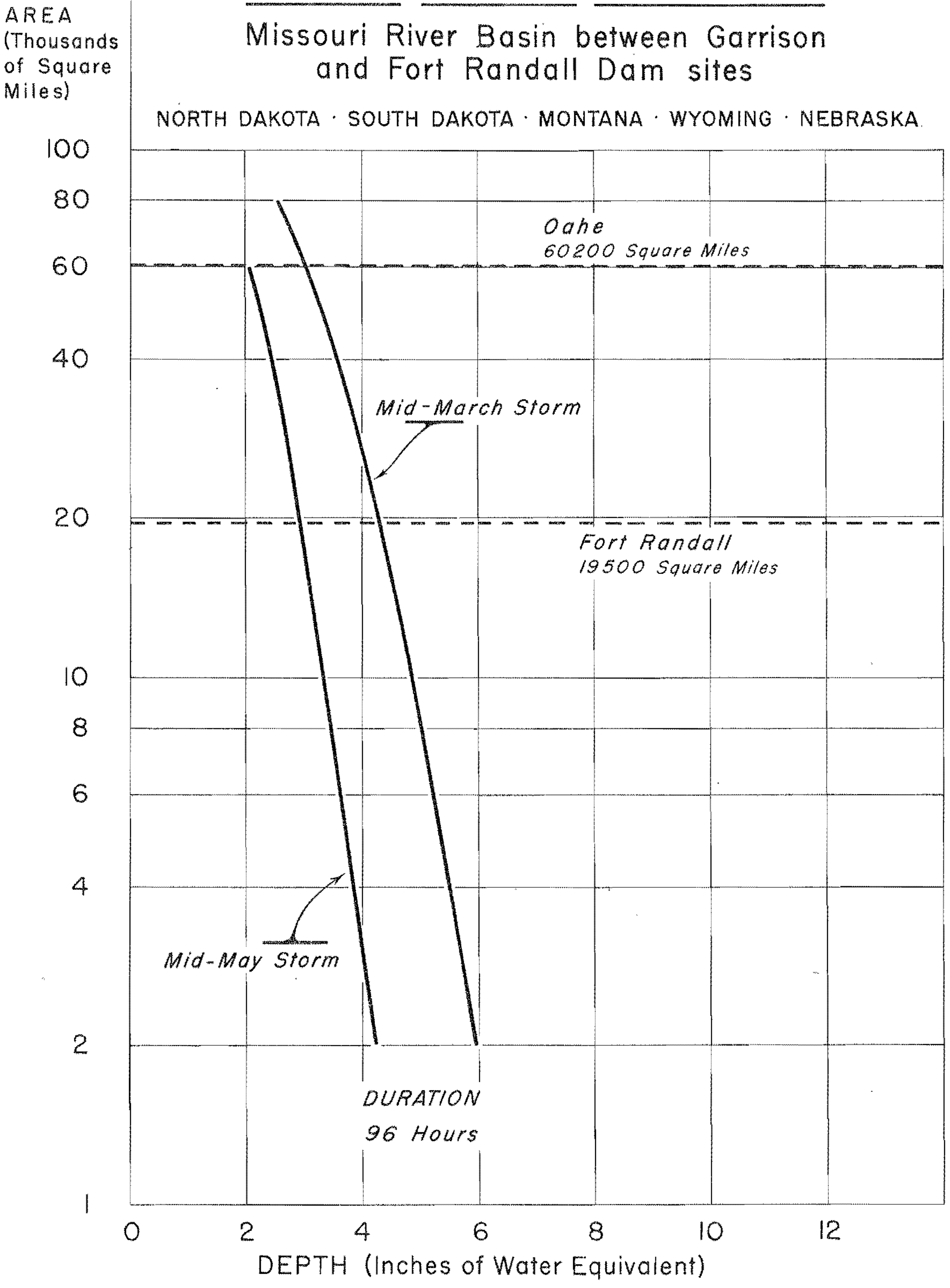

Figure 4

SEASONAL VARIATION (March thru October) OF MAXIMUM POSSIBLE GENERAL SNOWSTORM

Missouri River Basin between Garrison and Fort Randall Dam sites

NORTH DAKOTA · SOUTH DAKOTA · MONTANA · WYOMING · NEBRASKA

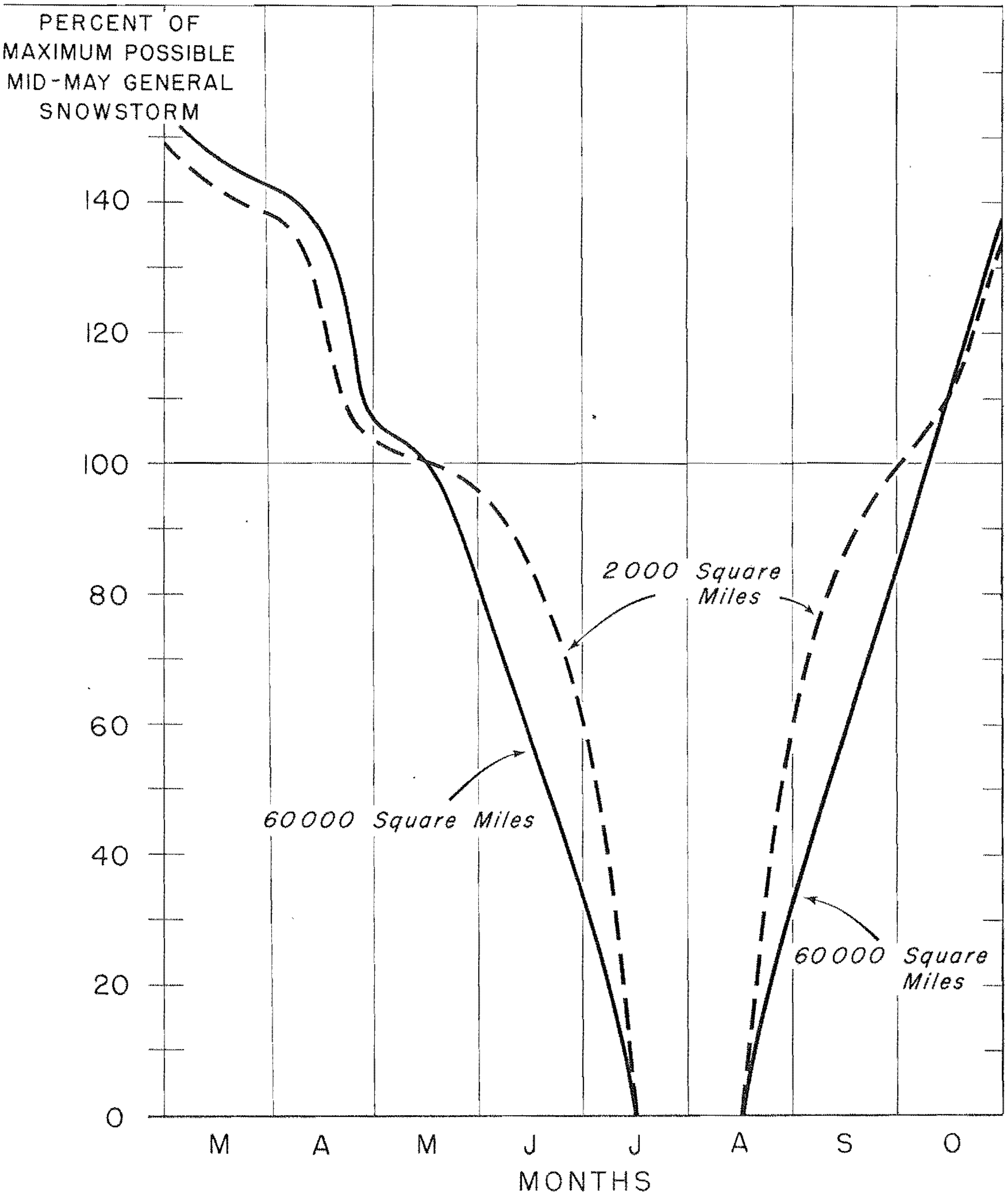

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Figure 5

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SEASONAL VARIATION OF MINIMUM RECURRENCE INTERVAL BETWEEN MAXIMUM POSSIBLE GENERAL RAINSTORMS

