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1952-1955 ILLINOIS DROUGHT
with special reference to
IMPOUNDING RESERVOIR DESIGN

BY

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114

CONTENTS

SUMMARY

A large part of central and southern Illinois experienced a severe drought beginning early in 1952. By June 1955 the drought situation had greatly improved. Water shortages occurred in the fall of 1952 as a result of rainfall deficiencies. The situation was partially relieved by above-normal rainfall during the first three months of 1953. Rainfall deficiencies began to grow again after April 1953. By September 1953 it was apparent that the effect of the 1952 rainfall deficiency had not been fully overcome. The situation grew worse and by January 1954 there were 41 Illinois communities with serious water problems.

In January 1954 a program was set up by the Water Survey to report the drought situation monthly. Data were obtained on water supplies through visits, correspondence and telephone communications with communities affected by the drought. This program was continued until January 1955. By June 1955, all drought-connected water shortages had ended. Figure 50 shows locations of places mentioned;

Sources of Water Supply

To appreciate the drought, it is necessary to have an understanding of the normal water supply situations in Illinois. Public water supplies are most frequently obtained from groundwater sources in the northern part of Illinois. In the southern part of the State glacial deposits are much thinner and their effect upon the storage and travel of water underground less important. The groundwater contribution to the low flow of streams is consequently lower.

Municipal water supplies depending upon surface water are most common in the southern portion of the State where groundwater is generally more difficult to develop. Cities in southern Illinois located on major streams take water directly from them. Other cities generally provide an impounding reservoir on a smaller stream, or a side-channel reservoir into which water is pumped from a main stream.

In the drought region of the state 202 public water supplies obtain water from groundwater sources. Ninety-eight systems in the region utilize surface water.

The majority of the impounding reservoirs in the drought region have been constructed since 1920. Eighty per cent of them were built prior to 1940. Ninety per cent of the reservoirs utilize drainage areas of less than 20 square miles. Median runoff required to fill these reservoirs is 3.3 inches.

Normal annual rainfall in Illinois varies from 34 inches in the northern part of the State to 46 inches in the extreme southern tip.

Average annual runoff in Illinois displays a marked geographic variation within the State. Runoff varies from less than 8 inches in the west and northeast portions of the State to more than 15 inches in the area south of the Shawnee Hills. These results are indicated by the analysis of 25 of the 165 gaging stations in the state.

Quantitative indications can be obtained of movement of water in the hydrologic cycle by comparison of rainfall, runoff, transpiration and evaporation, and water levels in shallow wells. From April 1 until mid-September vegetative and evaporative demands exceed the water available. This difference is made up either by water taken from the soil or by the reduction of transpiration and evaporation. From mid-September until the end of March, in the average year, water returns to storage in the ground. From the behavior of groundwater hydrographs for shallow wells which commonly show no particular recovery before the end of November, it is judged that the excess water available during September-November largely goes to make up deficiencies in capillary moisture. The groundwater level recovers between December 1 and April 1.

Vegetative and evaporative demands are so great that below-normal rainfall through July and August leads to recession of groundwater levels, reduction of soil moisture, and delay in recovery of streamflow. Such a situation occurred during the summer periods of 1952-55 drought.

Municipal Water Supply Difficulties

Total groundwater pumpage for municipal supplies in Illinois increased from 40 million gallons daily in 1900 to about 106 mgd in 1940 and to 135 mgd by 1948.

Of the 41 communities that faced possible water shortages in January 1954 all but 8 experienced population increases for the period 1930 to 1950. In 24 instances the increases were less than 20 per cent. The highest population increase was 57 per cent. Municipal pumpage in 24 of these communities increased by more than 100 per cent from 1938 to 1953. In three cases pumpage increased 600 per cent or more.

Deficiencies in hydrologic data appear to have had an important role in the failures of public water supply sources. At the time of design of most of the reservoirs now in use there were few streamflow data available. .

Twenty-two of the 202 public water supplies in the drought region relying on groundwater sources experienced shortages. Of the 98 systems in the region that utilize surface water, 53 suffered shortages. Fifty-eight of the surface water systems in the region rely on impounding reservoirs, and 40 of these suffered shortages.

During the drought it became apparent that grave water shortages occurred most frequently with impounding reservoir supplies. This report therefore emphasizes hydrologic information directly applicable to design and appraisal of impounding reservoir sources of supply.

Of the 75 Illinois communities suffering water shortages during the drought, 38 experienced difficulty because developed source capacity was insufficient to meet demands, 28 had trouble because of unexpectedly large increases in demand, and 9 encountered difficulty because of declining capacity of facilities.

Extent and Intensity of the Drought

The area covered by the drought was generally within the southern half of the State although it extended northward into Hancock and McDonough Counties and north of Champaign County at times.

Maximum rainfall deficiency in the drought region of the State for the period April to December 1952 amounted to about five inches. Deficiencies in the drought region range from 10 to 15 inches during 1953 and from 5 to 10 inches during 1954. These deficiencies are depicted in map form in the report.

Maps of runoff during the drought are presented. These are based on streamflow records of the U. S. Geological Survey at 15 stations in the drought region. The patterns of runoff were generally similar to those of precipitation. For the 12-month period ending June 30, 1954, runoff in the area of Pike, Scott and Greene counties was 0.2 inches or less as compared with a normal streamflow of approximately nine inches per year for this area.

A procedure for analysis of rainfall and runoff data to determine the frequency of recurrence of drought periods of various durations has been developed. Using this procedure the frequencies of occurrence of low flows of various durations were worked out for five drainage basins in the southern half of the State for which records of 34 to 45 years duration were available. Similar frequency determinations were made for five rain-gaging stations in the same area having 48 years of record.

On the basis of streamflow data for the period 1914-1955 the drought in 1952-54 appears to have been a severity that would occur once in 75 to more than 100 years. The driest 36-month period (ending June 1955) appears to have been a severity that would occur once in approximately 100 years. Rainfall data indicate the drought to have been of a severity that would occur once in 60 to 100 years. The most representative value available for evaluating the drought as a single event was the median recurrence interval. On this basis the drought of 1952-55 appears to have been a severity that would occur once in 83 years.

Estimating Reservoir Storage Requirements

The report reviews the methods available for calculating the amount of storage necessary for an adequate surface water supply. In general, these methods do not make possible the calculation of the amount of storage required to meet droughts of various durations and frequencies. The available methods do not provide a direct approach to the evaluation of evaporation losses from reservoirs. Most of the early reservoirs in Illinois were designed without allowance for loss of storage due to reservoir silting.

A new procedure, utilizing the streamflow frequency determinations discussed above is proposed for the determination of impounding reservoir capacity. The procedure may be divided into two parts: (1) determination of storage required for various draft rates and drought frequencies, and (2) evaluation of evaporative and sedimentation losses. For the study of draft rates, a weighing of low-flows of various frequencies and durations leads to the determination of the most critical storage requirement and drought duration for any given draft rate. These values have been consolidated into a single graph which enables rapid determination of the storage required at a given site for any drought frequency and draft rate in southern Illinois.

The data available on reservoir sedimentation in Illinois are summarized graphically in a way that enables the rapid estimation of damage rates.

The treatment of evaporative losses makes use of data on evaporation from lakes, which are reworked in such a way as to establish the most critical values resulting from the seasonal variations in evaporation rates. The report includes a study of the lake surface area exposed to evaporation and concludes that this value may be approximated by applying evaporation loss data to an area which is 64 per cent of the area of the lake when full.

A method of correcting gross evaporative losses by subtracting from them the amount of rainfall falling on the water surface is presented. This method takes into account the frequency of periods of low rainfall of various durations. These net evaporative rate losses are then applied to the effective area of the lake.

The effective surface area may readily be estimated by assuming a value of average depth for the lake. The median of the average depths of 41 reservoirs studied was 8.7 feet, but the use of an average depth figure of 1 0 to 15 feet is recommended, depending on location and reservoir size.

After combining the various factors, evaporative losses have been expressed in per cent of mean annual streamflow. So expressed, these losses are called net evaporative draft rates. A correlation between net evaporative draft rate and storage volume required was found. This correlation indicates that for a. 10-foot average depth: at low values of storage, as for example a reservoir storing 50 per cent of one year's streamflow, the net evaporative draft rate would be 5 per cent of the mean streamflow, while for a reservoir storing three years' streamflow, net evaporative draft rate would be 15 per cent of the mean streamflow. These net evaporative draft rates appeared to be substantially independent of low-flow frequencies.

Values of net evaporative draft rate may be subtracted from the draft rate mentioned earlier in the study to produce values of net yield from reservoirs. The net yield is the quantity of water which may be taken from the reservoir for use, expressed as per cent of the mean stream-flow.

A graph showing the relationship of net yield to storage required for various low-flow frequencies has been prepared. This graph covers draft rates up to 80 per cent of the mean streamflow, storage values up to 300 per cent of the annual discharge, and low-flow frequencies having recurrence intervals ranging from 4 to 100 years.

It is suggested that the results of this study may be used for preliminary estimates of reservoir storage requirements and yields, and that the method developed may be applicable to local data for detail design purposes.

1952-55 ILLINOIS DROUGHT WITH SPECIAL REFERENCE TO IMPOUNDING RESERVOIR DESIGN

H.E. Hudson, Jr., Head, and W.J. Roberts, Associate Engineer, Engineering Subdivision.

INTRODUCTION

A large part of central and southern Illinois experienced a severe drought beginning early in 1952. By the spring of 1955 the drought situation had greatly improved but had not ended. In comparison with experiences during the 1930-31(1) and the 1940-41 droughts, a high incidence of water supply shortages became apparent. As the drought progressed, itbecame evident that a disproportionately large number of problems appeared to occur at communities relying on stored surface water sources of supply.

To orient the reader this report includes a section that outlines the history of the hydrologic and water supply deficiencies that arose during 1952-55 in Illinois. This history is followed by a brief description of the work needed to keep track of the situation.

For further orientation, a summary of the normal situation is included. This is followed by an analysis of the water-supply problems that arose and of the hydrologic characteristics of the drought. Data assembled in studying the drought proved useful for design studies and the report concludes with the presentation of the application of these data to impounding reservoir design.

Development of Drought Situation

Rainfall deficiencies commencing in April 1952 produced some water shortages by the fall of 1952. Supply shortage difficulties were reported at such widely separated locations as Marion and Pittsfield in southern and western Illinois. However, above-normal rainfall occurred in the first three months of 1953 throughout much of Illinois, raising water-supply reservoir levels, although in many cases, the reservoirs were not filled by these rains. The waterworks operator at Virginia, in west central Illinois, for example, reported that the spring of 1953 was the first spring since the reservoir was completed in 1933 in which it had not filled to spillway level.

Deficiencies in precipitation began to increase again after April 1953. By September 1953 it was apparent that the effects of deficient precipitation in 1952 had not been fully overcome by the above-normal precipitation in early 1953; and municipal water supply problems were much more numerous than in 1952. A survey in September 1953 indicated that 64 cities in Illinois were suffering some water shortages as evidenced by official restrictions of use. In 32 of the 64 communities, the shortages were attributed to deficiencies in distributive or treatment facilities. No field surveys of these cities were made by Water Survey personnel at this time, however, and there is reason to believe that some of the reported shortages were exaggerated in order to insure maximum public compliance with the restrictions.

There was no material improvement in the situation through the fall of 1953, and by January 1954 there were 41 communities with serious water problems in southern Illinois.

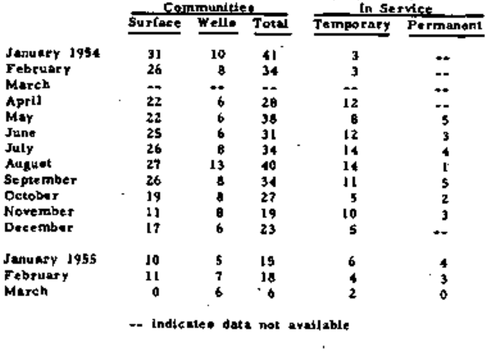
Table 1 shows by months, beginning with January 1954, how many communities were faced with shortages of supply from deficient surface-water sources or from seriously diminished yields caused by low water levels in wells. The data given summarize conditions at the end of each month. The standards for determining whether a community was faced with shortage were: (1) restrictions on use enforced by local authorities as a result of apparent inadequacies; or (2) in the case of surface-water sources, less than six months' supply on hand.

Although the situation improved during the winter of 1953-54 there was a gradual increase in the number of communities experiencing shortages through the summer of 1954. During the fall, water requirements dropped. At the same time rains in September, October, and December helped several communities through critical periods.

During the period 1953-55, 8 communities hauled water, 8 developed supplemental groundwater supplies, and 13 laid pipelines to emergency sources. Seven communities built additional reservoirs, but had to wait many months before the new reservoirs impounded water sufficient for use.

TABLE 1

NUMBER OF COMMUNITIES FACED WITH WATER SHORTAGES, AND SUPPLEMENTARY SOURCES IN USE, BY MONTHS



	Number of Communities			Supplementary Sources In Service	
	Surface	Wells	Total	Temporary	Permanent
January 1954	31	10	41	3	--
February	26	8	34	3	--
March	--	--	--	--	--
April	22	6	28	12	--
May	22	6	38	8	5
June	25	6	31	12	3
July	26	8	34	14	4
August	27	13	40	14	1
September	26	8	34	11	5
October	19	8	27	5	2
November	11	8	19	10	3
December	17	6	23	5	--
January 1955	10	5	15	6	4
February	11	7	18	4	3
March	0	6	6	2	0

-- indicates data not available

While the maximum number of communities facing shortages during any single month in 1954 was 41, there were 75 communities that faced shortages at one time or another during the period 1952-55.

Table 1 also gives information on supplementary sources placed in service to relieve shortages. These sources were especially developed for use during the drought to supplement existing sources. Some of the temporary sources were subsequently converted into permanent installations for future use. Others were either exhausted, or abandoned for other reasons. From March to October 1955 there continued to be shortages at four communities, but these appear to be due to source inadequacies that were apparent prior to 1952.

Collection of Data

Rainfall deficiency mapping was commenced in the fall of 1952, and carried on throughout 1953 and 1954. This mapping program, plus reports from normal Water Survey field work, newspaper clippings, and conferences with representatives of other State agencies and persons from various sections of the State, enabled maintenance of a continuous picture of the extent and severity of the drought.

In the fall of 1953 studies were begun of frequency of rainfall deficiencies at Mt. Vernon, Olney, Urbana, Springfield and Quincy. These studies were continued throughout 1954 and into 1955. Studies of low-flow duration and frequency were commenced in the summer of 1954.

In November 1953, a tabulation of surface water supplies in Illinois (excluding those using Lake Michigan as a source) was made. It showed that there were 102 communities using surface-water sources. Of these, 17 drew water from major rivers such as the. Ohio and Mississippi, whose flow was sufficient to preclude shortages. The remaining 85 communities were visited, and data were collected on adequacy of source, nature of source, water levels, pumpage, etc. Reports summarizing results of this field survey were submitted through state administrative channels in December 1953 and January 1954.

In January 1954 a program of regular monthly data collection through visits, correspondence, and telephone communications with communities affected by the drought was set up. A report of the status of the drought was prepared monthly. Each report included reviews of: precipitation in the drought region during the preceding month; streamflow and groundwater conditions; and the status of municipal water supplies. While a continuing check has been made, the program of reporting each month was terminated July 31, 1955.

Scope of Report

During 1954 it was observed that difficulty with water shortages appeared to occur most frequently with impounding reservoir supplies. Special effort was therefore made to assemble information that would be helpful toward the prevention of such difficulties in the future. The present report is therefore largely devoted to hydrologic information directly applicable to design and appraisal of impounding reservoir sources of supply. Some of the information is relevant to design of side-channel reservoirs, and some sheds light on the reliability of sources of supply like those using direct intakes with no storage.

The report deals with a small part of the total information available. Although the data used appear to have sufficient homogeneity to indicate certain general conclusions with respect to impounding reservoir supplies, the findings of this report may not be considered as a substitute for a detailed examination of all the local records for design of a specific project, since local conditions can cause considerable deviation from a regional average.

Acknowledgments

This study was carried out during the administration of A. M. Buswell, Chief of the State Water Survey Division. The writers are indebted to H. F. Smith, B. O. Larson and J. B. Stall of the Engineering Subdivision for critical comments and helpful suggestions throughout the course of the study. Robert and Ronald Russell did the drafting for this report and Dhiru N. Desai and Ray Schuster aided greatly in tabulation and computation work.

The writers are indebted to J. H. Morgan, District Engineer for Illinois, Water Resources Division, U. S. Geological Survey, and to his operational assistant Warren Daniels, Hydraulic Engineer, for making available provisional streamflow data used in this study much earlier than such data are ordinarily disseminated.

The authors are grateful for the review of a preliminary draft and for the valuable suggestions givenby: W. D. Mitchell, J. H. Morgan, and Richard Godfrey of the U. S. Geological Survey; Professors J. J. Doland and V. T. Chow of the University of Illinois; to Paul Sutton of the U. S. Weather Bureau; to R. D. Wilson, Consulting Engineer; and to Floyd Huff, N. L. Rupani, H. F. Smith, J. B. Stall, Glenn E. Stout, and Max Suter of the State Water Survey staff.

Throughout this study, there was excellent cooperation between representatives of the Division of Sanitary Engineering, Illinois State Department of Public Health, and members of the State Water Survey staff. By means of working arrangements between these two agencies, information gathered

on municipal situations throughout the drought region was exchanged freely through letters, reports, and conferences. The information furnished by Health Department engineers was a substantial factor in making it possible to keep the necessary field work within the limits of the personnel available for the study.

In the course of the regular visits to the cities that had water supply difficulties during the period 1952 to 1955, information was obtained from the waterworks operators, water superintendents, and city officials. In many instances the visits stimulated local officials to take regular observations. These observations were most helpful in the study. The local officials, who were very cooperative about assembling information on pumpage, water use, reservoir levels, etc., are too numerous to name, but their assistance was invaluable. Similar fine cooperation was extended by consulting engineering firms, which were extremely helpful in providing current and past data on communities that had retained them.

HYDROLOGIC ASPECTS OF WATER SUPPLY

Evaluation of the many problems encountered in public and private water supplies during the drought of 1952-55 requires knowledge of the water resource conditions that ordinarily prevail in Illinois. These conditions include the types of sources developed for water supply, the usual rainfall and runoff patterns in the State, the normal seasonal variations in availability of moisture, and particularly, the usual practice in design of impounding reservoir supplies. With a few exceptions, existing installations in Illinois functioned satisfactorily when conditions were normal, or when more water was available than usual. This was the condition from 1944 to 1952. The paragraphs under this heading describe average conditions in the State.

Sources in Use

There is much variation in the nature of the water resources throughout Illinois. Figure 1 shows a generalized map of the water resource provinces of the State. This map indicates that groundwater may be obtained readily from bedrock wells in the northern quarter of the State, but that bedrock wells are much less extensively available elsewhere. Most of northern Illinois is covered by thick glacial deposits(2) in which sand-and-gravel-wells are frequently constructed. Some of these wells have capacities exceeding 1000 gallons per minute. These glacial deposits readily receive and yield water. They therefore play a role in the reception of precipitation, and in its discharge to streams in those portions of the State where these deposits are thick and permeable.

The glacial deposits are thinner and less permeable in the southern part of Illinois, and there the storage and travel of water underground are generally very limited. As a result, groundwater contributions to streamflow are generally smaller in the southern part of the State than in northern Illinois.

Extensive alluvial deposits, associated with many of the major streams of the State shown in Figure 2 increase groundwater discharge and availability. In addition to these alluvial deposits there are buried valleys containing sand-and-gravel formations at many locations in the State(3), which also increase local streamflow and groundwater availability.

Figure 3 shows the location of municipal groundwater supplies in Illinois as of 1948. It will be noted from this figure that there is a heavy concentration of groundwater sources in the northern portion of the State, and that these sources are less common in southern Illinois. Figure 4 shows the public surface-water supplies in Illinois. These are seen to be much more common in the southern portion of the State than in the north, where groundwater is generally available in sufficient quantity for municipal purposes.