Missouri River Basin between Garrison and Fort Randall Dam sites

NORTH DAKOTA · SOUTH DAKOTA · MONTANA · WYOMING · NEBRASKA

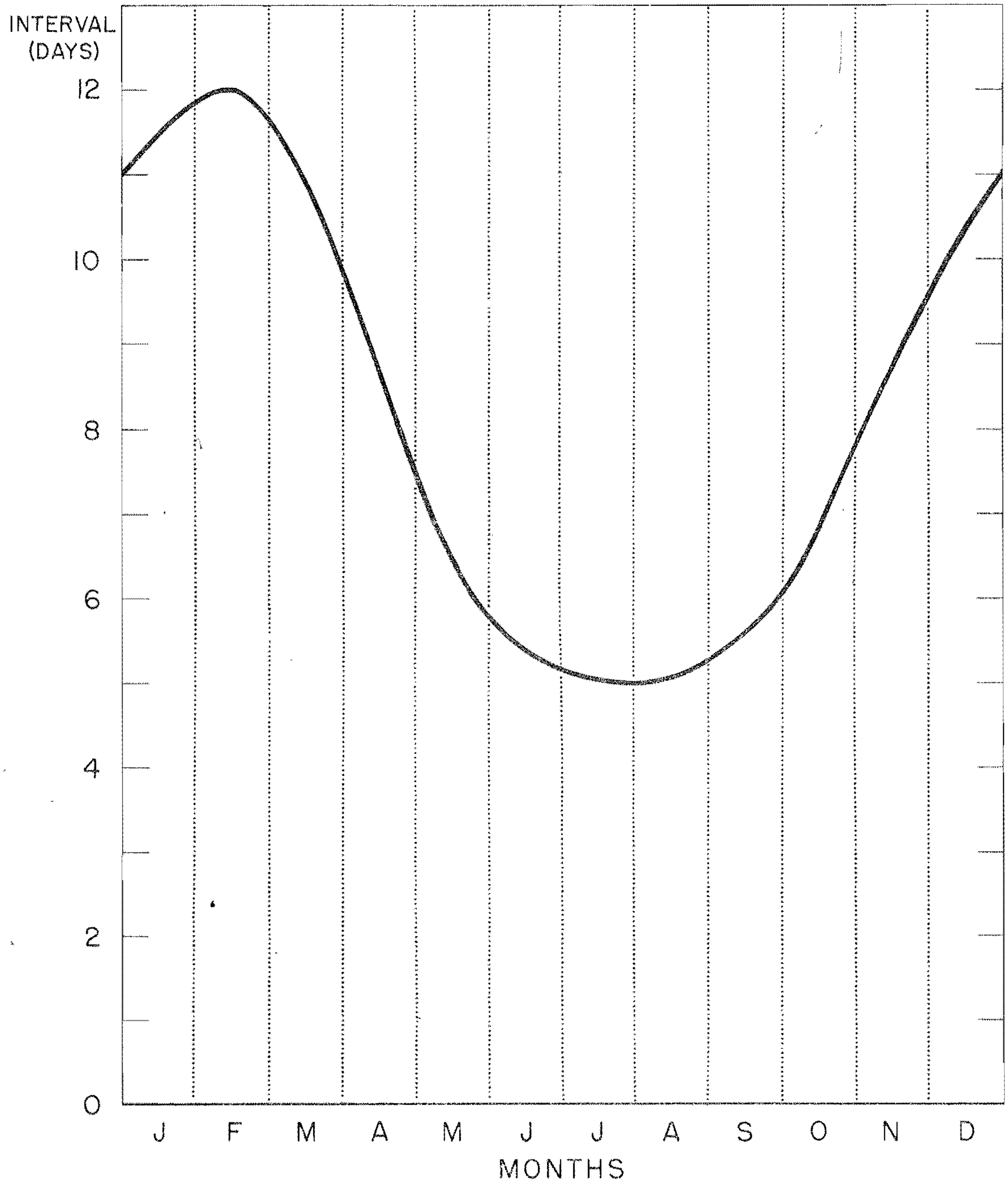

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Figure 6

ACCUMULATED DEGREE-DAYS AT BISMARCK AND FORT STEVENSON, NORTH DAKOTA