Comparison of Figures 2 and 4 shows that many communities are located near major rivers in the State. Some of them can draw water from these rivers without raw water storage facilities. Small storage facilities, in the form of channel dams, are common along some of the larger secondary streams. There are few streams large enough to yield water supplies to direct intakes or channel dams in southern Illinois. Impounding reservoir sources and side-channel storage reservoirs, as shown by Figure 4, are therefore numerous.

A side-channel storage reservoir is a reservoir having a relatively small tributary drainage area, into which water is pumped from a large stream during those periods when the flow in the stream is sufficient. The rates of pumping into side-channel reservoirs vary from amounts slightly in excess of the average daily community demand to rates of pumpage 20 times the demand. Many municipal supplies in the southern half of Illinois began with impounding reservoir sources, which relied upon the runoff from the watershed upstream of the reservoir. As Figure 4 shows, there is still a large number of these, but many of them have been converted into side-channel storage units by the installation of pumping facilities on larger streams nearby. Some of them are in an intermediate state of development. Thus, it is difficult to decide whether to classify them as side-channel or as impounding reservoir sources.

Table 2 shows the sources of supply of public water systems in the 66 counties in the drought zone. These counties are located south of line AA_1 in Figure 4. Line AA_1, was located after study

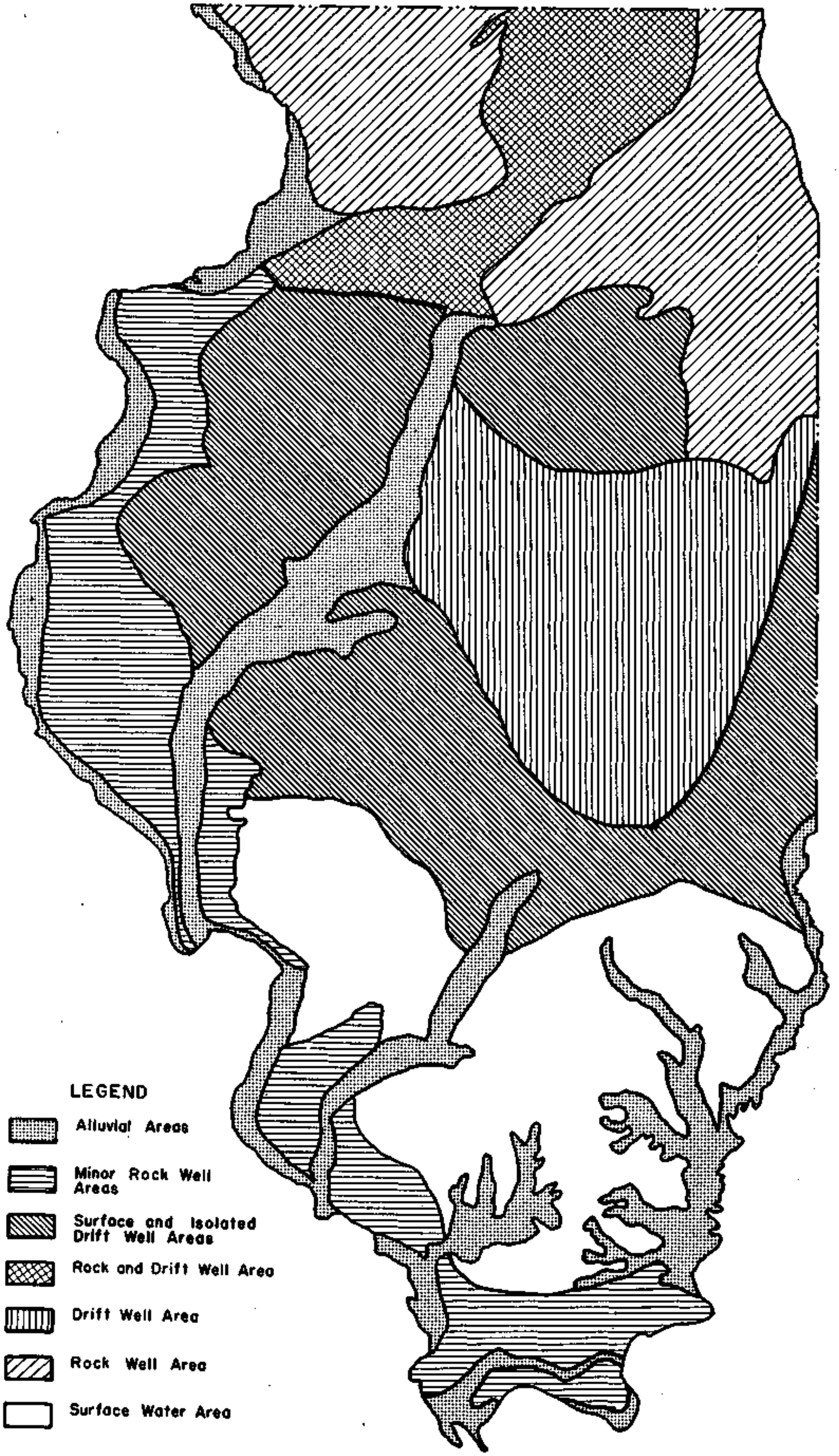


FIGURE 1. GENERALIZED MAP OF WATER SOURCE PROVINCES IN ILLINOIS.

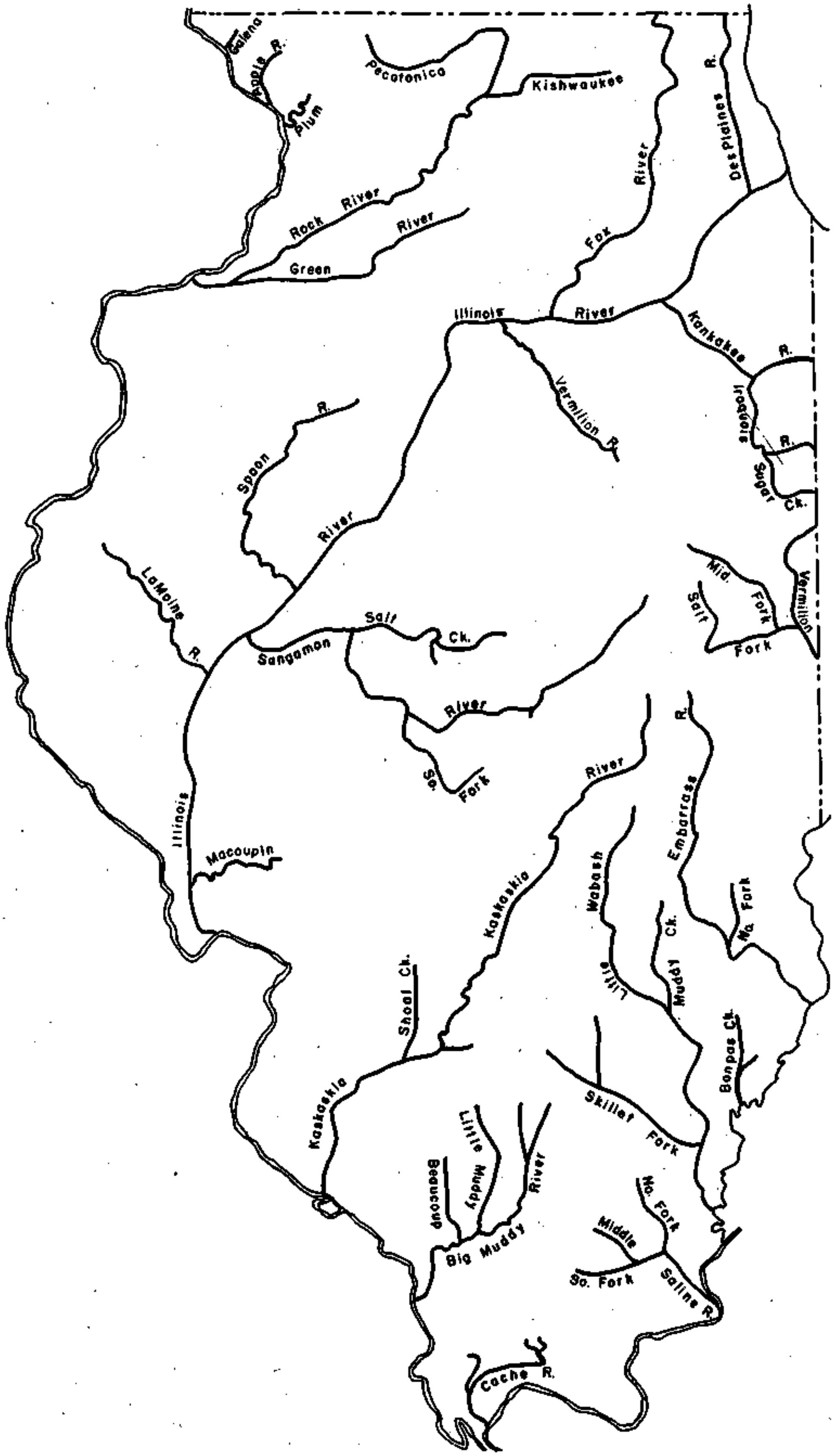


FIGURE 2. MAJOR STREAMS IN ILLINOIS.

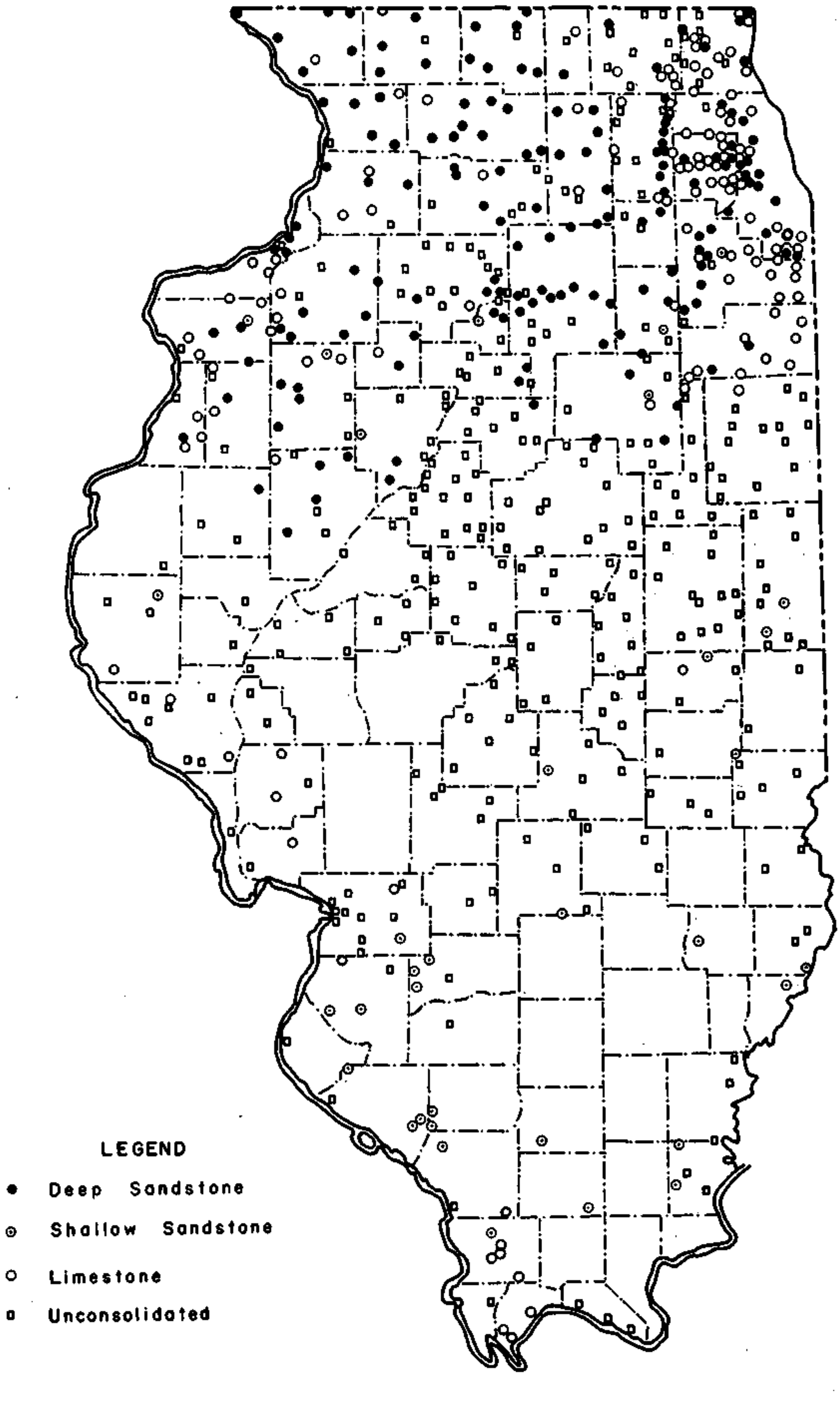


FIGURE 3. SOURCES OF PUBLIC GROUNDWATER SUPPLY IN ILLINOIS.

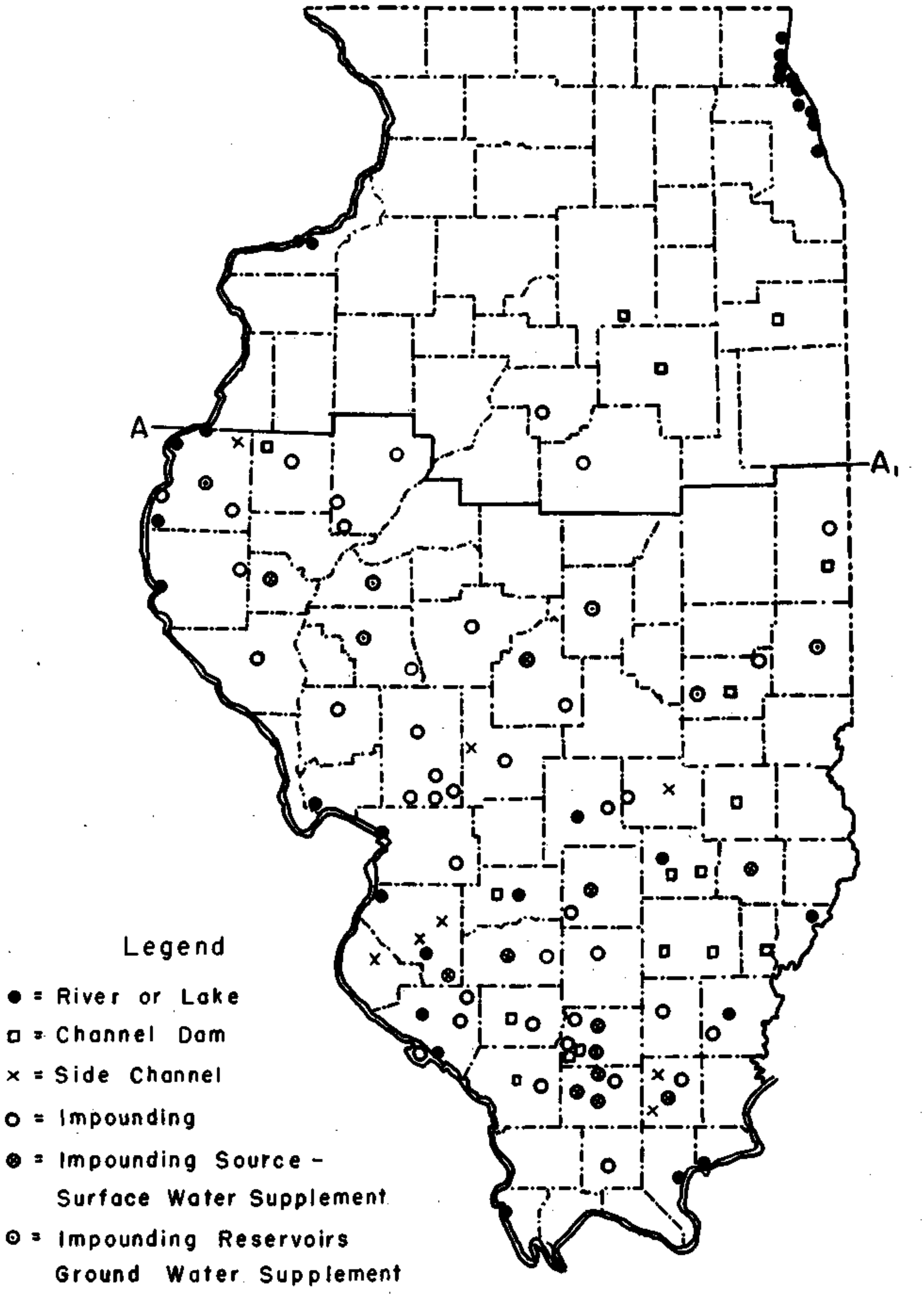


FIGURE 4. SOURCES OF PUBLIC SURFACE WATER SUPPLIES IN ILLINOIS.

of runoff and rainfall data revealed that the effects of the 1952-55 drought were felt throughout the area below the line.

Also listed in Table 2 are the numbers of communities in each source category that had water shortage difficulties during 1952-55. Since the data indicate an extremely high incidence of water source difficulties with impounding reservoirs, the information available on impounding reservoirs with which difficulties were experienced has been assembled and is presented in Table 3. This gives the year of construction for each of the major reservoirs in use in 1952, watershed area, surface area, capacity, average depth, and inches of runoff required to fill the reservoirs at the time of their construction.

TABLE 2

SOURCES OF SUPPLY FOR PUBLIC WATER SYSTEMS IN THE DROUGHT REGION

Source of Supply	Number of installations	Number of communities having shortages 1952-55	Per Cent having Shortages
Groundwater			
Deep sandstone	12	0	0
Shallow sandstone	16	2	12
Limestone	14	4	29
Unconsolidated	160	16	10
Total	202	22	11
Surface Water			
Direct Intake	18	0	0
Channel Dam	15	7	46
Side Channel Reservoir	7	6	86
Impounded Reservoir	58	40	69
Total	98	53	54

An analysis of these data in Table 3 indicates that the median watershed area was 2.5 square miles, and that 90 per cent of the communities use drainage areas of less than 18 square miles. The median runoff required to fill these reservoirs was 3.3 inches. Extreme low and high values of runoff required to fill reservoirs were, respectively 0.34 inches and 14.7 inches. Median of the average depths was 8.65 feet.

Normal Rainfall in Illinois

The normal precipitation pattern, from the 45-year averages for the period 1898-1942 provided by the U. S. Weather Bureau(4) is shown in Figure 5. From this illustration it will be seen that rainfall in the State varies from less than 34 inches per year in a portion of northern Illinois to more than 46 inches per year in part of southern Illinois, a geographic variation of more than 35 per cent. In many years, as in the period 1952-55, the rainfall does not approximate the normal pattern.