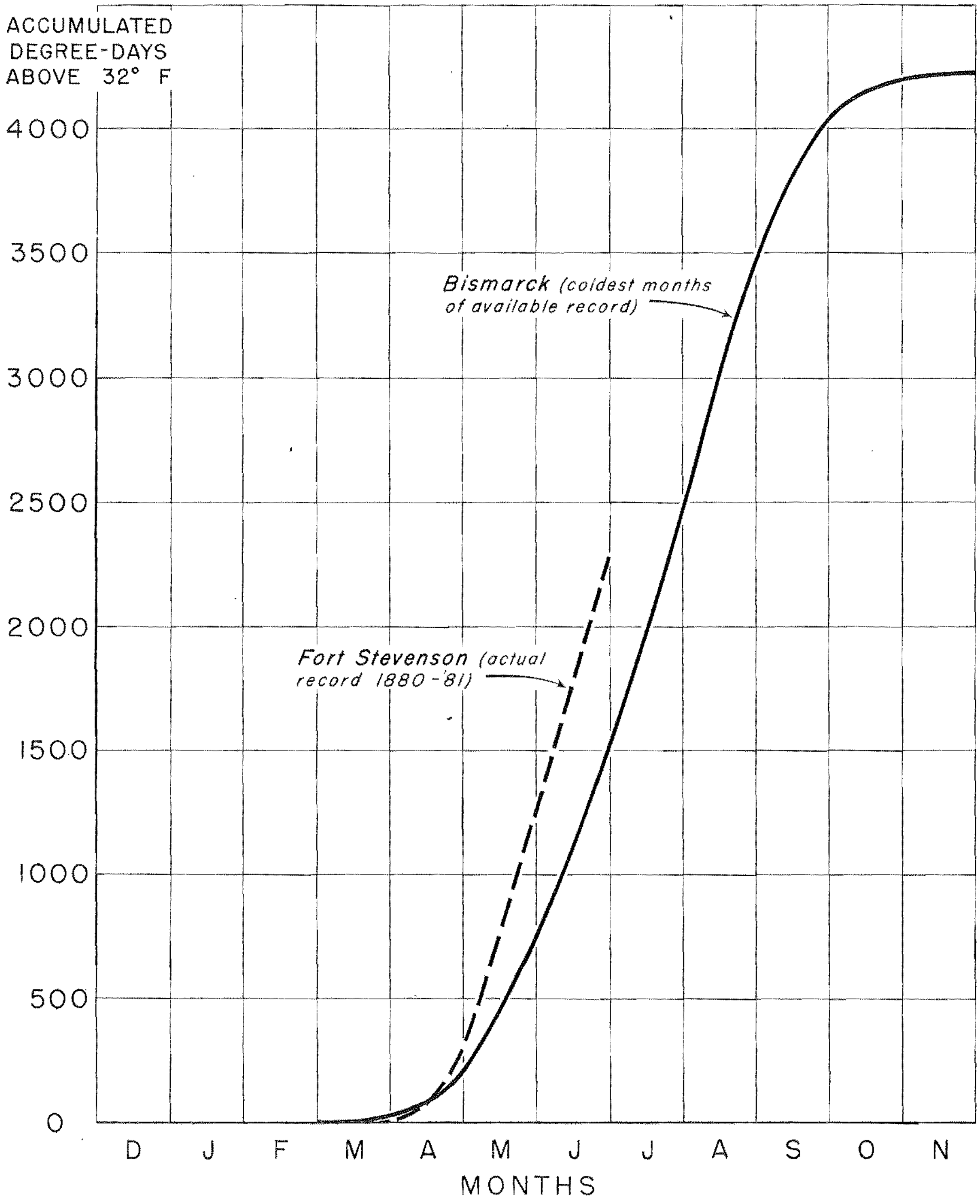

Figure 7

WATER EQUIVALENT OF MAXIMUM POSSIBLE ACCUMULATED SNOW IN PERCENT OF MEAN ANNUAL PRECIPITATION

Missouri River Basin between Garrison and Fort Randall Dam sites

NORTH DAKOTA · SOUTH DAKOTA · MONTANA · WYOMING · NEBRASKA