Normal Runoff in Illinois

Several generalized maps for the United States indicate the distribution of runoff in Illinois(5)(6) but no detailed mapping of Illinois mean annual

TABLE 3

IMPOUNDING RESERVOIR SOURCES FOR COMMUNITIES FACED WITH WATER SHORTAGES 1952-55

City	Year Built	Watershed Area Square Miles	Lake Surface Area, Acres	Original Capacity, Million Gallons	Average Depth, Feet	Runoff Required to fill Reservoir Inches
Altamont	1935	2.9	30	75	7.7	1.5
Ashley	1941	1.24	21	49	7.1	7.4
Astoria	1924	0.47	6.07	28	14.1	3.4
Augusta	1945	3.40	14	35	7.6	0.59
Benton	1937	2.6	100	284	8.7	6.3
Bunker Hill	1937	7.19	27.6	43	4.8	0.34
Carterville	1923	2.3	45.0	154	10.5	3.8
Carthage	1926	2.9	39.7	133	10.2	2.6
Centralia	1910	6.87	261	1064	12.5	8.8
	1942	38.0	960	1920	6.1	2.9
Christopher	1925	0.6	20.0	60	9.2	5.7
		1.50	40.0	160	12.2	5.6
Coulterville	1944	1.22	26.8	65	7.4	3.0
Decatur	1922	906	2747.0	6340	7.1	0.4
DuQuoin	1937	10.0	250.4	900	11.0	5.2
Eldorado	1920	2.23	98.0	258	8.1	6.6
Elkville	1937	1.5	62	175	8.6	6.7
Gillespie	1923	5.73	70.5	260	11.3	2.6
Hillsboro	1918	7.5	96.0	500	15.6	3.8
Jacksonville	1939	24	250.0	590	7.2	1.4
Johnston City	1922	3.85	65	149	7.0	2.2
Kincaid	1940	2.4	36	89	7.6	2.1
Marion	1921	6.48	110	231	6.4	2.4
Marissa	1938	0.6	--	25	--	2.4
Mattoon	1937	18	240	1000	12.7	3.2
McLeansboro	1912	1.52	35	228	19.9	8.6
Mt. Sterling	1935	1.8	35	100	8.7	3.2
Mt. Vernon	1900	9.2	128	760	18.2	4.7
	1944	4.65	147	521	10.9	6.4
Nashville	1936	1.39	39.5	104	8.1	4.3
Norris City	1937	0.83	21	46	6.7	3.2
Olney	1903	0.78	34	200	18.0	14.7
Paris	1937	17.7	180	315	5.4	1.0
Pittsfield	1923	1.84	46.0	120	8.0	3.7
Pana	1949	8.4	218	1006	14.1	6.9
Sesser	1925	1.1	45.0	54	3.7	2.8
Sparta	1915	1.2	35.0	105	9.2	5.0
St. Elmo	1935	3.0	14.3	36	7.7	0.6
Vienna	1937	2.34	21.0	35	5.1	0.86
Virginia	1933	1.5	19.0	60	9.7	2.3
West Frankfort	1946	3.8	149	354	7.3	5.3
White Hall	1897	0.97	34	150	13.5	8.9

runoff has been done. For the purposes of this report, an approximation of runoff in Illinois was obtained by using the average data given in the study by Mitchell$^{(7)}$. Mitchell's data are for 25 stations having periods of record ranging from 9 years to 35 years, but most of the data are for periods of 15 years or more.

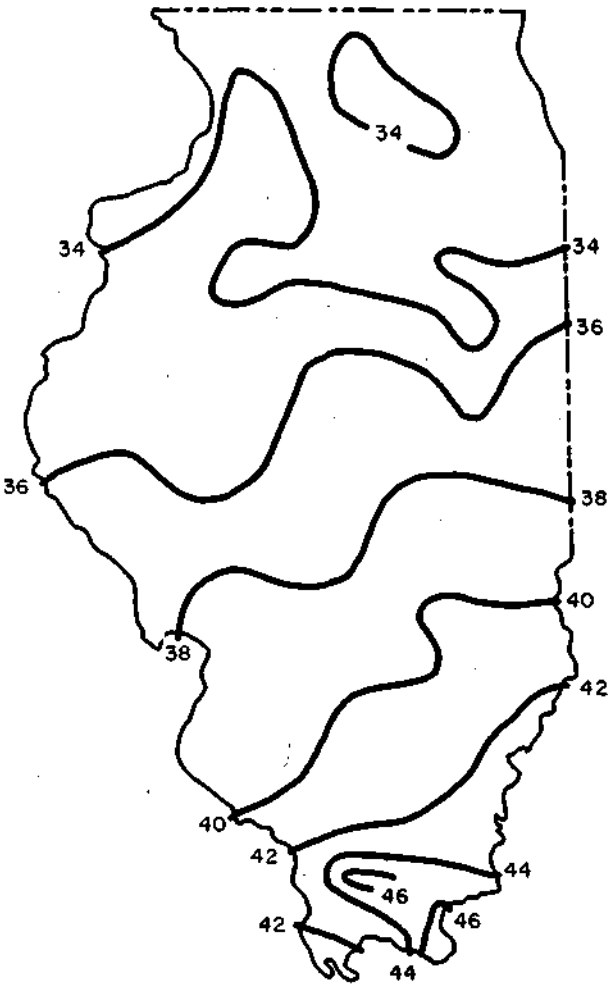


FIGURE 5. 45-YEAR AVERAGE ANNUAL PRECIPITATION IN INCHES.

Drainage basins for these stations reach into Wisconsin in two instances and into Indiana in one. Using these data, a map of mean annual runoff was prepared for the State (Figure 6). This map, which generally agrees with previously published information, indicates a considerable geographic variation of runoff within the State, ranging from less than 8 inches in the west and northeast portions of the State to more than 16 inches in the Shawnee Hills.

The unit usually used for quantitative expression of streamflow is cubic feet per second. As a rule this unit is applied to the entire flow at the gaging station, but it is sometimes converted to cubic feet per second per square mile of drainage area. This is equivalent to a unit of length per unit time. It is therefore proper to express runoff (or streamflow, or discharge, which are synonyms) in suitable length units such as inches per unit time. Such a unit has the advantage of being directly comparable with rainfall measurements, whichare customarily expressed in inches, and are therefore widely recognized. Accordingly, throughout this report, streamflow has been expressed in inches occurring during stated periods of time.

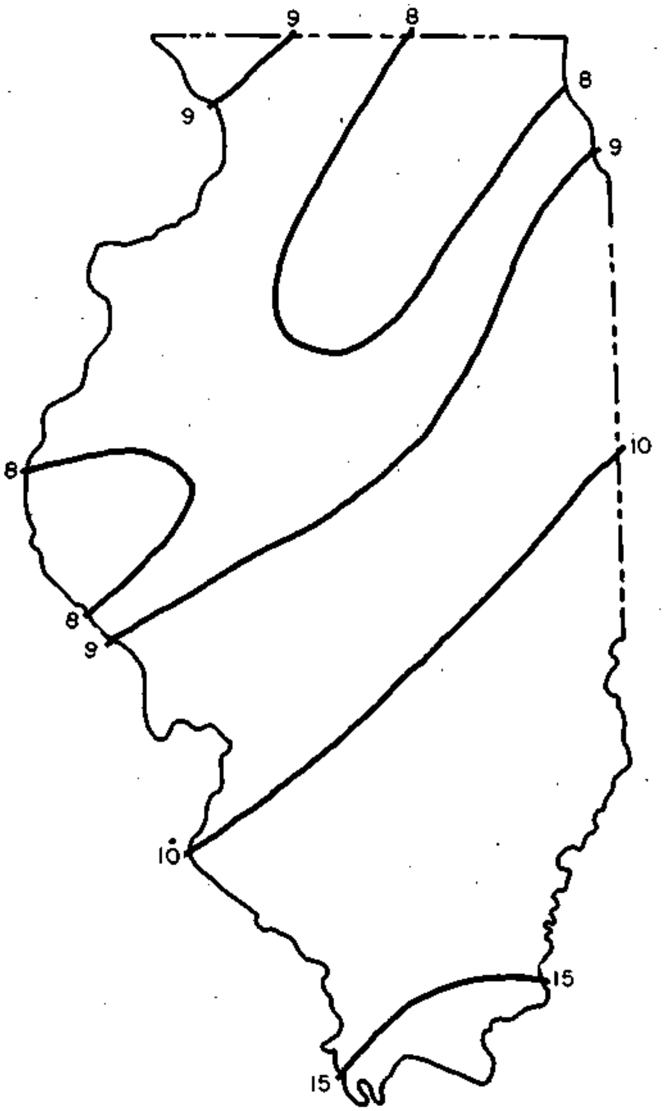


FIGURE 6. MEAN ANNUAL RUNOFF IN INCHES PER YEAR. 20 to 40 Year Records for 25 Stations.

It would be desirable to prepare such a map as that shown in Figure 6 for a uniform period of time and with more detailed information. This could be done either by choosing a representative recent short period for which abundant records are available, or by using a longer period and extending(7) the discharge values for the stations of short record. Inasmuch as there are 165 gaging stations in the State, the preparation of a detailed map was impractical for the present report.

Seasonal Variances in Hydrologic Cycle

Water that reaches the earth's surface as precipitation continues to be in motion. Its destination is determined by a number of processes, which include infiltration, evaporation, transpiration, underground travel and detention, percolation, and overland flow. The effect of each process on the others varies seasonally. These effects may best be studied by beginning with data available for measured processes (rainfall and runoff), and then calculating the effects of the less-well-determined processes (evaporation and transpiration) in order to evaluate the large unknown - underground storage.

Monthly averages of runoff from five stream-gaging stations in the drought region were prepared, together with monthly averages of rainfall as indicated by rain-gaging stations in or close to their drainage areas. The five monthly averages were consolidated into an arithmetic mean for each month for rainfall and similarly for runoff. The stations used are listed in Table 4. Average annual discharge values are for the period of record listed.

TABLE 4

STATIONS USED IN STUDY OF SEASONAL VARIATIONS IN HYDROLOGIC CYCLE

Stream-Gaging Station	Watershed Area in Square Miles	Years of Record to 1955	Average Discharge, Inches per Year	Rain Gaging Station
Big Muddy at Plumfield	753	41	13.16	Mt. Vernon
LaMoine at Ripley	1310	34	7.79	Quincy
Little Wabash at Wilcox	1130	41	10.17	Effingham
Macoupin Creek at Kane	875	35*	8.76	Carlinville
Sangamon at Monticello	550	45	10.28	Urbana

*7 years estimated

The monthly data are shown graphically in Figure 7. As the illustration shows, some of the seasonal variances in rainfall are reflected in the runoff. The low precipitation in February seems to coincide with a reduction in runoff during that month. However, runoff does not increase proportionately to rainfall in March since infiltration begins with the thawing of the soil, usually in that month. A similar disproportion is noted in April when vegetative demands commence and temperature rises have induced a substantial increase in evaporation of soil moisture. The disparity between rainfall and runoff curves therefore becomes greater until cooler weather in the fall brings a decline in transpiration and land evaporation rates.

The difference between the rainfall and runoff curves, which is shown in Figure 7, represents the amount of water available each month for transpiration and evaporation. A second curve has been computed which shows the calculated evaporation plus transpiration(8), based on rainfall and temperature data. The areas between the curves in Figure 7 represent water taken from storage in the earth or returned to storage. From the areas between these curves, it may be seen that from the first of April until mid-September, the vegetative and evaporative demands exceed the water available. This difference must be made up either by water from the soil or by reduced transpiration and evaporation. It is noted that the greatest rate of withdrawal from storage occurs in July.

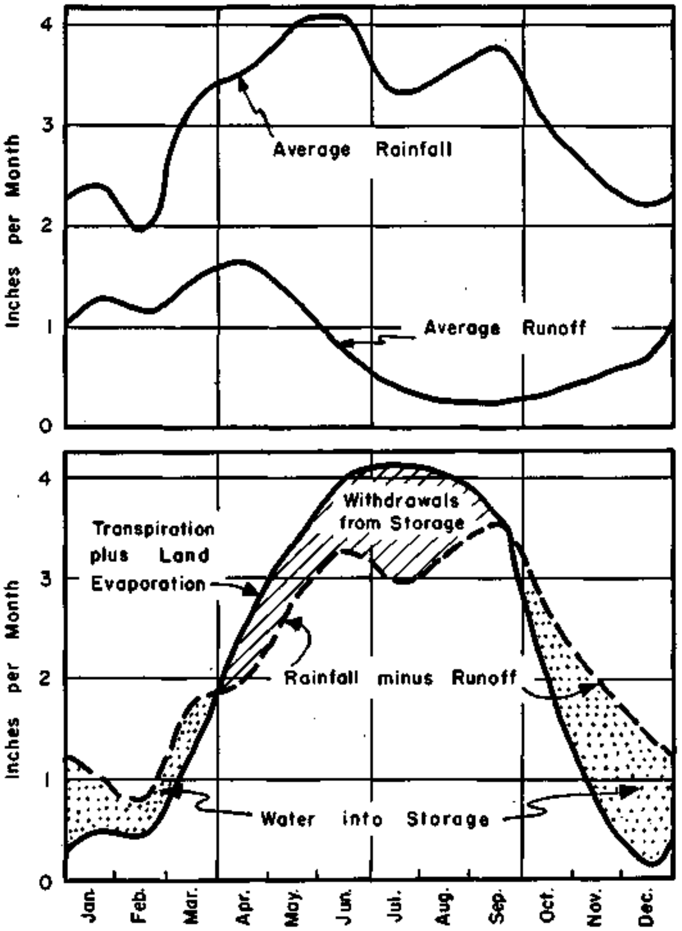


FIGURE 7. SEASONAL VARIATIONS IN THE HYDROLOGIC CYCLE. Southern Illinois.

From mid-September until the end of March, in the average year, water returns to storage. From the behavior of groundwater hydrographs for shallow wells, which commonly show no particular recovery until the end of November or later, it is judged that the excess available water for September, October, and November largely goes to make up deficiencies in soil moisture above the water table and does not add to storage below the water table, which recovers in the period between December 1 and April 1. Considerable variations from these general relationships will be found, depending on local infiltration rates, underground moisture storage capabilities, etc.

From these curves it may be seen that in the region studied, vegetative and evaporative demands are so great that excessive rainfall is required through July and August to prevent recession of groundwater levels and reduction of soil moisture storage. In abnormally dry years, when great deficiencies in soil moisture occur, recoveries of groundwater levels and of streamflow may be delayed by several months. Such a situation had occurred in the drought region at the close of 1953 and continued to intensify until the fall of 1954. Unfortunately, the soil moisture storage capacity in the drought region is lower than that in the northern half of the State where it may exceed 10 inches(9).

CAUSES OF WATER SHORTAGE

A number of factors other than the occurrence of an unusual drought have contributed to the water shortages occurring during 1952-55. Among those which contributed directly are; population increases, increases in domestic and industrial water requirements, reservoir siltation, and declines in capacity of wells. Factors that contributed indirectly to the occurrence of shortages were municipal finance problems, deficiencies in hydrologic data, lack of advance planning, and lack of records of waterworks operation. Population growth and increases in industrial and residential water use are closely linked. There is a relationship between sediment production and runoff into reservoirs but, in years past, hydrologic data have been insufficient to determine this relationship. Municipal finance problems and insufficiency of operating records seem to be separate topics not closely related to the other factors mentioned above.

Onset of Shortages

There are distinctive differences between the behavior of groundwater and surface-water sources of supply with respect to their adequacy. A shallow, locally-recharged groundwater-producing formation that is being used to capacity is usually incapable of furnishing water at rates greatly in excess of its perennial capacity except for very short periods. Peak loads on such sources are therefore apt to produce occasional low pressures in distribution systems even though the source is adequate for the average use of the community.

Groundwater sources of supply of too-limited capacity demonstrate their inadequacy by a continuing decline of water well levels. Over-use of water from these groundwater-producing formations is therefore quite evident to the operator (if he makes regular measurements of water levels), and frequently becomes apparent to the consumers on peak days through occasional shortages of supply even in years of normal precipitation. In years of deficient precipitation, declining water levels and increasing frequency of unsatisfactory service on days of peak demand warn the community of the inadequacy of the source.

On the other hand, surface water sources that rely upon streamflow are designed to meet dry weather conditions, when streamflow may be only a fraction of the normal flow. Periods of very low streamflow occur comparatively seldom and are interspersed with periods of normal or above-normal streamflow, during which the source of supply is capable of yielding as much as two to ten times more water than may safely be taken during a critical period of low flow. Accordingly, except for deficiencies in pumping and distribution facilities, a surface water source of supply may give little indication of inadequacy even in years that are considerably below normal. It is possible during normal or near-normal years for pumpage from an impounding reservoir supply to be increased several-fold above the long-term safe yield of the supply without causing signs of shortage. Accordingly, during periods such as the relatively wet period from 1944 to 1952, symptoms of inadequacy of surface water sources may not occur unless the demand has very grossly outgrown the safe yield. (The relative wetness of the 1944-52 period became apparent during the course of this study, through examination of data such as those shown in Table 9).

Increases in Water Demand

General. Total groundwater pumpage for municipal supplies in Illinois increased from 40 million gallons daily in 1900 to about 106 mgd in 1940(10). From 1940 to 1948 pumpage increased to 135 mgd, or about 28 per cent. The upturn in total pumpage after 1940 was very sharp. A similar striking increase of more than 40 per cent for the period 1940-1947 was reflected in the average for the five communities: Aurora, Champaign-Urbana, Dekalb, Elgin, and Rockford. Most of this increase took place following the World War II, when it occurred almost explosively.

Indications of rapid growth in demand caused Decatur to revise the plans prepared in 1948 for expansion of its water system. A survey of industrial and other uses in Decatur completed in 1954, indicated that the average daily pumpage had increased nearly 40 per cent from 1947 to 1953, and was expected to increase from 10 mgd in 1953 to

13 mgd by 1955, an increase of approximately 30 per cent. At Carthage, Illinois, pumpage increased from 0.130 mgd in 1945 to 0.225 mgd in 1950, more than 70 per cent.

A number of factors contribute to the increases in water demand that have occurred in recent years. Most obvious of these is the population growth, but increases in water demand have generally been greater than could be explained simply by greater population. A preliminary review of available data from Illinois communities in the region affected by the drought indicates that an increasing proportion of the urban population is receiving service from public water supply systems. Whereas in some communities, as few as one-quarter of the residences were connected to the public water supply system in 1930, this proportion has been rising and approaches 100 per cent in some of the communities. Industrial requirements for water have also increased as a result of the development of technological processes requiring water for cooling and processing purposes. Increased plumbing facilities and water-using devices in the home have also caused a growing demand. These devices include automatic washing machines, garbage grinding units, and air conditioners. Factors affecting water use are being given detailed study by Water Survey engineers and will be discussed in a subsequent report.

TABLE 5

POPULATION AND PUMPAGE CHANGES AT SELECTED MUNICIPALITIES IN THE DROUGHT REGION

	Population		Pumpage	
City	1950	Per Cent Change 1930-1950	1953 (1000 gpd.)	Per Cent Change 1938-1953
Altamont	1,580	+ 29.8	75	+ 87
*Arcola	1,700	+ 0.8	90	+ 50
Ashley	738	- 4.4	75	+ 370
*Assumption	1,466	- 5.6	85	+ 41
Astoria	1,308	+ 10.0	70	+ 133
*Barry	1,529	+ 1.5	76	+ 110
Blandinsville	918	- 3.6	34	+ 162
Bunker Hill	1,238	+ 30.7	60	---
*Camp Point	969	- 3.1	23	+ 130
Carrier Mills	2,252	+ 5.2	75	+ 243
Carthage	3,214	+ 43.4	240	+ 200
Decatur	66,269	+ 15.3	10,000	+ 43
*Dongola	704	+ 10.8	48	+ 435
Effingham	6,892	+ 38.4	600	---
Elkville	934	- 17.5	45	+ 125
Eureka	2,367	+ 54.3	175	+ 75
Galatia	933	0	35	+ 400
*Greenfield	987	- 4.9	45	+ 137
Harrisburg	10,999	- 5.3	700	+ 75
Highland	4,283	+ 29.0	400	+ 92
Jacksonville	20,387	+ 14.8	1,900	+ 90
Johnston City	4,479	- 24.7	170	0
*Jonesboro	1,607	+ 29.3	70	+ 133
Kincaid - Bulpitt	2,169	+ 6.4	210	+ 600
LaHarpe	1,295	+ 10.2	70	+ 133
McLeansboro	3,008	+ 39.1	280	+ 180
Marissa - Tilden	2,558	+ 57.0	85	+ 430
Mattoon	17,547	+ 19.9	2,325	+ 86
Mt. Sterling	2,246	+ 30.2	150	+ 178
Nashville	2,432	+ 8.4	300	+ 900
Norris City	1,370	+ 23.5	80	+ 209
Olney	8,612	+ 40.2	700	+ 95
Pittsfield	3,564	+ 51.2	275	+ 244
Sesser - Valier	2,894	+ 38.7	200	+ 100
Sparta	3,576	+ 5.6	250	0
*Teutopolis	919	+ 28.7	35	+ 85
Vienna	1,085	+ 24.1	46	+ 229
Virginia	1,572	+ 5.2	100	+ 300
Waterloo	2,821	+ 25.9	180	+ 445
White Hall	3,082	+ 5.2	160	+ 19
*Windsor	1,008	+ 8.7	75	+1,150

•Indicates groundwater source. All other surface sources.

Water Demand in Drought Area. Table 5 contains preliminary information on water use in the 41 communities that faced possible shortages in January 1954. It is to be noted that the population changes for the period 1930 to 1950 were considerable in some instances, but none of the population increases exceeded 57 per cent, and in 24 instances the increases were less than 20 per cent. Pumpage data for these communities were available from field visits in 1953-54 and from other sources for 1938. The per cent change in pumpage has been computed and is given in Table 4 for each community. Pumpage increased 600 per cent or more in three cases and increased by more than 100 per cent in 24 cases.

Detailed study of the factors influencing the water use in these communities is being made, and no generalizations have yet been reached concerning communities that did not show large increases. It is noted, however, that a number of the communities for which pumpage increases were either small or negative, experienced population declines during the period of study. In other instances, the lack of pumpage increase was known to be linked to the inadequacy of the water source development, so that it was recognized in these communities that frugal use of water was essential to prevent a general shortage.

In some instances part of the increase can be attributed to leakage and wasteful use, but this is believed to be a relatively small proportion. Most of the increase appears to be due to two factors: (1) increase in number of service connections, and (2) increases in per capita and industrial use. In many of the communities studied, these increases have not yet fully materialized, and may be expected to develop in future years.

National Trends. The American Water Works Association surveys of 1945 and 1950 water pumpage indicate that a 10 per cent increase took place in per-capita consumption between these years. However, many communities throughout the nation, such as Oklahoma City, have noted such great increases in water use since 1940 as to necessitate substantial, ahead-of-schedule expansion of facilities(11). A study by the U. S. Department of Commerce indicated that the national total pumpage through municipal systems would rise about 35 per cent in the decade 1950-1960(12).

Deficiencies in Hydrologic Data

Basic items of hydrologic data for water works design include information on streamflow, groundwater levels and precipitation data. The precipitation data are used at times, in combination with other information, to aid in the estimation of streamflow data when streamflow records are lacking. Precipitation data may also be of value for correlation with variances in groundwater levels.

Precipitation data have been available for a number of years from several hundred rain gaging stations in Illinois, and some of the records reach back well into the 19th century. On the other hand, stream-gaging records for use in design of impounding reservoirs are available only since about 1908 in Illinois, and few of the streamflow records reach back that far.

Groundwater data, collected on a long-term basis, are almost totally lacking in the drought region with the exception of certain measurements in areas where heavy pumpage has attracted attention to groundwater problems. Groundwater level and productivity data are not generally available throughout the southern half of Illinois covering a sufficient length of time and a sufficient number of locations to enable precise design of dependable groundwater sources of supply.

Inasmuch as data previously given have indicated that the highest proportion of difficulties in water supply during the 1952-55 drought occurred at communities having surface water storage, and since streamflow data are essential for design of storage facilities for such installations, it is clear that the most critical hydrologic data with respect to water supply development are those gathered from stream-gaging.

An analysis has been made of the 144 streamflow gaging stations operated within the State of Illinois as of January 1, 1955, classifying stations by drainage area and date of initiation of measurement program. These data are shown in Table 6 which indicates that of the 144 stations, only 30 are for drainage areas less than 20 square miles. Table 3 shows the distribution of drainage areas of impounding water supplies that experienced difficulty in 1952-54. It will be seen that 90 per cent of the drainage areas used were smaller than 18 square miles.

Table 6 shows that no stream-gaging stations now in operation on drainage areas of less than 50 square miles were established prior to 1931, and that only eight stations had been established prior to 1940 on drainage areas of less than 50 square miles, as compared with 43 subsequent to 1940.

These data reflect the growth of interest in the gaging of flows from small drainage areas since 1930.

As the population and demands for water grow in the future, it would be expected that larger drainage areas will be required than those now in use. Taking this into account, it would appear desirable, in the region where surface waters comprise the major available sources, to increase considerably the collection of streamflow data for drainage areas of 50 square miles or less.

TABLE 6

CLASSIFICATION OF STREAMFLOW MEASURING STATIONS IN OPERATION IN ILLINOIS, JANUARY 1, 1955

Year Started	Number of Stations on Drainage Basins of Various Areas, (sq. mi.)					
	0-5	5-10	10-20	20-50	50-100	100+
Before 1921	0	0	0	0	0	23
1921-30	0	0	0	0	1	7
1931-40	1	2	1	4	5	27
1941-50	2	8	8	7	3	31
1951-54	3	1	4	2	1	3
Total	6	11	13	13	10	91

Observations from stream-gaging stations are of limited value for design purposes until they have been collected for a period of years. In the past, it has been considered that 20 years is a minimum time for obtaining trustworthy streamflow records at a given location. The fruits of the increase in stream-gaging immediately prior to 1940 are therefore now becoming available but, until the last two or three years, little use had been made of these data for design.

Data from the five reservoirs on which the Illinois State Water Survey has been keeping records since prior to 1930(13) had not been widely disseminated when most of the present reservoirs were built. Drainage areas for these reservoirs range from 2.95 to 61 square miles.

Study of the dates of construction (and presumably of design) of the sources for the 53 surface-water-using communities that experienced difficulty during the 1952-55 drought shows that 9 were built in the period prior to 1920; 14 in 1920-29; 19 in 1930-39; 11 in 1940-49. Thus it is seen that only 20 per cent of these reservoirs were designed after 1940, when the collection of small-basin streamflow records was intensified.

It is therefore clear that the streamflow data necessary for design of reservoirs were not available at the time when most of the Illinois municipal water supply impoundments were constructed. Far better design information is now available but there is still question as to whether appropriate information is being collected for economical and safe design of the impounding reservoirs that will be needed for water supply in Illinois.

Municipal Finance Problems

Problems of municipal finance have attracted increasing attention in recent years. The severe difficulties encountered in financing necessary local functions so preoccupied many communities that insufficient attention was paid to water supply problems. In other cases, communities that experienced shortages in 1952-55 had been aware in earlier years that their sources of supply were not adequate, but were unable to finance the necessary improvements. These communities had managed to eke out their water supplies by the application of local restrictions during the drier periods.

Of the 75 southern and central Illinois communities that have faced water source problems during 1954, 26 had developed new permanent sources of supply as of June 1955. Eight more had work under construction and 19 were planning to develop additional sources. Twenty-two had taken no action.

Insufficient Records

The low-water situations for both surface water and groundwater supplies have emphasized the desirability of maintenance by cities of careful records of water levels in wells and reservoirs. Many communities do not have the necessary equipment for determination of water levels. Equipment of this kind includes airlines in wells for determination of water levels, and staff gages on intake towers in impounding reservoirs. By means of such devices, water levels may readily be determined at regular intervals. Readings should be taken by local waterworks personnel at weekly intervals and entered in the permanent records of the system.

By analysis of these records two or three times per year, it is possible to anticipate shortages and to take appropriate action to forestall them.

Experience of Communities Affected

A classification was made of the sources of supply for the 75 communities that experienced or faced shortages in 1952-55. At these communities restrictions were placed on water use in nearly all cases. In a few instances, no local restrictions were applied, but the quantity of water on hand was sufficient to last less than six months. Such communities were therefore considered to be facing shortages.

Computation of the quantity of water on hand in storage reservoirs was begun in December 1953. In January and February 1954, communities were estimated to be endangered by shortages if the quantity of water on hand was less than an eight months' supply. As the more favorable season for runoff approached (See Figure 7) the quantity on hand to insure a safe supply was estimated to be a six months' supply. This figure could have been increased again as the likelihood of runoff lessened in late spring and early summer, but the six months' figure was maintained for purposes of uniformity. Designers in Illinois have commonly provided capacity for storing one or more years' supply of water, depending on local conditions. The six months' supply is considered a minimum amount to have on hand as a season of high runoff (January through May) approaches, and it is considered that a larger quantity would be desirable at the close of the season of high runoff.

Relation of Source to Incidence of Shortages. The data from the classification by sources are given in Table 2, which shows that only 11 per cent of the cities having groundwater sources faced shortage problems as compared with 54 per cent of those using surface-water sources.

There were no problems in the groundwater-using-communities having deep sandstone sources, although these are relatively rare in the drought region. Highest proportionate incidence of groundwater shortages was in the limestone sources of supply, but the largest group of groundwater shortage problems was in communities having wells drilled into sand-and-gravel formations.

The median depth of wells for the 16 communities using sand-and-gravel sources of supply was 40 feet. Depths of wells ranged from 28 to 130 feet for these communities, and three-quarters of the communities had wells 68 feet or less in depth. Seasonal effects and immediate local recharge play a very important part in the operation of wells as shallow as this.

There were no problems at the surface-water-using communities having direct intakes, since these communities are located adjacent to rivers whose minimum flows are in excess of the community's requirements. The remaining three categories (channel dams, side-channel reservoirs, and impounded reservoirs), all of which use artificially-produced storage as an essential element of the supply scheme, showed a very high incidence of shortages. Of this group, 68 per cent faced shortages, with the highest incidences of shortage problems occurring in the side-channel and impounding reservoir supplies. Occurrence of difficulties with these sources was so general as to make clear that either (1) the drought was of an extraordinary severity, and/or (2) the existing reservoirs were not adequate to meet the needs of the communities.

Source Capability versus Water Demand. A study was made of causes of shortages at the communities that have had difficulties related to source inadequacies during 1952-55. The history of each community's water system was reviewed to determine: (a) the change in pumpage in the period 1938 to 1953, (b) losses in capacity due to sedimentation in surface water reservoirs, and to declines in capacities in groundwater installations caused by aging of wells, and (c) the adequacy of the source, as of 1938, to meet the demands that could have been expected to develop by 1955.

In those groundwater using communities that experienced shortages, particular attention was paid to distinguishing between shortages caused by exhaustion of available groundwater and those caused simply by declining well capacities, as indicated by reductions in specific capacities.

The causes of shortages were placed in either of three categories:

1. Capacity insufficient to meet anticipated demands.
2. Decline in capacity.
3. Unexpectedly large increase in demand.

Table 5 shows some of the experiences with increases in demands for water in communities in the drought region. Median increase for the group of 41 communities was of the order of 100 per cent for the period 1938 to 1953. For classification of causes of difficulties a 100-per cent increase was therefore arbitrarily chosen as a value of pumpage increase which might usually have been anticipated during this period in the drought area.

Where the increase in pumpage exceeded 100 per cent for the period 1938 to 1953, the cause of shortage was usually considered to be unexpected increase indemand. There were two exceptions to this rule, however. One exception covered those instances in which designers of new systems had planned for increases in demand greater than 100 per cent. In these cases the shortages were attributed to other causes. The other type of exception dealt with communities whose water systems had been in service for several decades prior to 1938. Some of these appeared to have needed expansion in 1938 to meet demand increases less than 100 per cent that could be expected by 1953; the cause of their difficulty was deemed to have been insufficient capacity.

In many instances it was difficult to attribute the cause of shortage to any single factor. In several cases all three factors were operative. In each of these cases a decision was therefore made on a basis of the judgment of Survey engineers as to which was the determining factor.

Adequacy of surface water sources as of 1938 was judged on the basis of reasonably-anticipatable increases in demand and the draft-storage criteria presented later in this report. (Figure 40.)

In several instances, such as at Johnston City andHillsboro, calculations indicated that the reservoir design was such that the system should have been capable of supplying the current community demands for droughts such as those covered by Figure 40. The fact that water shortages became imminent at these communities indicates that the drought of 1952-55 was more extreme at these locations than the low-flow periods involved in the preparation of Figure 40. Inasmuch as shortages impended at these communities, they were classified as having capacity insufficient to meet the drought. Neither Johnston City nor Hillsboro had to resort to emergency sources of supply, and at the worst of the drought, the quantities remaining on hand were sufficient to supply the communities on a restricted basis for two months at Johnston City and five months at Hillsboro.

Summary of Causes of Shortages. The analysis of the data to determine causes of water supply difficulties is summarized in Table 7. From this table it is seen that, considering all the water systems studied, the principal cause of failure was insufficient capacity, that the second most frequent cause was increased demand, and that declining yield was the least frequent cause of shortages.

TABLE 7

CAUSES OF WATER SUPPLY DIFFICULTIES.
MUNICIPAL SUPPLIES IN THE DROUGHT REGION

	Surface Water Sources	Groundwater Sources	Total
Capacity insufficient to meet anticipated demands	23	15	38
Decline in capacity	4	5	9
Unexpectedly large increase in demand	26	2	28
Total	53	22	75

For surface-water-using communities the most frequent cause of shortage was unexpectedly large increase in demand, followed by insufficient capacity, and decline in capacity. In many cases two or more of these causes entered in; where there was question, the difficulty was attributed to the easily-measured increase in demand. For groundwater sources, insufficient capacity came first, declining capacity was second in importance and increased demand, third. This difference in the order of causes of difficulty appears to be due to the fact that, in a number of groundwater-using communities where shortages did occur, peak day shortages before the drought had shown that the supplies had no excess capacity, and demands therefore did not increase. In the case of surface waters, as mentioned previously, there was frequently no such public awareness. Uses therefore tended to increase rapidly at surface-water source communities.

The second most frequent cause of shortage of surface supplies was insufficiency of reservoir capacity. These failures were due primarily to inadequacies in hydrologic data for safe design of reservoirs. Least frequent cause of shortage of surface-water source was decline in capacity (due to silting). This was the primary cause in only five communities, and only a contributing factor in many of the others.

EXTENT AND INTENSITY OF THE DROUGHT

The area within Illinois covered by the drought was generally within the southern half of the State, although moisture deficiency conditions extended northward into Hancock and McDonough Counties, west of the Illinois River, and north of Champaign County at times. As precipitation occurred, the area expanded, contracted, and shifted.

In the following studies, the data used for mapping and tabulating are monthly totals. These monthly totals are available from U. S. Geological Survey and Weather Bureau publications.

Rainfall Conditions

The drought area can be outlined by mapping rainfall data for various periods. Rainfall departure maps were prepared for various periods beginning April 1, 1952, which was chosen as the beginning date for the drought on a basis of published U. S. Weather Bureau Records(14). From these records, preliminary values of average precipitation and departures from normal for Northern, Central, and Southern divisions of the State were obtained. March 1952 showed above-normal precipitation for all three divisions, but below-normal precipitation occurred in April and May in all three divisions. Slightly above-normal precipitation was recorded in June for all three, but below-normal precipitation occurred in the Northern and Central districts in July, and for August 1952, precipitation was below normal in both the Southern and Northern divisions. In the Southern division, where most of the 1952 water supply difficulties occurred, rainfall was generally below normal continually for the remainder of 1952(14). For the rainfall analysis carried on during the drought, 39 of the 183 U. S. Weather Bureau rain gaging stations in Illinois were used. These particular stations were chosen because regular monthly reports for them were issued by the U. S. Weather Bureau within the first week of each month.

Since there are significant geographic variations in rainfall within the State, as shown in Figure 5, it seemed desirable to analyze the rainfall data on the basis of departures from normal precipitation rather than on the actual amount that occurred. Rainfall departures may be calculated with monthly data, using the actual rainfall for the month and the 45-year normal values published by the Weather Bureau(4). A departure is the amount by which the actual amount differs from the normal. Departure values may be cumulated to produce total departure values for any desired period. On the maps which follow, deficiencies have been indicated by minus signs, and above-normal rainfall has been indicated by plus signs. Inasmuch as, in certain parts of the State, above-normal rainfall occurred, and since the maps show both the excesses and the below-normal rainfall, they have been called departure maps, although this report is primarily concerned with deficiency data.

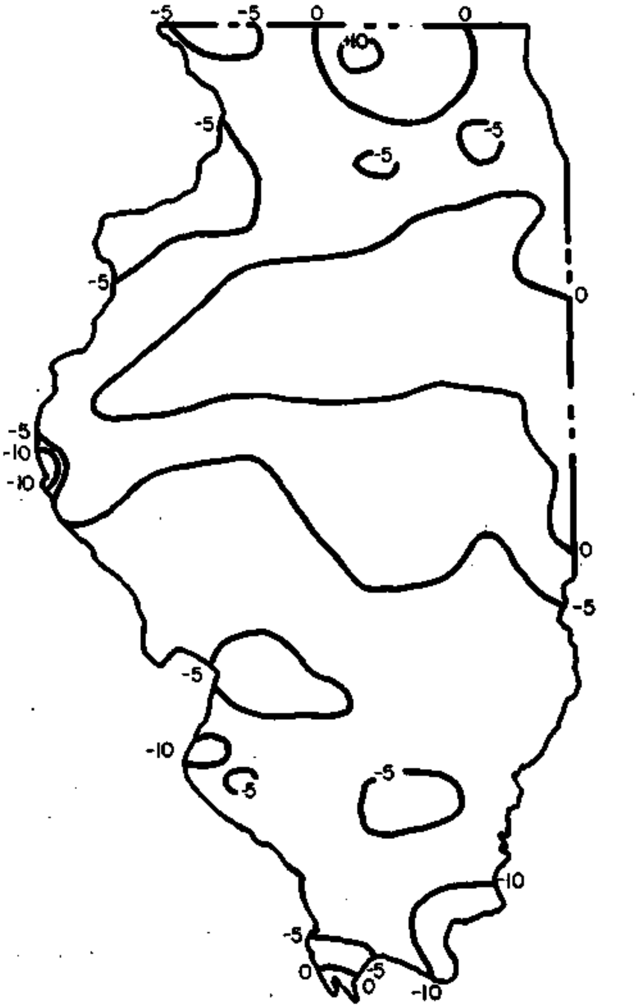


FIGURE 8. RAINFALL DEPARTURE FROM NORMAL IN INCHES. April to December 1952.

As the drought extended into 1954, it was recognized that the effects of rainfall deficiency on water supplies would not extend in full force much more than one year. This lack of full cumulative effect is due to the limiting value of soil moisture storage, which is of the order of 10 inches$^{(9)}$. As deficiencies increase toward a value of 10 inches, water may be withdrawn from soil moisture storage. When the soil moisture deficiency exceeds approximately 10 inches, transpiration virtually stops and larger values of deficiency become relatively less meaningful. There are some seasonal opportunities for replenishment of the soil moisture but, with respect to soil moisture and overland flow, there is little hydrologic reason for cumulating rainfall deficiencies more than one year when they become much greater than 10 inches. Accordingly for mapping 1953 conditions, the beginning month for tabulation was shifted to January 1, 1953 and, for 1954, the deficiency computations were shifted to begin with January 1954.

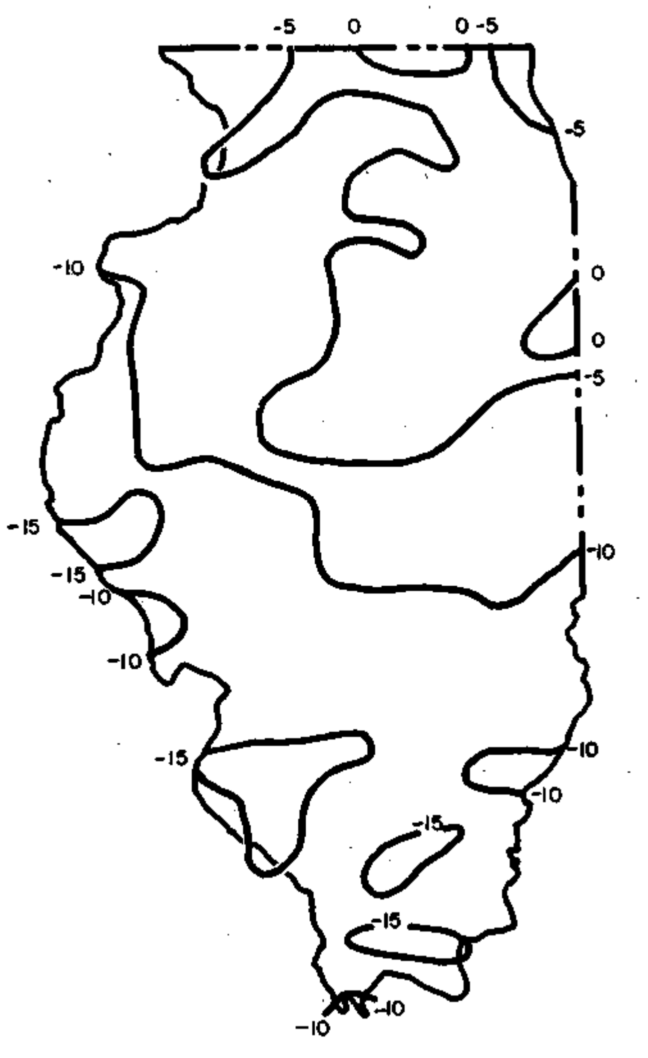


FIGURE 9. RAINFALL DEPARTURE FROM NORMAL IN INCHES. January to December 1953.