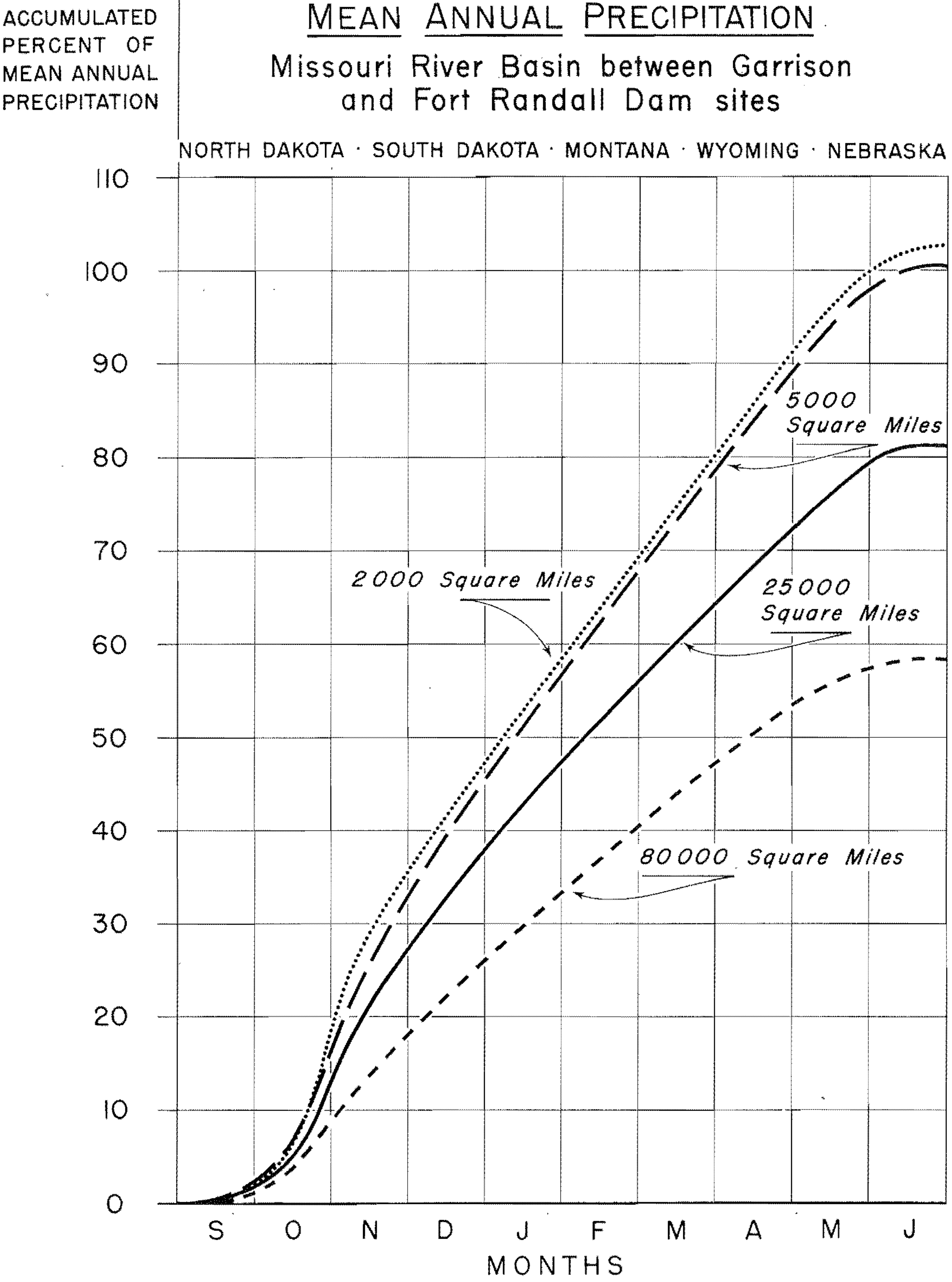

Figure 8

VARIATION OF MEAN MONTHLY SURFACE TEMPERATURES WITH ELEVATION

Missouri River Basin between Garrison and Oahe Dam sites

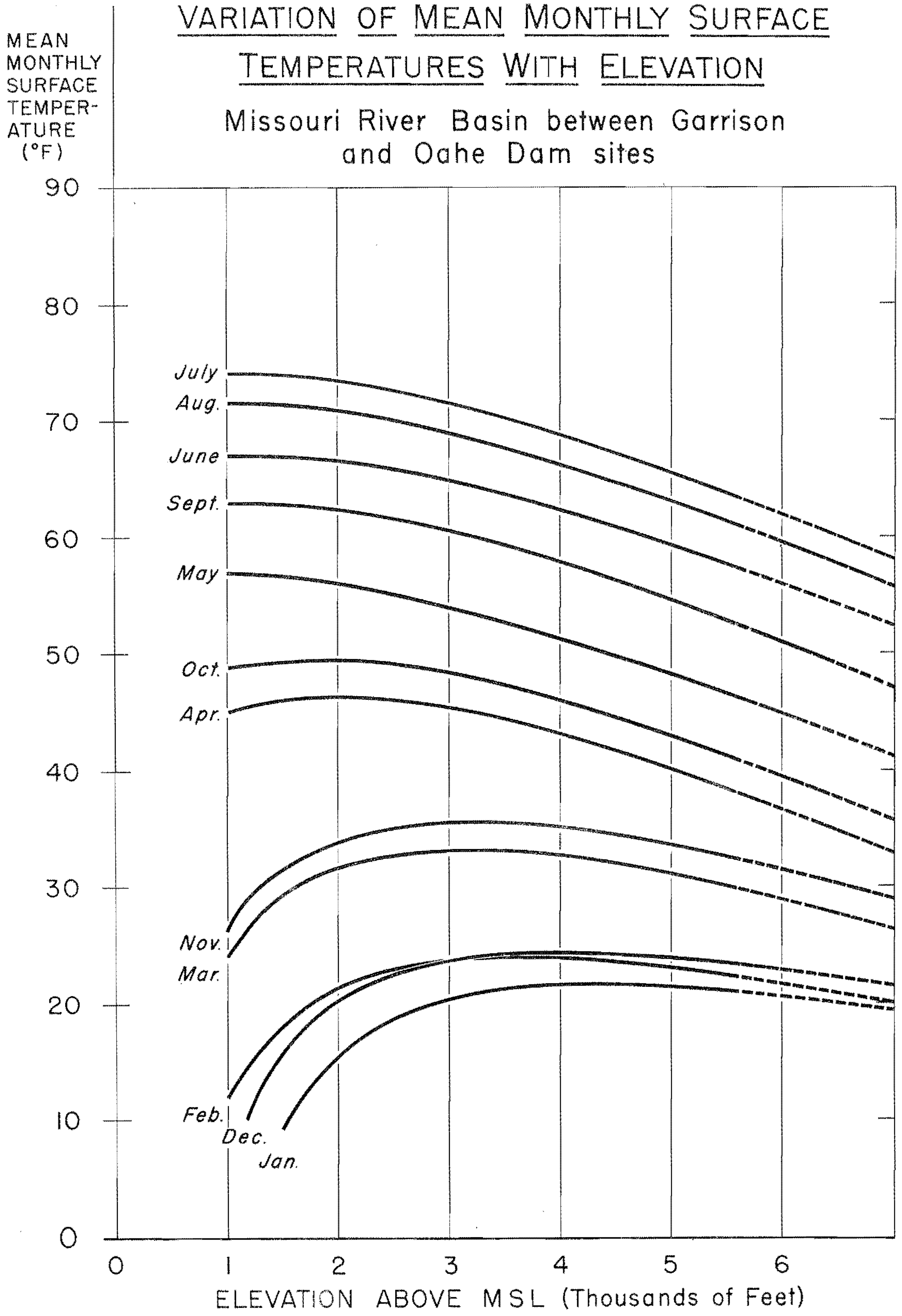

Figure 9

VARIATION OF MEAN MONTHLY SURFACE TEMPERATURES WITH ELEVATION