Rainfall Deficiency Patterns. Figure 8 shows the rainfall deficiency pattern for the period April through December 1952; it reveals that the southern half of the State had deficiencies of 5 to 10 inches. Figure 9 shows the rainfall deficiency pattern for 1953, for which the deficiency was 10 to 17 inches throughout southern Illinois. In addition, an area in the western part of the State experienced rainfall deficiencies of 10 inches or more.

The precipitation pattern for 1954 was similar to those of the previous years in that deficiencies again appeared in the southern half of Illinois (Figure 10). The greatest deficiency reported was at Windsor, Shelby County (14 inches), and deficiencies were relatively small in the area south of Route 50, which runs from East St. Louis across the state to Lawrenceville. There was only slight deficiency in the Randolph-Perry County area. Above-normal rainfall occurred in a large part of northern Illinois, especially in the Chicago region, where the excess was largely due to the storm of October 1954$^{(15)}$.

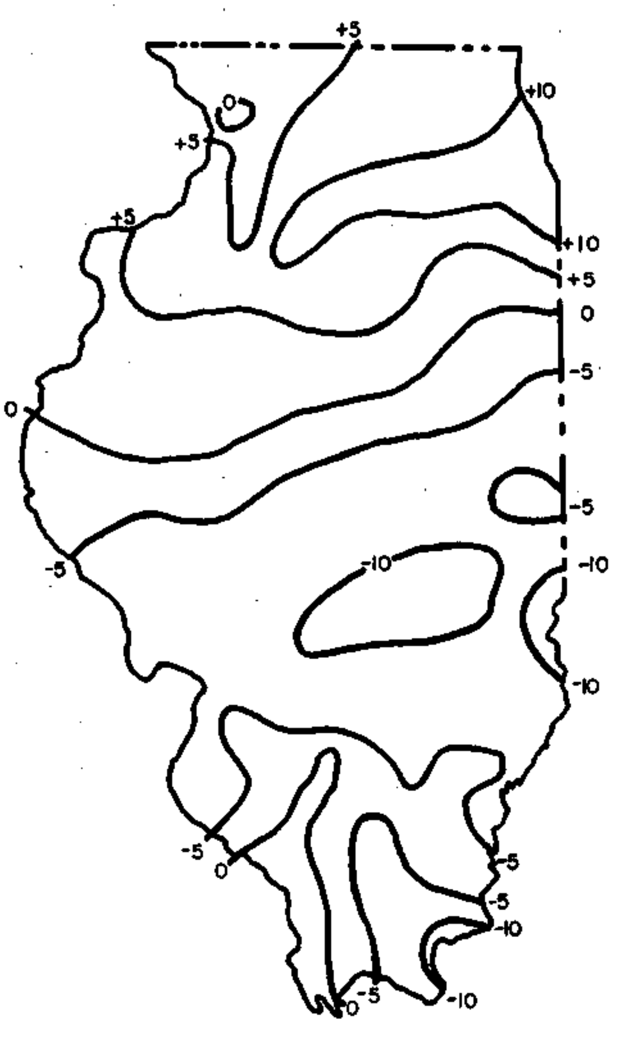


FIGURE 10. RAINFALL DEPARTURE FROM NORMAL IN INCHES. January to December 1954.

Figure 11 is a graph of the rainfall trends during the period 1952-55, showing the cumulative departures from normal rainfall for each of five stations. Three of these stations, Quincy, Taylorville, and Urbana, are in the northern part of the drought zone, while the Centralia and East St. Louis stations represent more nearly the central part of the drought zone. From this figure it will be seen that there was an improvement in conditions at Quincy commencing about the middle of 1954. This was followed later in 1954 by a rapid improvement in conditions at Centralia. A less marked improvement took place at East St. Louis later in 1954. The slopes of the cumulative departure curves for Taylorville and Urbana reduced during 1954, but no marked recovery was indicated by the data.

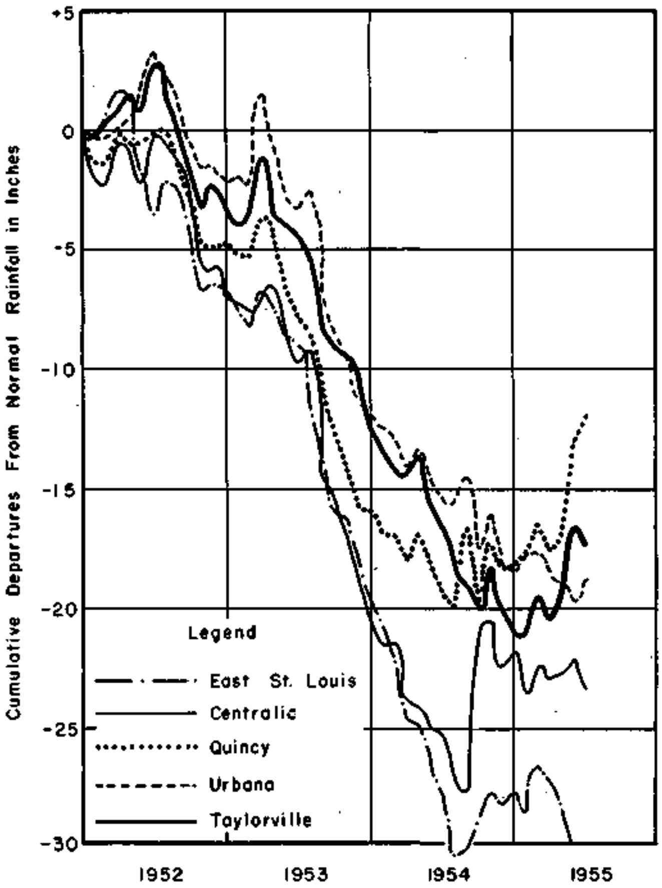


FIGURE 11. CUMULATIVE RAINFALL DEPARTURES FOR 1952 to 1955.

Runoff Conditions

Early in 1954 arrangements were made with the U. S. Geological Survey to expedite reporting of current runoff data from certain key stream-gaging stations in the southern half of Illinois. These data were combined with earlier runoff data to produce cumulative 12-month maps of runoff conditions, prepared each month until precipitation relieved the situation in the fall of 1954. The information reported by the U. S. Geological Survey consisted of provisional runoff values that are subject to revision when computation for publication is completed. These provisional data have, however, been used throughout this report for the entire period commencing in October 1953. Data prior to that date were final and not subject to revision. The watersheds for the 15 stations used are shown in Figure 12.

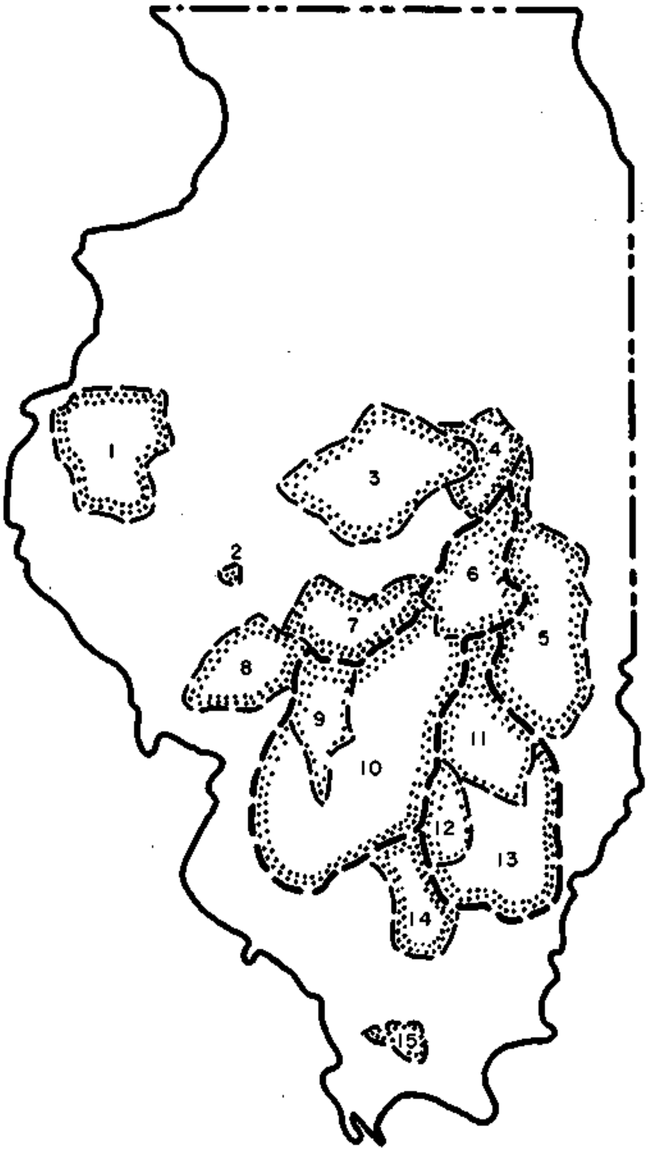


FIGURE 12. DRAINAGE AREAS USED IN STREAMFLOW MAPPING

1. LaMoine River at Ripley
2. No. Fork Mauvaise Terre Ck. near Jacksonville
3. Salt Ck. at Greenview
4. Sangamon River at Monticello
5. Embarrass River at Ste. Marie
6. Kaskaskia River at Shelbyville
7. So. Fork Sangamon River at Kincaid
8. Macoupin Ck. near Kane
9. Shoal Ck. near Breese
10. Kaskaskia River at New Athens
11. Little Wabash River at Wilcox
12. Skillet Fork at Wayne City
13. Little Wabash River at Carrhi
14. Big Muddy River at Plumfield
15. Cache River at Forman

There is some overlapping of the information supplied from these stations. Shoal Creek at Breese and the Kaskaskia River at Shelbyville are both tributary to the area measured by the Kaskaskia River gage at New Athens. Little Wabash River at Wilcox and Skillet Fork at Wayne City are both subdivisions of the drainage area of the Little Wabash above Carmi.

An additional factor to take into account in considering the runoff data was the substantial pumpage of groundwater into the Kaskaskia River near Bondville. In mapping the runoff, correction was made by subtracting the groundwater pumpage at Bondville (minus losses due to industrial use at Tuscola) from the discharge at both Shelbyville and New Athens. In order to make the data more representative for sub-areas-, such as the Kaskaskia drainage basin below Shelbyville, the weighted effects of runoff at Shelbyville and at Shoal Creek at Breese were subtracted, so that the runoff for the Kaskaskia River basin exclusive of these two drainage areas could be computed. Similar corrections were made for the Little Wabash River basin. While it would have been desirable to make adjustment for sewage discharge into the various streams, this was not done. On certain streams such correction could be a significant factor during extreme low-flow periods.

TABLE 8

COMPUTATION OF MOST EXTREME LOW-FLOW PERIOD
OF 12 MONTHS DURATION (1953-54 DATA)

Gaging Station	Streamflow in Inches for the 12-Month Period Through: April	May	June	July	Aug.	Sept.
Big Muddy River at Plumfield	1.64	.65	.73	.72	.77	.96
Embarrass River at Ste. Marie	1.57	.76	.57	.39	.36	.35
Kaskaskia River at New Athens	1.28	.69	.59	.38	.38	.51
Little Wabash River at Carmi	1.51	.48	.44	.40	.48	.66
Little Wabash River at Wilcox	.97	.37	.29	.24	.26	.43
Macoupin Creek at Kane	.87	.60	.22	.20	.23	.32
Mauvaise Terre Creek at Jacksonville	.58	.25	.08	.08	.22	.23
Shoal Creek near Breese	1.74	.96	.41	.33	.35	.49
Skillet Fork River at Wayne City	1.24	.48	.52	.53	.60	.91
Sangamon River at Kincaid	.98	.70	.52	.42	.42	.43
Kaskaskia River at Shelbyville	1.94	1.40	1.28	.74	.77	.78
Average	1.30	0.67	0.51	0.40	0.44	0.55

For mapping the runoff, the data (expressing discharge in inches) were entered in the center of the appropriate drainage areas. Contours were then drawn (Figures 13-18) on the basis that each runoff value represented the mean of the area, and that discharge within a gaged area was not necessarily geographically uniform. For example, streamflow for the 12 months through July 1954 for the Embarrass River at Ste. Marie was 0.39 inches. By comparison of Figures 14 and 12 it may be seen that several contours cross the drainage area of the Embarrass. In drawing the contours it was attempted to locate them so that the mean runoff for the drainage area would be 0.39 inches. It appeared from the data available that runoff was less than 0.2 inches in part of the basin and more than 0.6 inches in another part.

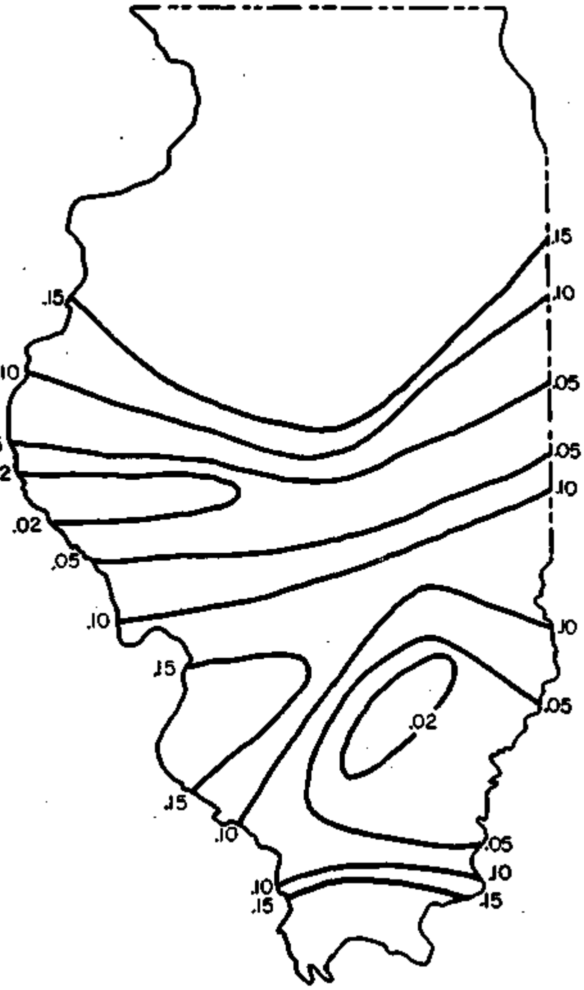


FIGURE 13. RUNOFF IN INCHES - 6 MONTHS ENDING JANUARY 1954.

Periods of Lowest Streamflow. For each map used in charting the progress of the drought, 12-month sliding totals of runoff from all of the 15 areas were prepared. Subsequently one map was drawn for each of the 6, 12, 18, 24, 30 and 36-

month duration periods. The particular low-flow period for each of these durations was selected by averaging, by calendar months, the sliding totals for these gaging stations, except that the Sangamon River at Monticello, Cache River at Forman, Salt Creek at Greenview, and La Moine River at Ripley were excluded as being outside the principal area of drought.

Table 8 illustrates the method of computation of the most extreme of the low-flow periods of 12 months' duration. It will be seen from this table that the lowest average of the 11 stations occurred for the 12 months ending with July 1954,

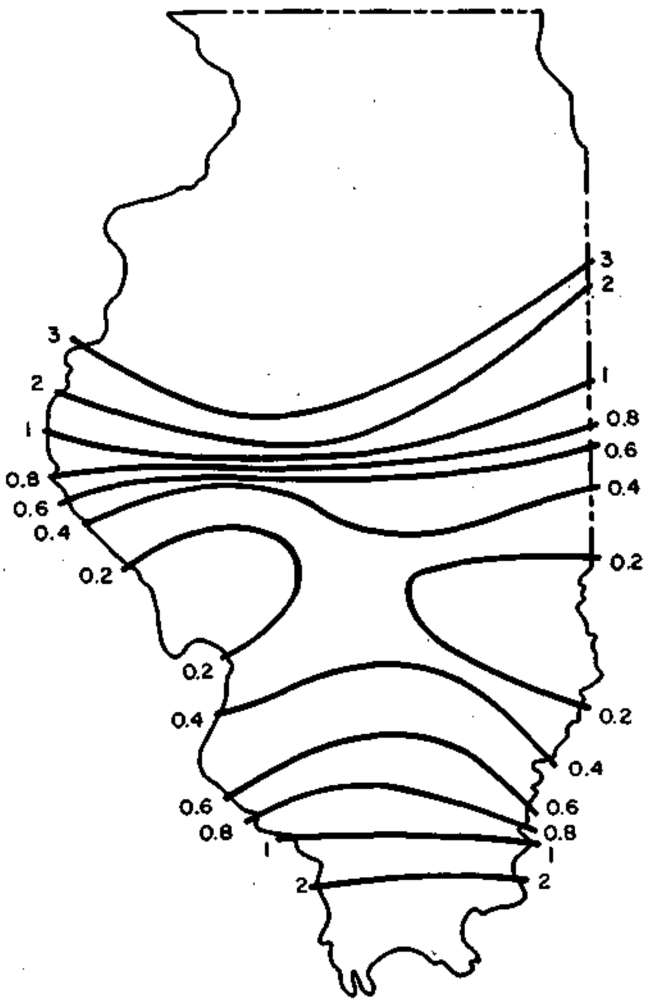


FIGURE 14. RUNOFF IN INCHES - 12 MONTHS ENDING JULY 1954.

Estimates of runoff computed from impounding reservoir records at Springfield, Waverly, Staunton, Nashville, DuQuoin, Carbondale, West Frankfort, Johnston City, McLeansboro, Norris City, Eldorado, Mattoon, and Oakland were also used in drawing the maps so far as the available data permitted the making of estimates. For the most part, these did not contribute usable data because of the lack of periodic readings of reservoir levels during 1953 and earlier. Qualitative guidance in the preparation of the contour maps was obtained, however, from observations made on the reservoirs during each month.

Figure 13 shows the streamflow pattern for the 6-month period during which the average of the runoff at the 11 stations considered to be within the drought area was the lowest in 1952-55. This 6-month period terminated January 31, 1954. Figure 14 shows the runoff picture for the lowest 12 months, which ended July 31, 1954. Figure 15 shows the total runoff for the 18 months ending December 31, 1954, the lowest 18 months' period found. Figures 16, 17, and 18 show respectively the lowest 24, 30 and 36 months' totals found. No runoff data later than May 1955 were available at the time these maps were prepared.

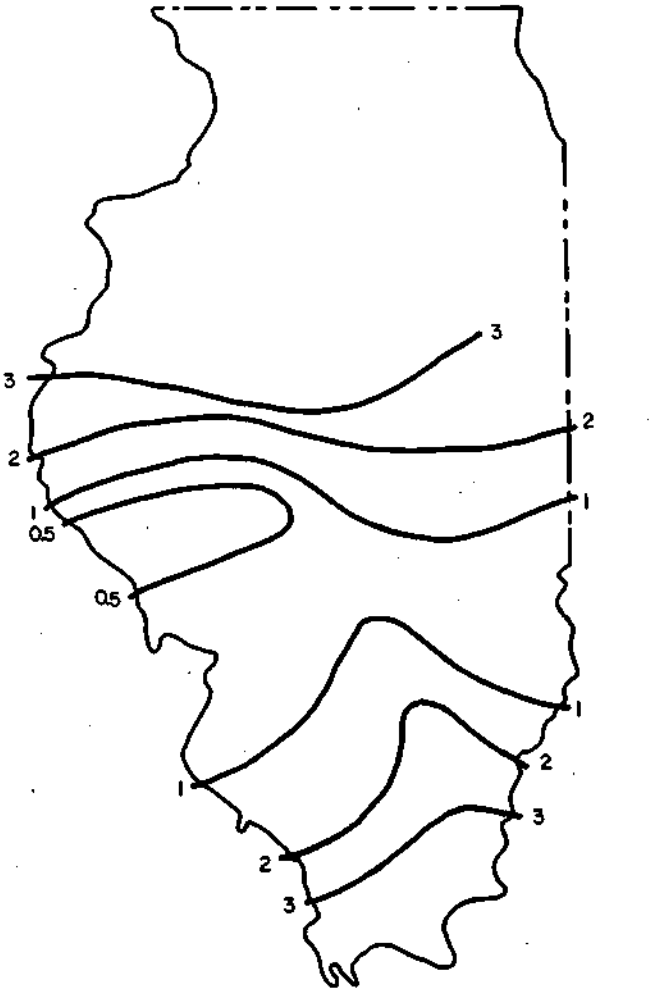


FIGURE 15. RUNOFF IN INCHES - 18 MONTHS ENDING DECEMBER 1954.

These maps depict the streamflow patterns for periods in which low runoff occurred over large areas within the current drought. In several cases, values as low as those indicated on the maps occurred over considerable areas during other periods. For example, for the 12-month period ending June 30, 1954, run-off in Pike, Scott, Greene, and in the southern portions of Morgan, Sangamon and the north part of Macoupin counties was 0.20 inches or less. Runoff during this period for Mauvaise Terre Creek at Jacksonville was 0.11 inches. A few anomalous values were obtained from reservoir records, as for example at Mattoon, where runoff in 1954 was less than evapotranspiration along the waterways and in the reservoir bottom. During this period Mattoon was unable to pump any water from its lake, and relied upon groundwater sources.

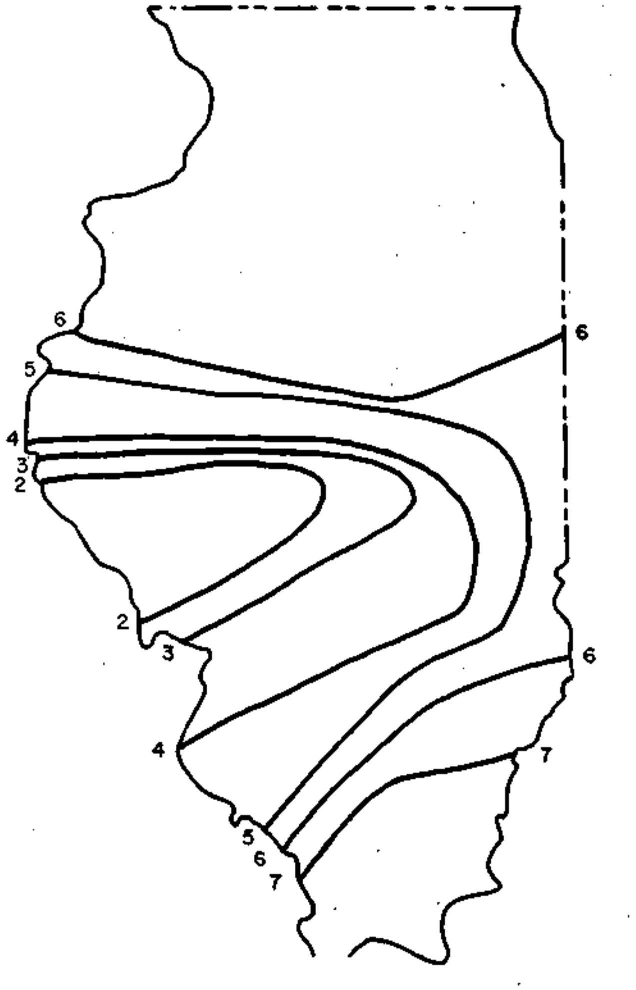


FIGURE 16. RUNOFF IN INCHES - 24 MONTHS ENDING DECEMBER 1954.

For the purposes of this report, the maps have been prepared on the assumption that unit runoff is independent of drainage basin area. This may be incorrect, but the relationship between these two factors has not been established(16), and requires extensive additional study. It would seem reasonable to expect smaller low-flow values from a small basin than from a large one. A study to evaluate this effect is of importance for safe and economical design of water works.

Drought Frequency Studies

Streamflow records in Illinois extending back prior to 1915 are available for Little Wabash River at Wilcox, Embarrass River at Ste. Marie, Big Muddy River at Plumfield, Kaskaskia River at Vandalia, Sangamon River at Riverton, Sangamon River at Monticello, Spoon River at Seville, and Pecatonica River at Freeport. Four of these stations began operating in 1908 or 1909, but all of them were interrupted in 1912-14. In addition, records are available beginning in 1921 for LaMoine River at Ripley and Macoupin Creek near Kane (although the records for 1934 to 1939 were estimated for the latter), and similar data are available for Mackinaw River near Green Valley. These records were examined and, because of manpower limitations, it was decided to limit runoff frequency studies to five long-record stations in or near the drought region.

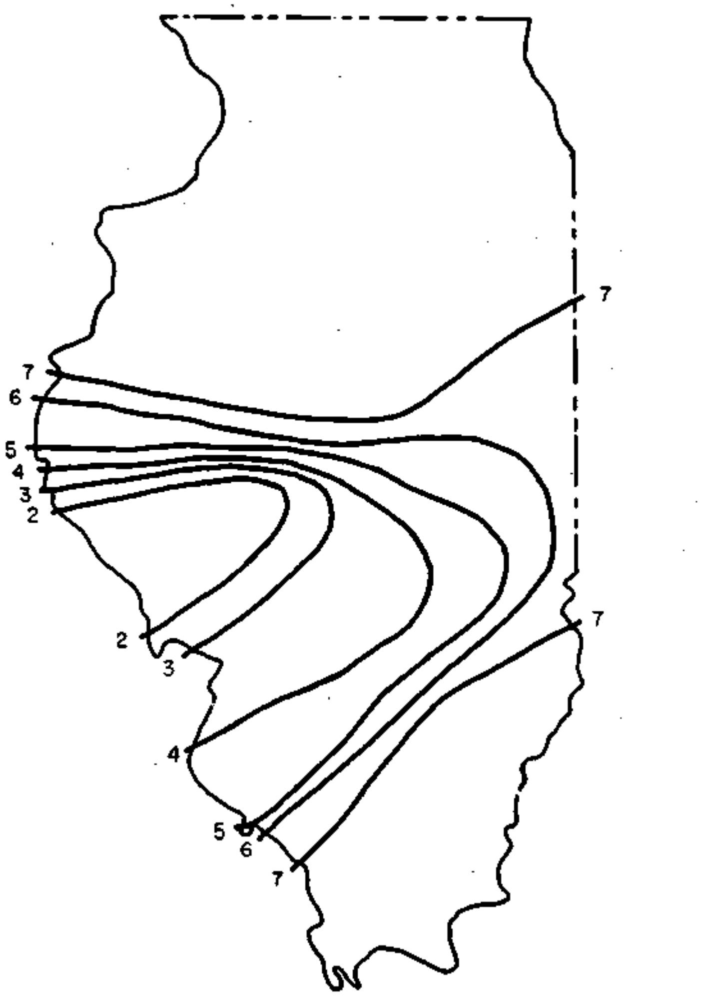


FIGURE 17. RUNOFF IN INCHES - 30 MONTHS ENDING. DECEMBER 1954.

Period of Record. The period chosen for use was the longest for which records were available in the area and generally covered the 41 years, 1914 to 1955. Some of the streamflow data were available beginning in 1908, and some did not begin until as late as 1921. The specific periods used for the determinations of frequency are given elsewhere, but there may be question as to whether the period 1914to 1955 was a representative sample in time.

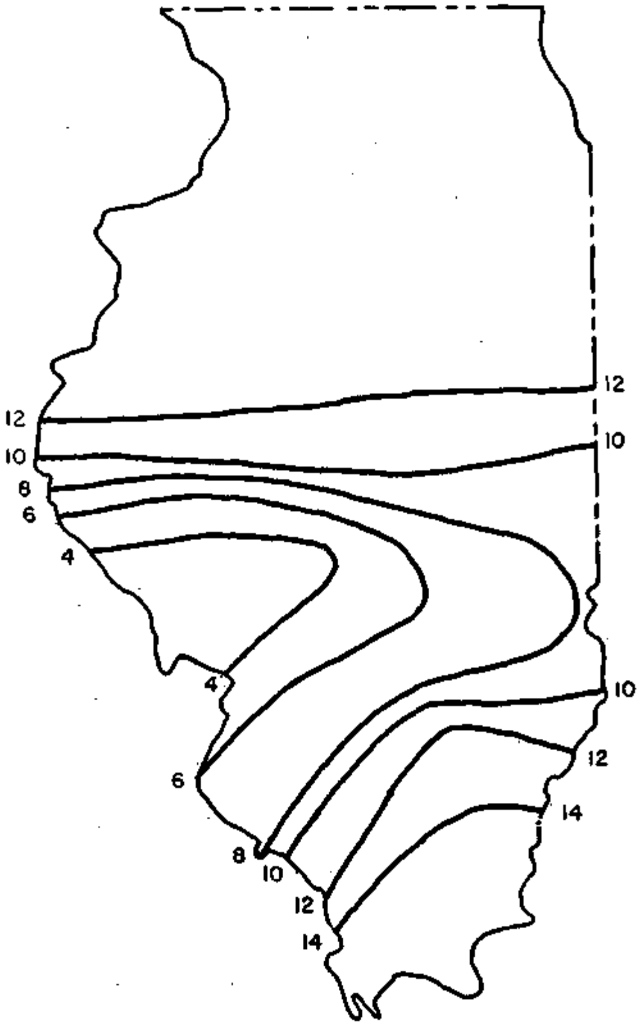


FIGURE 18. RUNOFF IN INCHES - 36 MONTHS ENDING APRIL 1955.

Rainfall data were available from 1906 at four of the five stations studied. A determination of frequency of low-rainfall periods by methods described below for Springfield, Quincy, Olney, Mt. Vernon, and Urbana, indicated that the values of rainfall for the 48-year period 1906-54 checked within 4 per cent those for a 40-year period of 1914-54 for 20-to 40-year frequencies.

The longest rainfall record available in the area was that for St. Louis, Missouri, which extends from 1837 to the present. Frequency determination based on 12- and 24-month low rainfall periods for the St. Louis gage indicated that the period 1914-54. generally gave values of rainfall 5 to 10 per cent lower than those for corresponding recurrence intervals for the period 1837 to 1954. Accordingly an attempt was made to check the St. Louis rainfall record against other long-time records by double-mass correlations. The nearest stations having records of comparable length were those for Cincinnati and Portsmouth, Ohio. Double-mass correlations of these stations against the St. Louis record, and against each other, indicated changes in slope attributable to the St. Louis record in the years 1845 and 1860, and the data indicate that the rainfall values recorded for St. Louis between these years may have been as much as 20 per cent too high. It was felt that it would be necessary to make an investigation of locational factors at all three stations, with special attention paid to changes in the St. Louis gage at about 1845 and 1860. Adjustment of high values for St. Louis would have brought the frequency determinations for the period 1837-1954 into closer comparison with the period 1914-54. Since it was not possible to study the representativeness of the period more completely without study of the histories of the St. Louis, Cincinnati, and Portsmouth gages, it was decided to treat the data available as though the period of record from 1906 to 1955 was a representative period.

Computing Sliding Totals. Stations chosen from intensive drought-frequency study were Big Muddy River at Plumfield, LaMoine River at Ripley, Little Wabash at Wilcox, Macoupin Creek at Kane, and Sangamon River at Monticello. These five gave reasonably good geographic coverage of the drought area and had periods of record of 34 to 45 years (See Table 4). Published runoff data are available for all of these stations from their inception to September 30, 1953. Provisional data were used for the period October 1, 1953 through May 1955. From these data, recorded as inches of runoff per month, sliding totals were computed for periods of 6, 12, 18, 24, 30, 36, 48, and 60-month duration for each of the five streams.

Rainfall data from five United States Weather BureauCooperative rain-gaging stations were similarly tabulated and sliding totals prepared for the 12- and 24-month periods. The rainfall stations used for the study were: Effingham, Mount Vernon, Olney, Springfield, and St. Louis. All but Effingham were for the period 1906-1955. The Effingham data were for 1918-55. In addition to the 12- and 24-month totals, 6, 18, 30 and 36-month totals were prepared from the St. Louis data.

In the preparation of this study, thought was given to the propriety of arraying all of the n-month totals of runoff, for determination of frequency. It appeared to the writers that this would be subject to possible error since many of the extreme values are related to each other. It was concluded that each drought or low-flow period is a separate event, properly characterized by the lowest n-month total, and that the inclusion in the array of other totals occurring within the most extreme "n" months would produce misleading probability determinations. This does not agree with the approach taken by others, notably Thompson(43) . To carry the writers' conclusion in this regard into effect, particular pains were taken to establish procedures thatwould make each extreme value independent of all others.

From each table of sliding totals, the lowest values were selected. The procedure used in making these selections was designed to eliminate dependence between values used. The procedure was as follows: First, the lowest value for the entire period of record was determined by scanning, and marked. Adjacent values prior to and following the chosen value were then "lined out" for a number of months equal to the duration period under study, less one month. This procedure manually cancelled these values from further consideration. The nextlowest value was then determined by scanning, and adjacent values similarly excluded. This procedure was continued until a number of values approximately equal to one-half of the period of

Table 9

12-MONTHS RUNNING TOTALS OF RUNOFF IN INCHES

Little Wabash River At Wilcox, Illinois

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
1915							7.74 16	~~10.91~~	~~11.11~~	~~11.03~~	~~11.22~~	~~12.30~~
16	~~15.95~~	~~15.77~~	~~16.02~~	~~16.15~~	~~15.26~~	~~14.19~~	~~12.63~~	~~9.61~~	~~9.32~~	~~9.27~~	~~9.08~~	~~8.03~~
17	~~5.14~~	3.25 6	~~3.46~~	~~4.52~~	~~6.30~~	~~7.81~~	~~7.83~~	~~7.74~~	~~7.74~~	~~7.77~~	~~7.82~~	~~7.71~~
18	~~6.80~~	~~8.01~~	~~7.63~~	~~8.68~~	~~8.98~~	6.87 15	~~7.48~~	~~7.56~~	~~9.01~~	~~9.11~~	~~9.37~~	~~13.03~~
19	~~12.63~~	~~11.97~~	~~13.14~~	~~10.98~~	~~9.69~~	~~10.88~~	~~10.56~~	~~10.42~~	8.97 20	~~9.63~~	~~11.77~~	~~10.48~~
1920	~~10.02~~	~~10.80~~	~~11.99~~	~~13.34~~	~~14.22~~	~~13.11~~	~~12.91~~	~~13.18~~	~~13.40~~	~~12.62~~	~~10.18~~	~~8.07~~
21	~~9.53~~	~~8.60~~	~~7.92~~	~~7.33~~	~~5.80~~	~~5.63~~	~~5.49~~	5.44 11	~~5.48~~	~~5.59~~	~~6.48~~	~~7.57~~
22	~~7.14~~	~~6.99~~	~~7.46~~	~~10.55~~	~~10.61~~	~~10.63~~	~~10.70~~	~~10.46~~	~~10.19~~	~~10.07~~	~~9.17~~	~~7.99~~
23	~~8.03~~	~~8.25~~	~~8.34~~	5.43 10	~~6.17~~	~~6.52~~	~~6.61~~	~~7.27~~	~~7.42~~	~~7.65~~	~~7.83~~	~~9.81~~
24	~~10.32~~	~~11.20~~	~~9.55~~	~~9.28~~	9.20 21	~~10.35~~	~~10.23~~	~~11.78~~	~~9.83~~	~~9.62~~	~~9.51~~	~~8.49~~
25	~~7.97~~	~~7.35~~	~~6.49~~	~~5.80~~	~~4.83~~	~~3.45~~	~~3.46~~	~~3.29~~	3.10 5	~~3.14~~	~~3.79~~	~~4.32~~
26	~~3.66~~	~~4.30~~	~~5.73~~	~~7.56~~	~~7.60~~	~~7.43~~	~~7.39~~	~~7.41~~	8.34 17	~~9.84~~	~~10.31~~	~~10.08~~
27	~~11.58~~	~~11.55~~	~~12.48~~	~~13.42~~	~~15.42~~	~~16.71~~	~~16.75~~	~~17.04~~	~~16.24~~	~~16.00~~	15.10 30	~~17.72~~
28	~~17.02~~	~~17.85~~	~~16.27~~	~~14.36~~	~~13.71~~	~~13.07~~	~~13.30~~	~~13.35~~	~~13.24~~	~~12.21~~	~~12.31~~	~~10.61~~
29	~~11.44~~	9.68 22	~~10.71~~	~~12.07~~	~~15.40~~	~~14.94~~	~~15.09~~	~~14.87~~	~~14.86~~	~~14.61~~	~~14.53~~	~~14.90~~
1930	~~16.70~~	~~17.61~~	~~16.41~~	14.51 29	~~10.83~~	~~9.61~~	~~9.14~~	~~8.95~~	~~9.30~~	~~9.30~~	~~9.00~~	~~7.34~~
31	~~3.31~~	~~1.94~~	~~1.79~~	1.49 9	~~1.54~~	~~1.57~~	~~1.79~~	~~1.95~~	~~2.36~~	~~2.48~~	~~3.59~~	~~5.38~~
32	~~10.29~~	~~10.70~~	~~10.33~~	~~10.35~~	~~10.30~~	~~10.59~~	~~10.43~~	~~10.38~~	~~9.96~~	~~9.83~~	~~9.27~~	~~8.45~~
33	6.42 13	~~6.55~~	~~9.62~~	~~12.26~~	~~16.49~~	~~14.28~~	~~16.23~~	~~16.19~~	~~15.90~~	~~15.88~~	~~15.32~~	~~14.28~~
34	~~11.43~~	~~10.78~~	~~7.93~~	~~5.56~~	~~1.29~~	1.21 2	~~1.63~~	~~2.11~~	~~2.41~~	~~2.64~~	~~4.41~~	~~5.51~~
35	~~7.33~~	~~7.79~~	~~10.27~~	~~10.42~~	~~14.88~~	~~15.21~~	~~14.95~~	14.41 28	~~14.05~~	~~13.81~~	~~12.39~~	~~11.37~~
36	~~9.80~~	~~10.46~~	~~3.02~~	~~9.04~~	~~4.74~~	~~4.38~~	~~4.23~~	4.22 9	~~4.23~~	~~4.25~~	~~4.49~~	~~4.46~~
37	~~8.62~~	~~9.39~~	~~8.62~~	~~9.20~~	~~10.72~~	~~11.15~~	~~11.23~~	~~11.28~~	~~11.29~~	~~11.50~~	~~10.93~~	~~11.92~~
38	~~7.66~~	6.66 14	~~9.55~~	~~11.90~~	~~10.76~~	~~10.62~~	~~11.27~~	~~11.42~~	~~11.46~~	~~11.22~~	~~11.33~~	~~9.38~~
39	~~10.61~~	~~13.14~~	~~11.03~~	10.06 24	~~9.61~~	~~10.14~~	~~9.47~~	~~9.82~~	~~9.78~~	~~9.78~~	~~9.65~~	~~9.56~~
1940	~~9.20~~	~~7.09~~	~~5.00~~	4.01 8	~~4.90~~	~~4.22~~	~~4.14~~	~~3.61~~	~~3.60~~	~~3.63~~	~~3.68~~	~~3.81~~
41	~~3.92~~	~~3.67~~	~~3.34~~	~~2.46~~	1.54 4	~~2.08~~	~~2.12~~	~~2.13~~	~~2.18~~	~~2.43~~	~~3.87~~	~~4.07~~
42	~~4.13~~	~~6.34~~	~~8.37~~	~~9.11~~	~~9.42~~	~~10.03~~	~~12.30~~	~~12.50~~	~~12.46~~	~~13.19~~	~~11.72~~	~~12.15~~
43	~~12.30~~	~~10.69~~	~~9.51~~	8.82 18	~~18.75~~	~~16.90~~	~~15.58~~	~~15.44~~	~~15.43~~	~~15.43~~	~~15.43~~	~~13.67~~
44	~~13.35~~	~~12.94~~	~~12.67~~	~~15.65~~	~~5.74~~	~~5.79~~	5.61 12	~~5.71~~	~~5.80~~	~~5.80~~	~~5.77~~	~~5.77~~
45	~~5.84~~	~~5.96~~	~~10.01~~	~~11.11~~	~~12.41~~	~~16.22~~	~~16.73~~	16.73 31	~~17.05~~	~~17.71~~	~~18.37~~	~~19.12~~
46	~~20.64~~	~~22.74~~	~~18.76~~	~~14.04~~	~~17.69~~	~~14.13~~	~~13.82~~	~~14.11~~	~~13.72~~	13.10 25	~~13.46~~	~~13.57~~
47	~~13.24~~	~~11.83~~	~~11.35~~	~~13.74~~	~~9.93~~	~~10.01~~	~~10.25~~	~~9.94~~	~~10.21~~	~~10.42~~	~~9.60~~	8.90 19
48	~~9.70~~	~~9.79~~	~~12.63~~	~~11.82~~	~~10.95~~	~~10.61~~	~~11.06~~	~~11.04~~	~~10.80~~	~~10.63~~	~~12.16~~	13.11 26
49	~~18.06~~	~~19.40~~	~~18.13~~	~~17.12~~	~~16.77~~	~~16.86~~	~~16.42~~	~~16.42~~	~~16.53~~	~~18.63~~	~~16.99~~	18.10 32
1950	~~20.24~~	~~22.24~~	~~22.25~~	~~23.28~~	~~23.40~~	~~24.24~~	~~24.27~~	~~24.28~~	~~24.50~~	~~22.36~~	~~22.98~~	~~21.57~~
51	~~14.35~~	13.65 27	~~14.03~~	~~13.81~~	~~13.50~~	~~12.47~~	~~12.77~~	~~12.72~~	~~12.42~~	~~12.51~~	~~12.64~~	~~12.72~~
52	~~12.17~~	9.69 23	~~10.58~~	~~11.48~~	~~11.44~~	~~11.78~~	~~11.07~~	~~11.04~~	~~10.98~~	~~10.84~~	~~10.00~~	~~9.13~~
53	~~7.73~~	~~6.40~~	~~5.04~~	~~3.46~~	~~3.99~~	3.46 7	3.46	~~3.45~~	~~3.44~~	~~3.44~~	~~3.43~~	~~3.40~~
54	~~3.38~~	~~3.32~~	~~1.71~~	~~0.97~~	~~0.37~~	~~0.29~~	0.24 1	~~0.26~~	~~0.43~~	~~0.61~~	~~0.62~~	~~0.75~~
55	~~1.02~~	~~2.38~~	~~3.42~~	~~3.60~~	~~3.78~~	~~4.30~~						