Missouri River Basin between Oahe and Fort Randall Dam sites

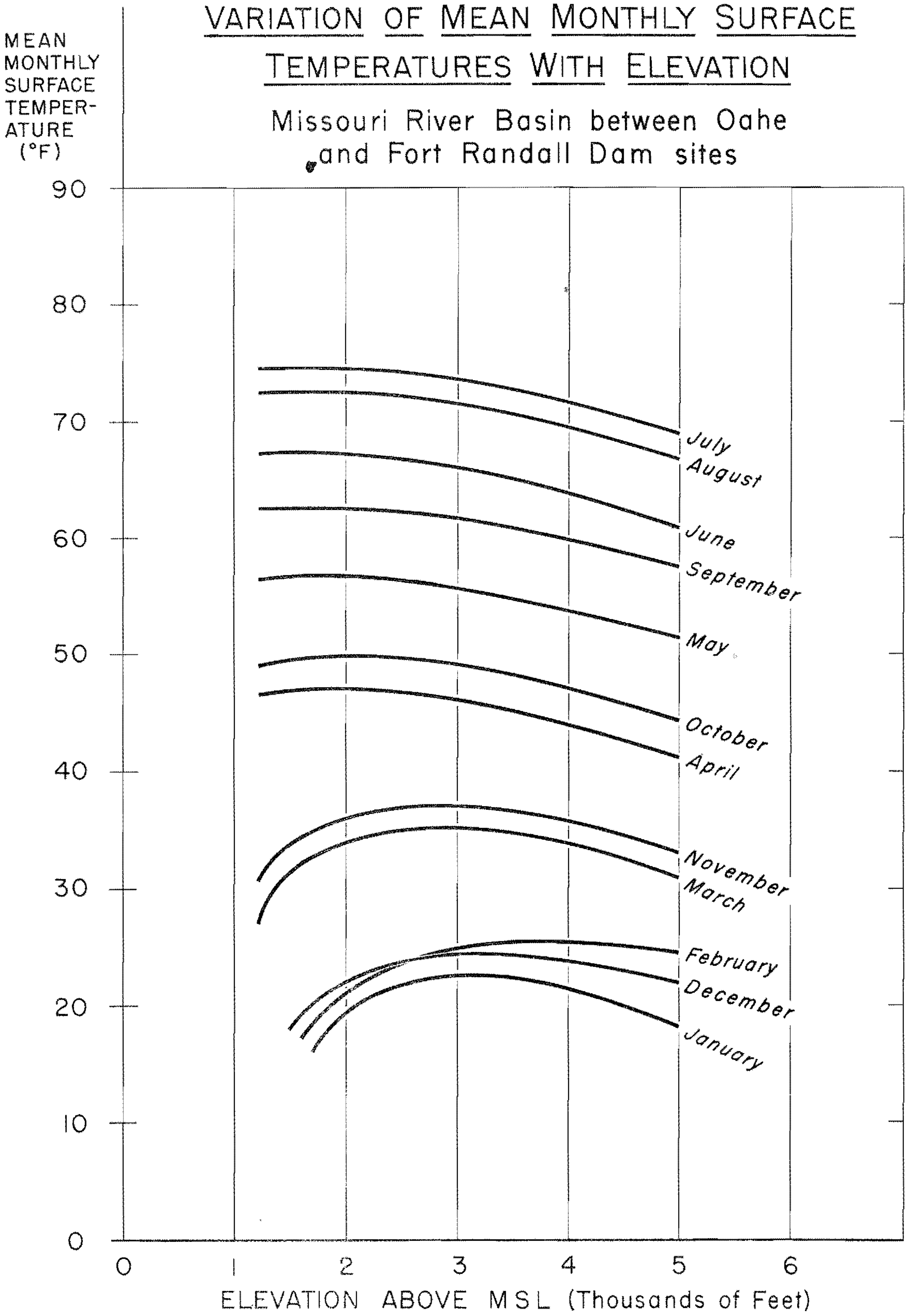

Figure 10

EXTREME DEPARTURES OF 30-DAY MEAN TEMPERATURES FROM MONTHLY NORMALS

Missouri River Basin between Garrison and Fort Randall Dam sites

NORTH DAKOTA · SOUTH DAKOTA · MONTANA · WYOMING · NEBRASKA