record divided by the duration period (expressed in years) was obtained. Choice of this number of values was arbitrary, and yielded sufficient terms to define the frequency curves satisfactorily. The values thus selected were then arrayed in order of magnitude.

The procedure used is illustrated in Table 9, which shows the 12-month sliding totals for the Little Wabash River at Wilcox for the period 1914-1954. Inspection of the data in Table 9 revealed that the 12-month period of lowest flow occurred for the period ending with July 1954. Accordingly the 11 values preceding and succeeding this month were ruled out as shown and the critical value was marked with the rank number "1". Next-lowest value in the table was found to occur in June 1934, and a similar procedure of exclusion was followed. This procedure was repeated until values exceeding the mean streamflow were reached. In the earlier stages of the work, it was attempted to commence at one end of the table and work toward the other, but it was found that this resulted occasionally in the choice of less extreme values and allowed some subjective error. Therefore the procedure of choosing successively the most extreme remaining values was adopted.

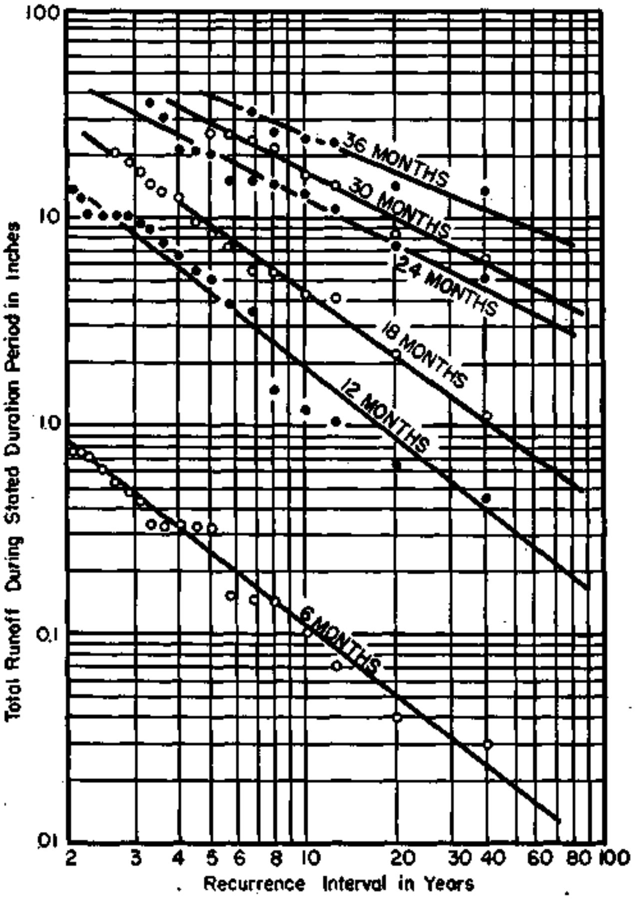


FIGURE 19. FREQUENCY OF LOW FLOW OF VARIOUS DURATIONS. Big Muddy at Plumfield.

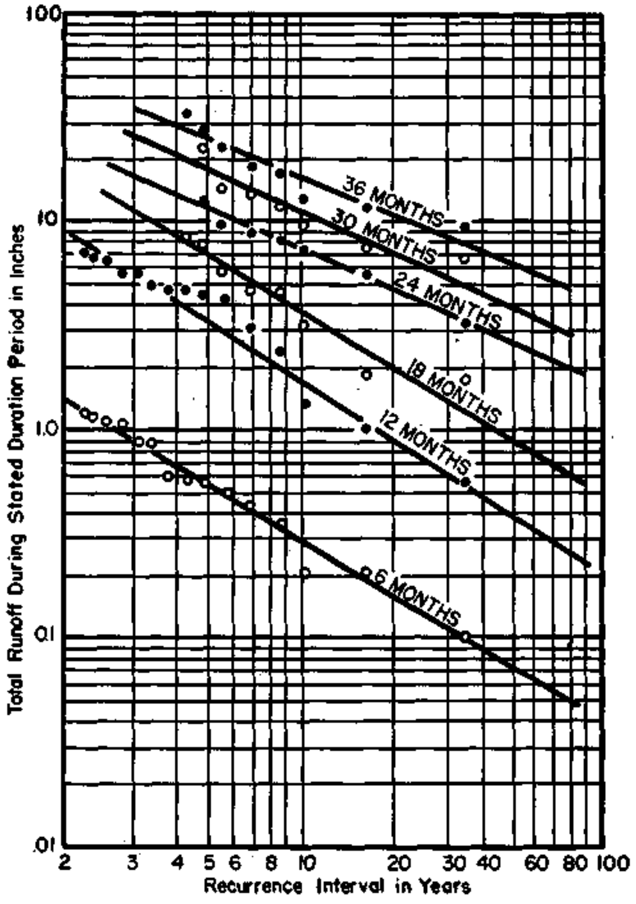


FIGURE 20. FREQUENCY OF LOW FLOWS OF VARIOUS DURATIONS. LaMoine River at Ripley.

After the manual computation and arraying described above was completed, monthly runoff values on key-punch cards became available. The use of the key-punch cards for this operation greatly speeded the work, but was subject to some limitations. For the conduct of the operation by punch cards, it was found most convenient to program the sorting operation so that it produced a deck of cards containing the sliding totals for the duration period under study. These were then arrayed in order of magnitude by machine sorting, the rank numbers were punched on the cards, the cards then re-sorted into chronologic order, and a printed tabulation of the sliding totals and rank numbers was prepared. No mechanical method for screening the values for independence was found, and it was necessary to choose values by inspection. For the determination of rank numbers out of each series of nearly 500 values, only the most extreme 100 values were arrayed and rank numbers printed. This procedure reduced the scanning required.

<u>Plotting Positions.</u> Study was given to the determination of plotting position. Methods have been proposed by Allen Hazen(17), E. J. Gumbel(18), C.S. Jarvis, et al(19) and others. The "California" method(20) was used as being the simplest and

apparently as meritorious as any of the others. With this method, the recurrence interval (R) is expressed as follows:

$$R = \frac{T}{m}$$

in which T is the length of record in years, and m is the rank number of the event when the events are arrayed in order of magnitude. For a 40-year record, the extreme event therefore would have a recurrence interval of 40 years, the second event - 20 years, the third - 13.33 years, etc.

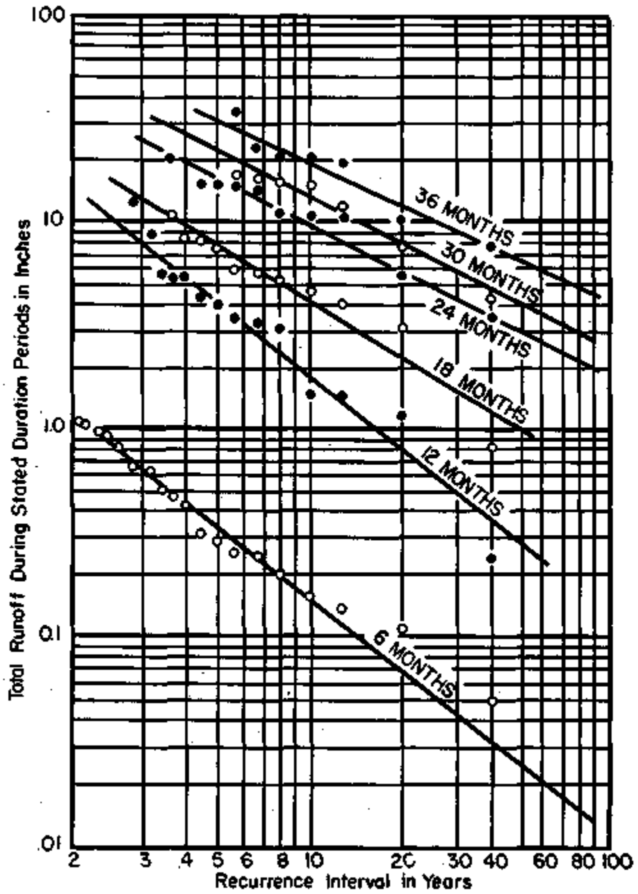


FIGURE 21. FREQUENCY OF LOW FLOWS OF VARIOUS DURATIONS. Little Wabash at Wilcox.

Stating the recurrence interval in years does not imply that an event having a recurrence interval of "R" years will happen every "R" years. It means instead that, in a period of time of length "n" much longer than "R", such an event would be expected to happen $\frac{n}{R}$ times. Thus a period of low steamflow having a recurrence interval of 100 years would be expected to be equalled or exceeded (in duration) 10 times in 1000 years. Obviously any estimates of recurrence interval values that are greater than the length of the period of record are extrapolated and must be regarded as approximations.

In the last few years advanced methods for analysis of probability of extreme events have been developed. Chow(21) has observed that, in many cases, hydrologic data follow a log-probability law, under which the logarithms of hydrologic events are found to correlate well against frequency parameters. Gumbel has also made use of the logarithms of hydrologic events in studying drought probabilities(22) . Gumbel had not, however used a general definition of drought. He considered a drought to be the day of minimum discharge for a stream. Apart from the work of Hazen(17) (23), little published work is known in the field of low-flow duration.

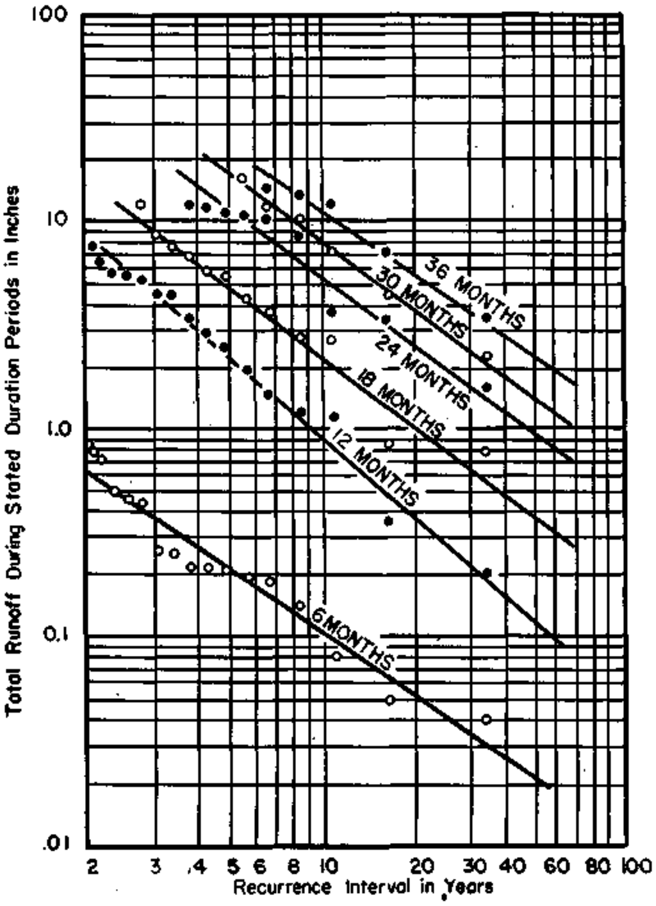


FIGURE 22. FREQUENCY OF LOW FLOW OF VARIOUS DURATION. Macoupin Creek at Kane.

Graphic Determination of Frequency and Duration of Low Flows. Preliminary graphical analyses were made by several different methods. The hydrologic data were plotted on arithmetic extreme-probability paper, and showed pronounced curvature. Curvilinear relationships were also noted in semi-logarithmic and logarithmic plots. Good approximations of straight lines appeared to occur when the extreme-probability paper designed by Gumbel was used in conjunction with logarithms of hydrologic data. The data for the five stream-gaging stations analyzed in this study are shown on extreme probability-logarithmic graphs in Figures 19 to 23. Each figure shows the data for six of the eight duration times considered. The 48- and 60-month data were omitted from these graphs but are presented in a subsequent figure.

Close examination of the data in Figures 19-23 indicates that, for any given recurrence interval, there are noticeable differences between runoff values for the 5 basins which may be related to drainage area, climatic differences, groundwater conditions, or other hydrologic data.

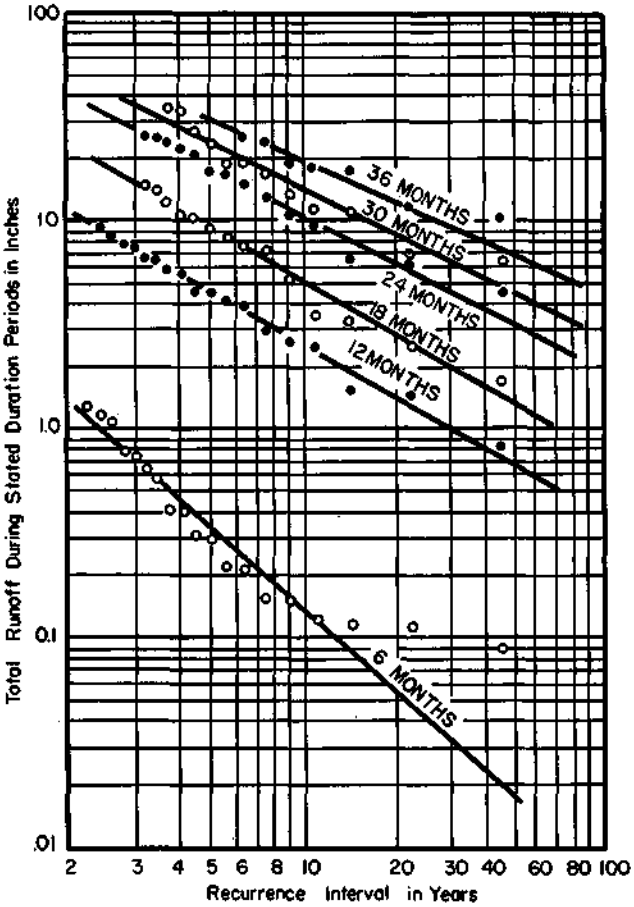


FIGURE 23. FREQUENCY OF LOW FLOW OF VARIOUS DURATIONS. Sangamon River at Monticello.

Families of curves for the various duration periods were drawn by eye in Figures 19-23. Since no systematic curvature was indicated by the data, all were drawn as straight lines. It will be noted that the curves for 12, 24, and 36 months appear to form a reasonable series for each station, but that the curves for 6, 18, and 30 months do not seem to correspond to such a series. Instead of drawing all the curves in each figure as members of one family, it was assumed, in drawing Figures 19 to 23, that the curves for 6, 18, and 30 months could comprise a separate series from the remaining curves, since the 6, 18, and 30 months' curves cover fractional parts of the annual hydrologic cycles. The appearance of these separate families of curves deserves further study; it is not considered that the data conclusively establish the presence of systematic differences, however seasonal variances suggest that such differences might be expected.

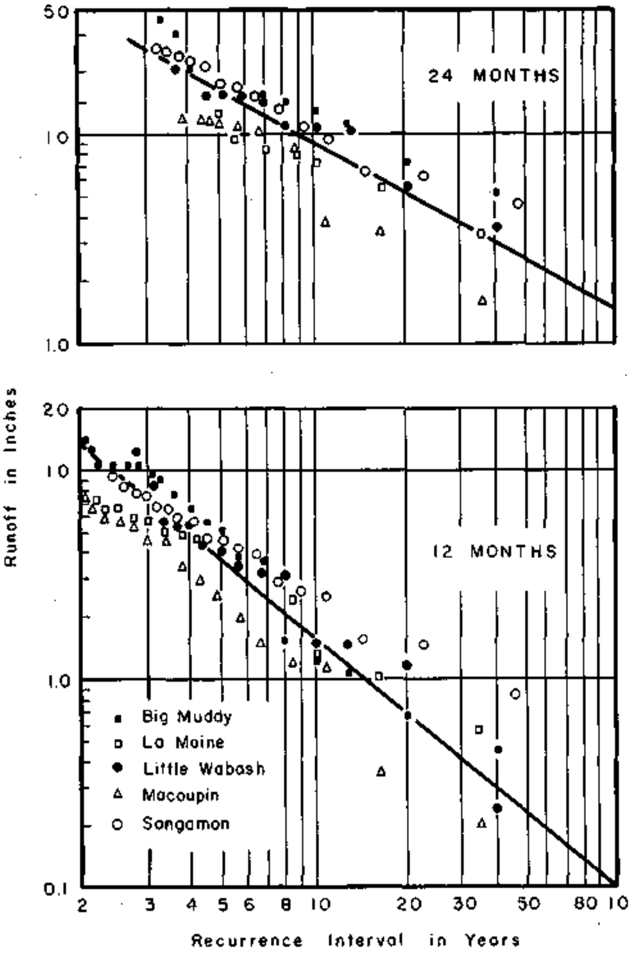


FIGURE 24. LOW FLOW FREQUENCY DATA CONSOLIDATED ON BASIS OF FLOWIN INCHES.