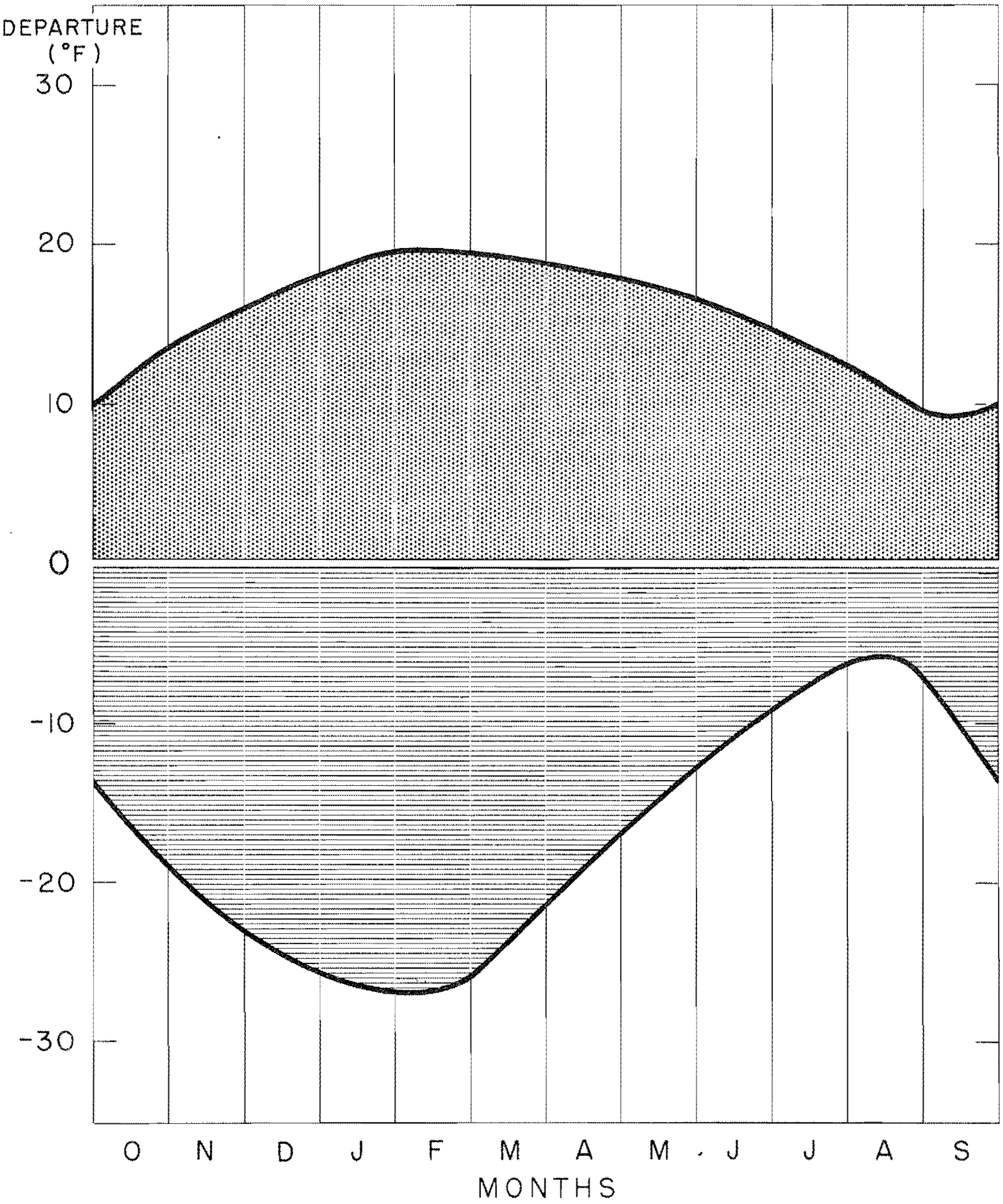

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Figure 11

SNOW-MELT RUNOFF VS DEGREE-DAYS

Cheyenne River near Eagle Butte, South Dakota

Area 24500 Square Miles

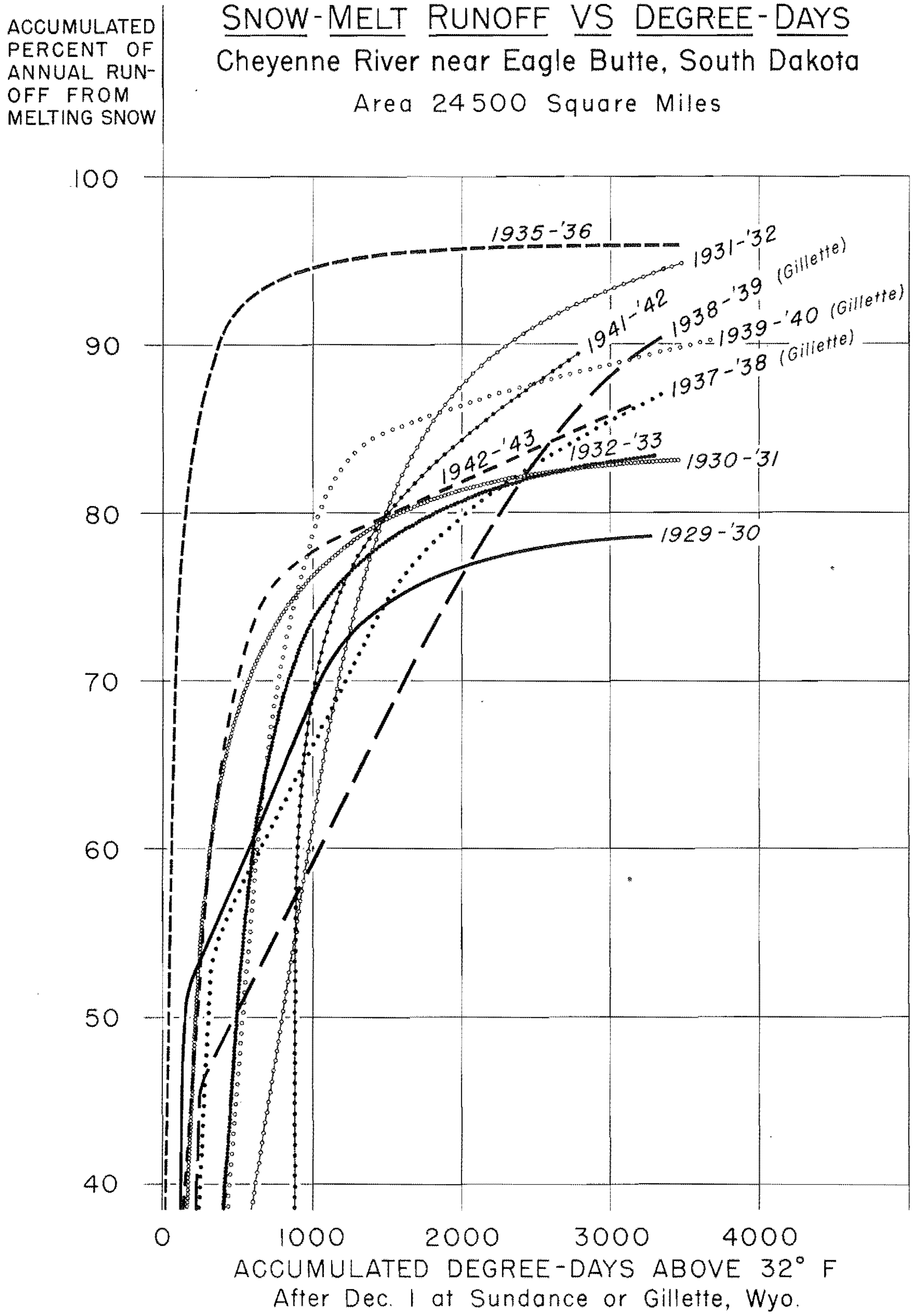

Figure 12

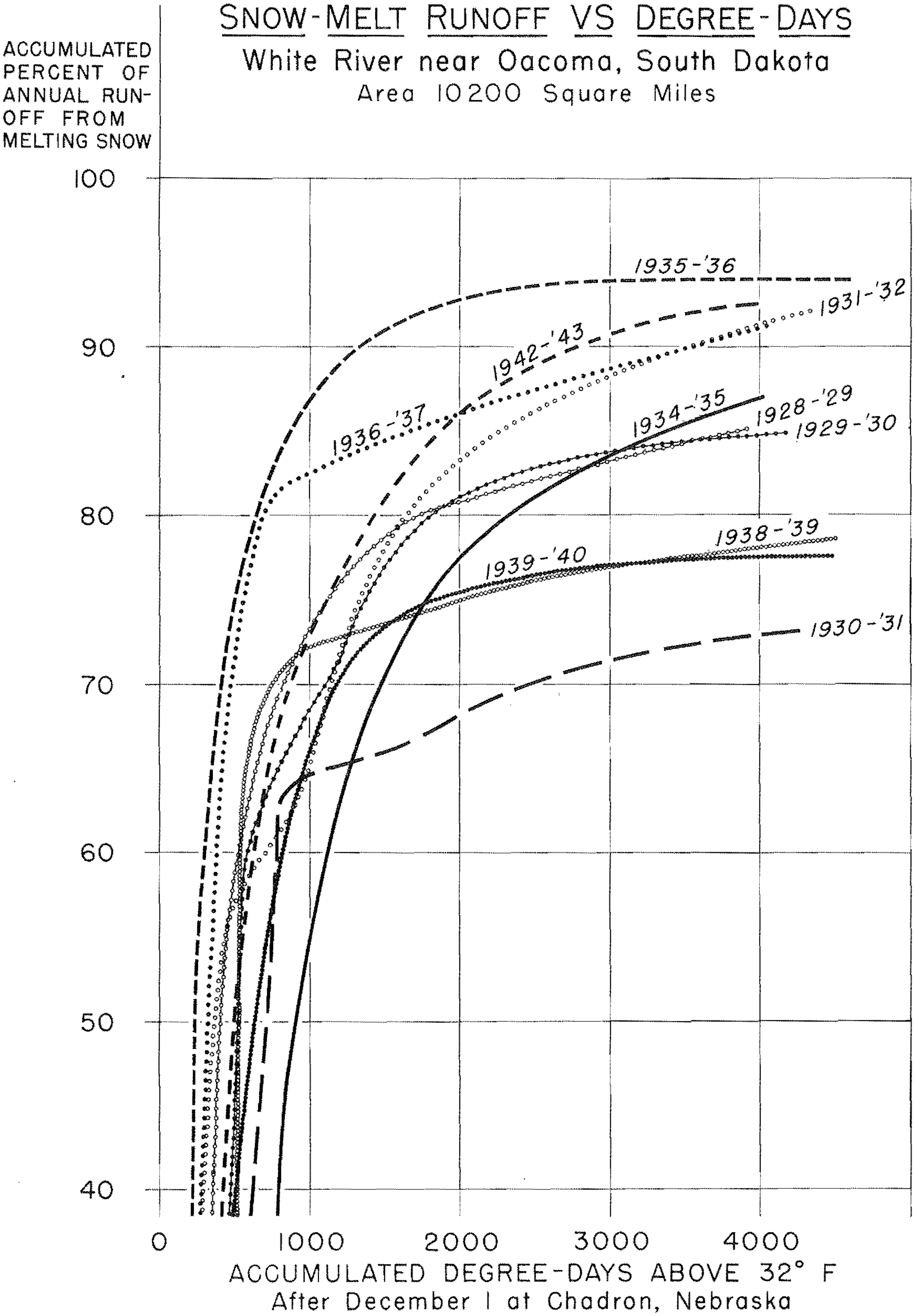

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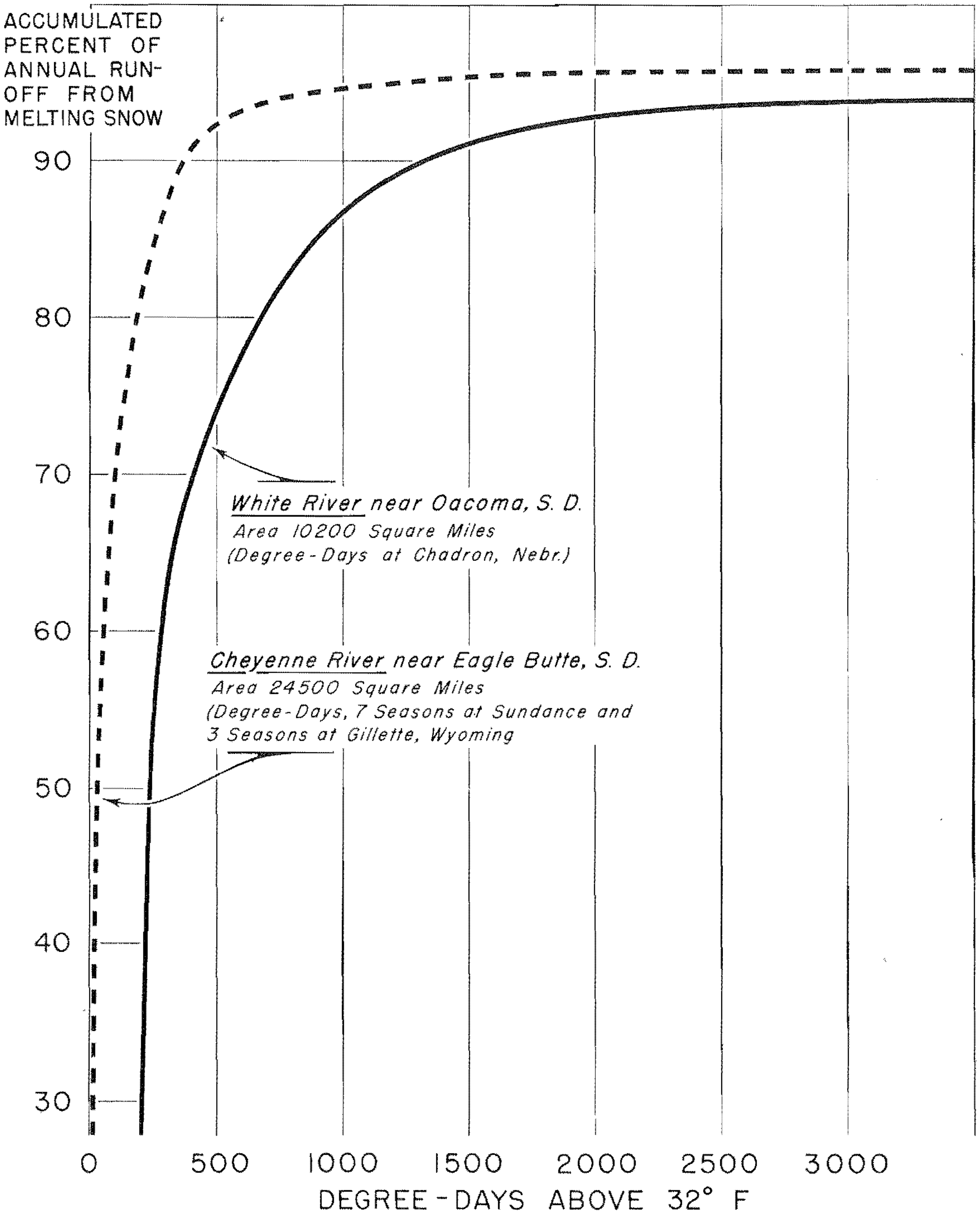
Figure 13

MAXIMUM VALUES OF SNOW-MELT RUNOFF FOR VARIOUS ACCUMULATIONS OF DEGREE-DAYS

(Based on Figures 12 and 13)



AVERAGE DEGREE-DAY ACCUMULATION

(Based on Figures 12 and 13)

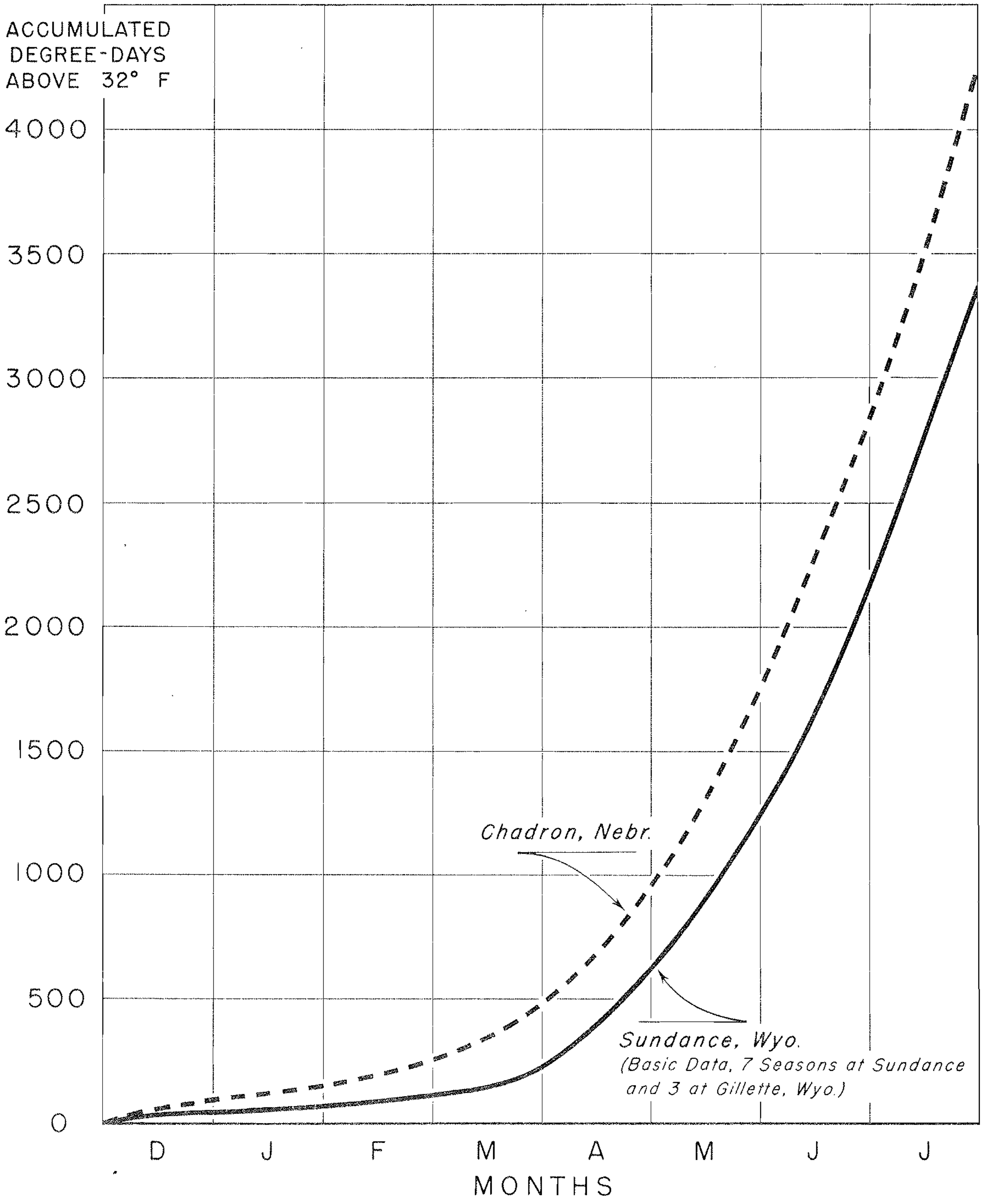


Figure 15

DISAPPEARANCE OF SNOW ON GROUND

Missouri River Basin between Garrison and Fort Randall Dam sites

NORTH DAKOTA · SOUTH DAKOTA · MONTANA · WYOMING · NEBRASKA

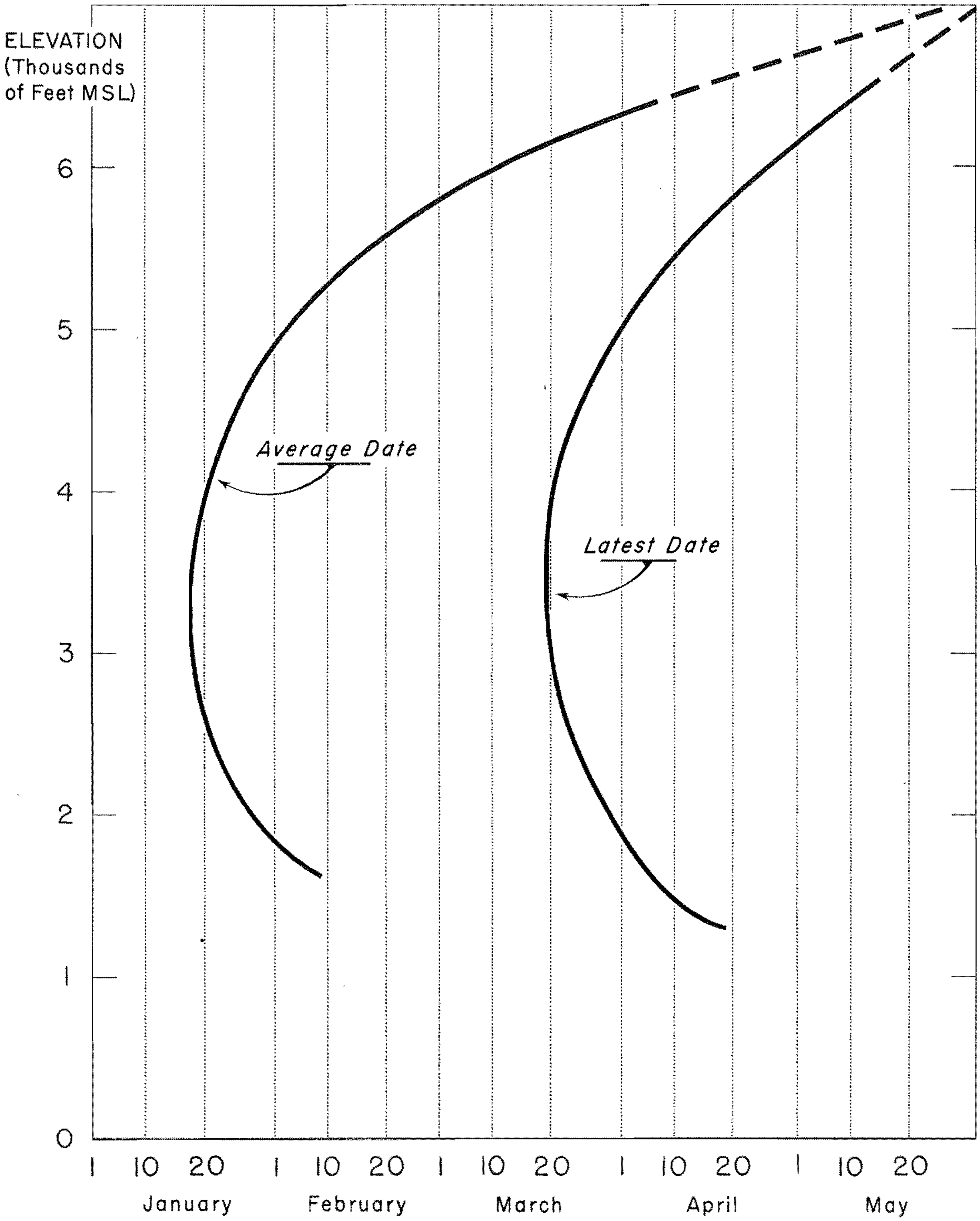


Figure 16