It should be evident that, in a record of 30 to 45 years' duration, very few low-flow periods of three-to-five year duration will occur. Because of this, it is felt that the estimates of recurrence interval for low-flow periods of three years or more, are not altogether dependable. In some cases frequency curves had to be based on very few values. The situation is somewhat improved by consolidating the data from five stations on one graph, as in Figure 24 but it still appears possible that the straight lines drawn may not accurately represent probable frequencies over a very long period. If the period of record were in excess of 100 years, more reliance might be placed on these determinations.

Graphs were made of the runoff in inches versus recurrence interval for each duration period, combining the data from the five stations. These showed some scatter of the data (See Figure 24).

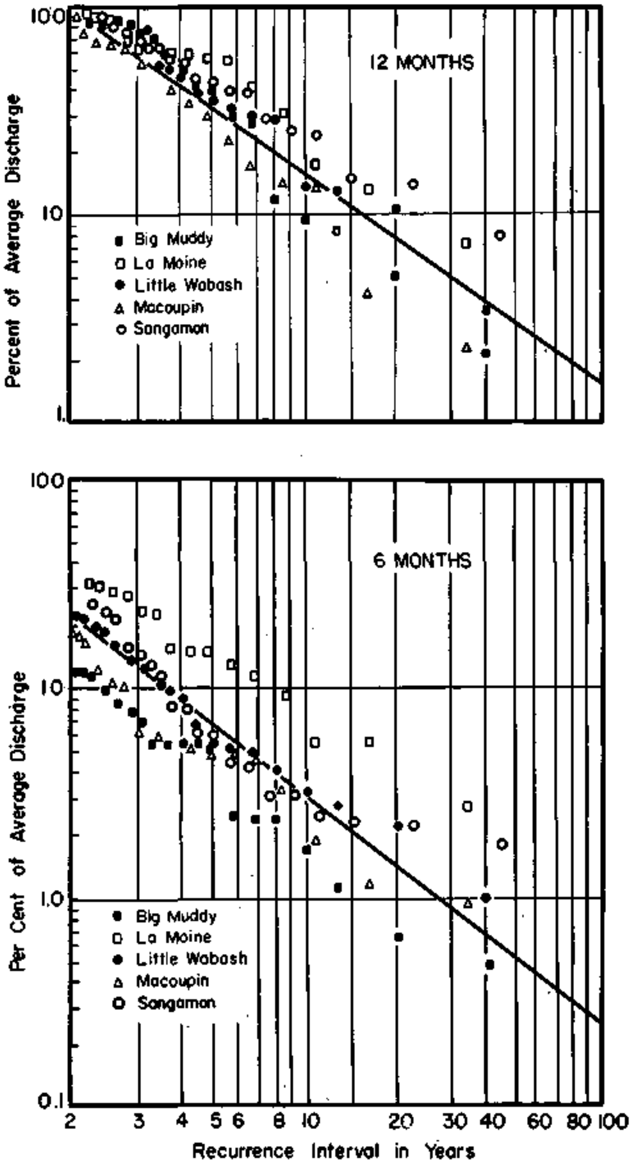


FIGURE 25. LOW-FLOW FREQUENCY DATA, CONSOLIDATED ON BASIS OF PER CENT OF AVERAGE FLOW. 6- and 12-Month Duration.

Seeking a better way of coordinating the data from the various stations, plottings were made of the per cent of average discharge rate versus recurrence interval. Average rate data are given in Table 4. These graphs showed better correlations of the data, especially for the more-numerous less-extreme events, than were obtained when the absolute amounts of runoffs were used. These unified plottings are shown in Figures 25-28.

Close inspection of the data in Figures 25-28 indicates that there may be significant differences in slopes of the lines for each particular station. For example, the slope of the 12-month curve (Fig. 25) which might be drawn for the Sangamon River appears to be smaller than that which might be drawn for Macoupin Creek. The differences between these lines may be due to sampling errors or they may be due to hydrologic differences between the areas gaged which cause differences in variability and in relative runoff between streams.

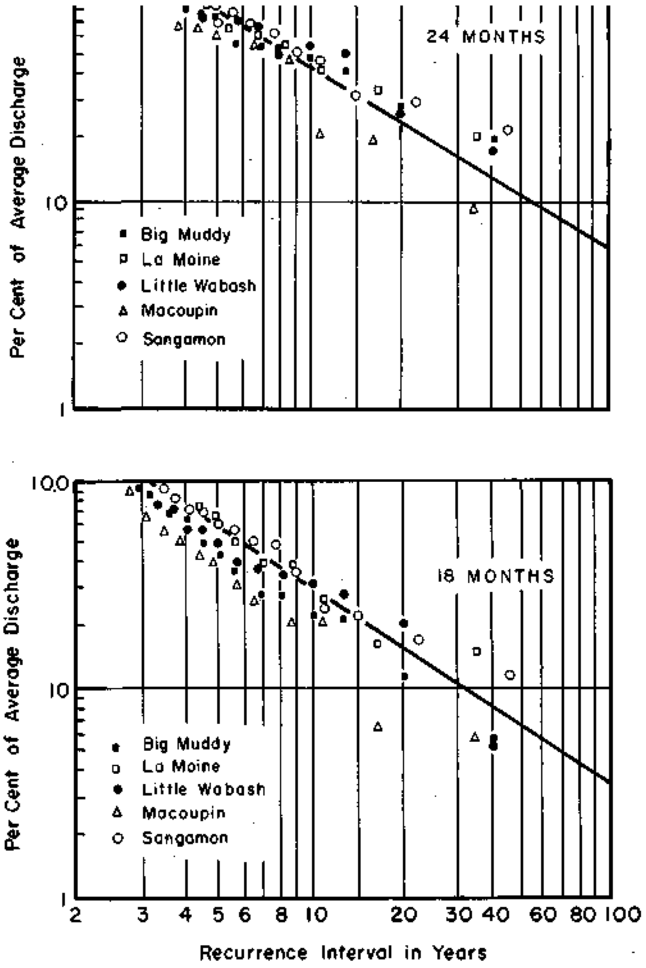


FIGURE 26. LOW-FLOW FREQUENCY DATA, CONSOLIDATED ON BASIS OF PER CENT OF AVERAGE FLOW. 18- and 24-Month Duration.

This topic deserves further study, but for the present (since the concordance of the data appears good) generalized estimates prepared on the basis of curves such as those shown in Figure 25 appear to produce serviceable values.

Because of possible significant differences in variability of flows from place to place, the caution is repeated that studies at any particular location should be founded on data from the immediate vicinity of the proposed development.

In order to verify further the consistency of the data obtained, a graph of the relationship between runoff (expressed in per cent of the annual streamflow) and the duration of the low-flow period was prepared, with a separate line for each of the following recurrence interval values: 4, 10, 20, 40 and 100 years. On this graph (Figure 29), using values from the lines sketched through the consolidated data in Figures 25 to 28, smooth curves through the various values were possible. In the initial preparation of the work drawing for Figure 29, some discrepancies in plotting positions for the long-duration low-flow period (30 to 60 months) were noted. By drawing smooth curves on Figure 29, and adjusting the lines shown in Figures 25 to 28, consistent results, in good accord with the basic data, were obtained in the placing of the lines in Figures 25 to 28.

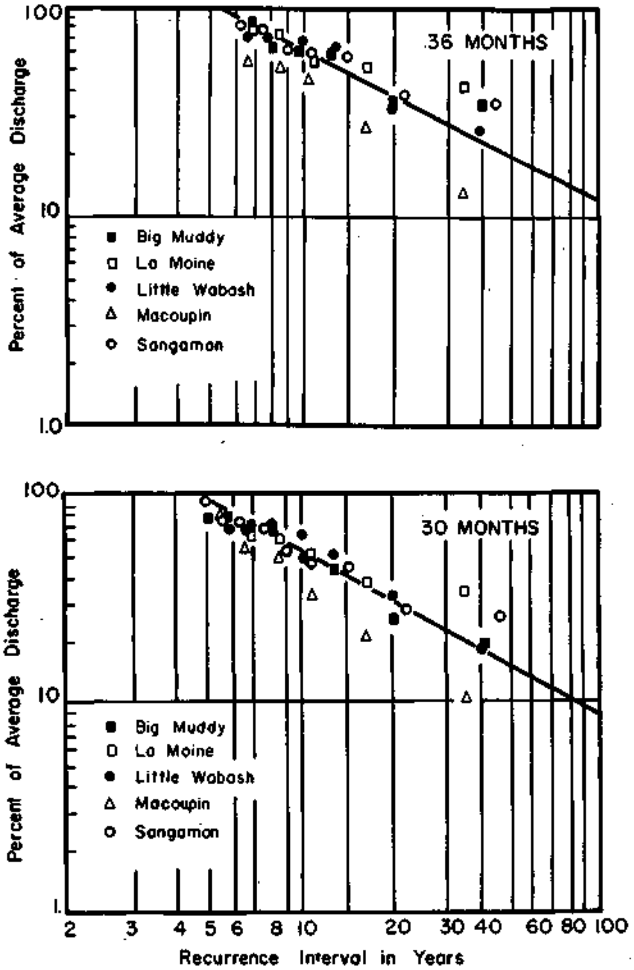


FIGURE 27. LOW-FLOW FREQUENCY DATA, CONSOLIDATED ON BASIS OF PER CENT OF AVERAGE FLOW.
30- and 36-Month Duration.

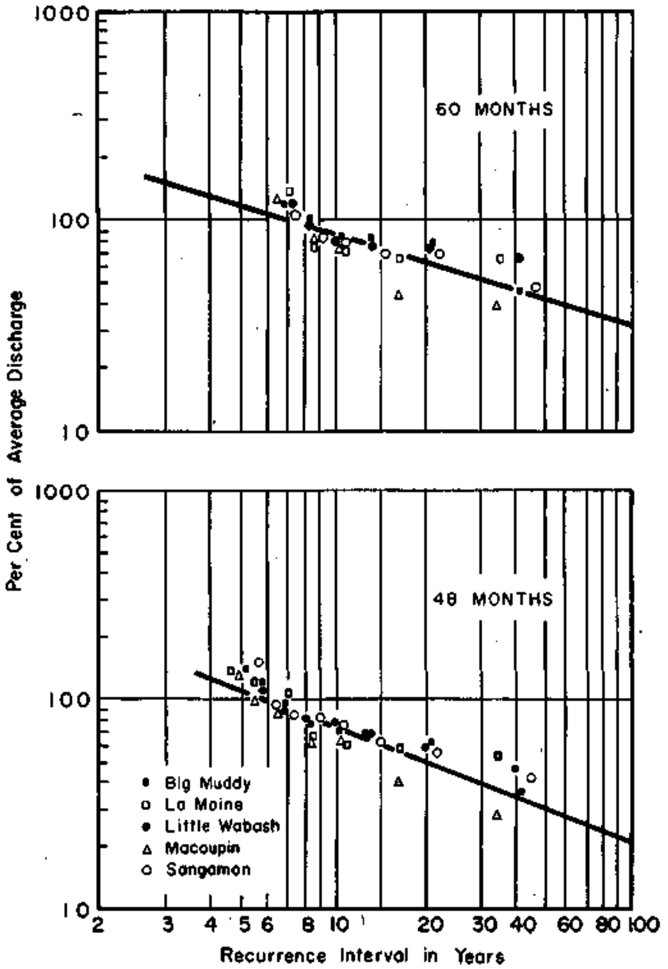


FIGURE 28. LOW-FLOW FREQUENCY DATA, CONSOLIDATED ON BASIS OF PER CENT OF AVERAGE FLOW.
48- and 60-Month Duration.

When the data for the five stream-gaging stations were consolidated in Figure 29 the tendency toward appearance of separate families of curves seemed to be lost. Seasonal variances might have been expected to cause the curves for various recurrence intervals in Figure 29 to be undulatory in accordance with the annual cycle. There was some indication of such behavior, but it is thought to be partially obscured by the fact that the duration periods chosen for study were in multiples of half-years. It is believed that study of low-flow duration periods of all lengths that are multiples of a quarter of a year or of one month, would reveal the effect of seasonal variations. Furthermore it is reasonable to expect that low-flow periods having durations slightly shorter than integral multiples of years, might indicate more adverse values than are shown in Figure 29. This would follow from the observation that the majority of periods of extreme low flow tend to commence in late spring. It appears that study along these lines is desirable, and might be expected to indicate departures from the results brought out by the present study.

Figure 29 includes an asymptote, which should be approached by the curves characterizing the data.

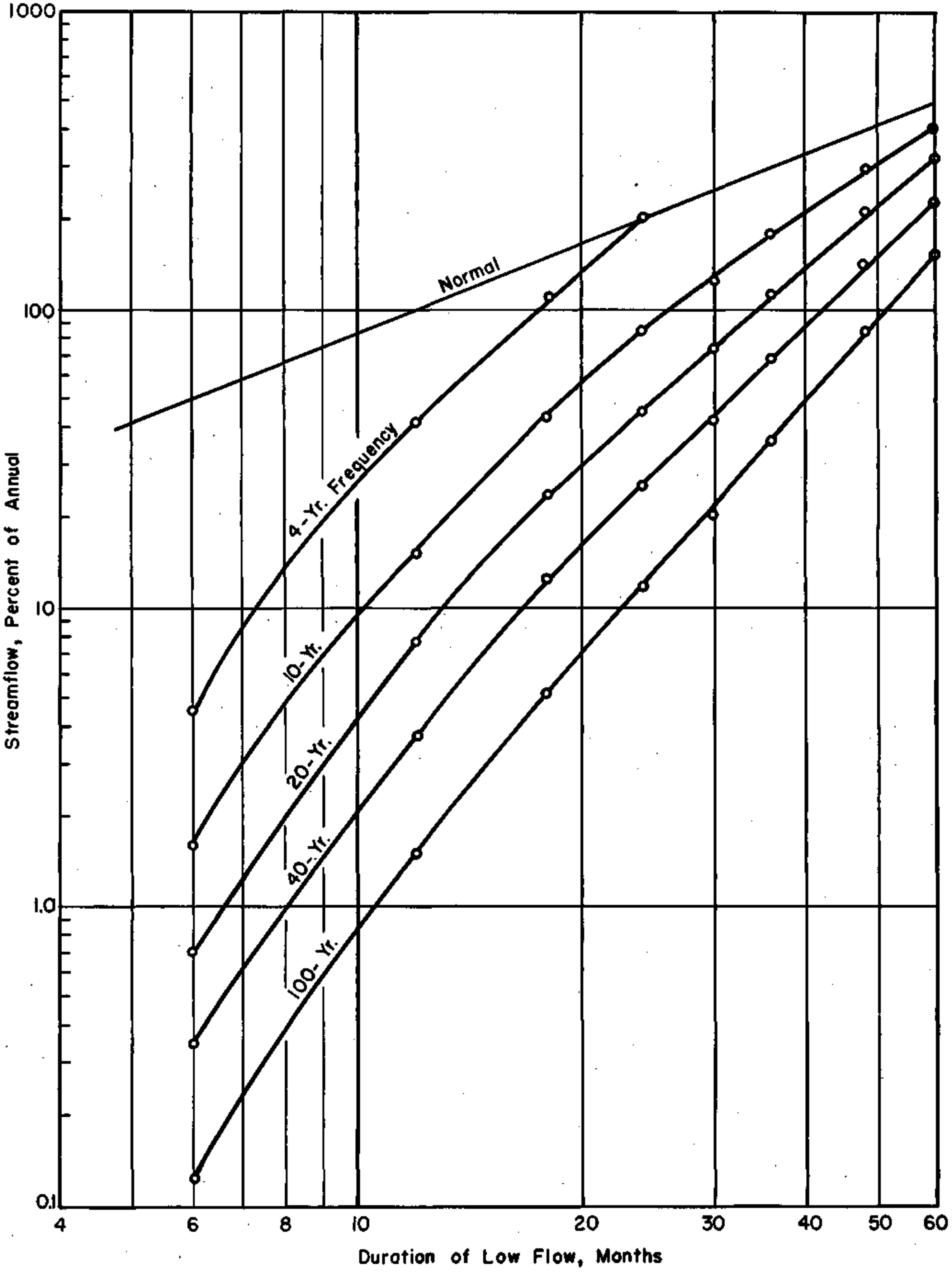


FIGURE 29. GENERALIZED RELATION BETWEEN DURATION AND FREQUENCY OF PERIODS OF LOW STREAMFLOW, SOUTHERN ILLINOIS.

This curve was constructed on the assumption that six months' flow would be 50 per cent of the annual average, that two years' flow would be 200 per cent of the average, etc. Some consideration was given to the points at which the curves for various recurrence intervals should approach the asymptote. It would appear that, in Figure 29, the 4-year recurrence interval curve should approach or join the asymptotic line at a value having an order of magnitude of approximately two years. The data bear this out. It would further appear that a 10-year recurrence interval curve should approach or intersect the asymptote at a value having an order of magnitude of approximately five years' duration. The data are in fair agreement with this concept.

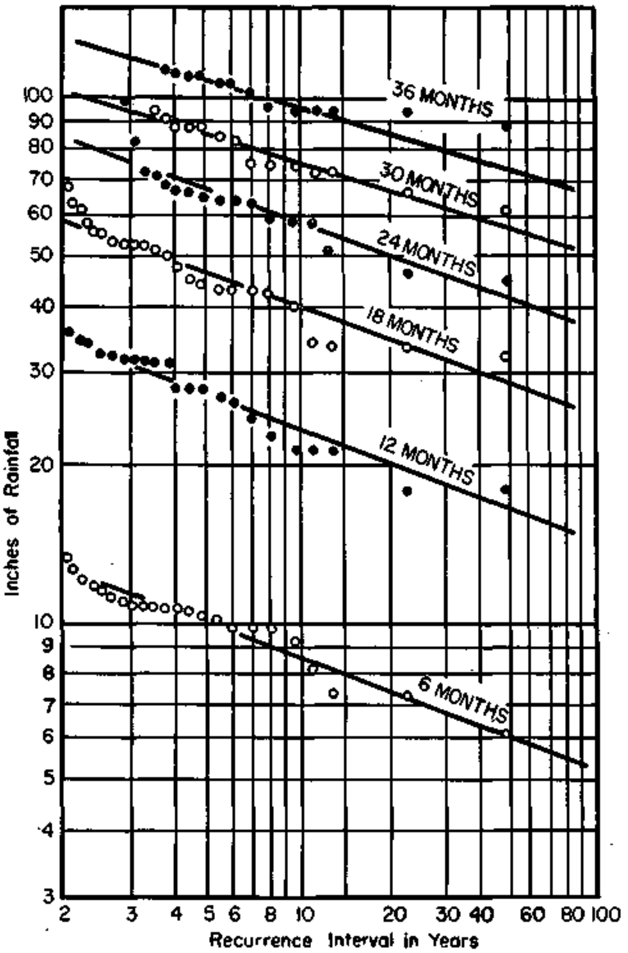


FIGURE 30. FREQUENCY OF PERIODS OF LOW PRECIPITATION, ST. LOUIS, MISSOURI.

It appeared that it might have been desirable to calculate streamflow values in per cent of median flow rather than in per cent of mean flow in order to enable more complete consideration of the data in Figure 29. However, analysis of the data showed the mean and median flows to agree quite well with the exception of those for six months duration, so the computations based on averages were retained.

In this report the approach used in working up the data on probability of low-flow periods of various durations has been empirical. Theoretical bases are available which indicate that relationships between frequencies for the periods of various lengths can be determined mathematically rather than empirically. A method for this has been suggested by Alexander(24) which makes use of the coefficient of variation for each stream, together with the mean flow for the stream. That there may be these differences is suggested by recent work of Mitchell (25) on floods in Illinois.

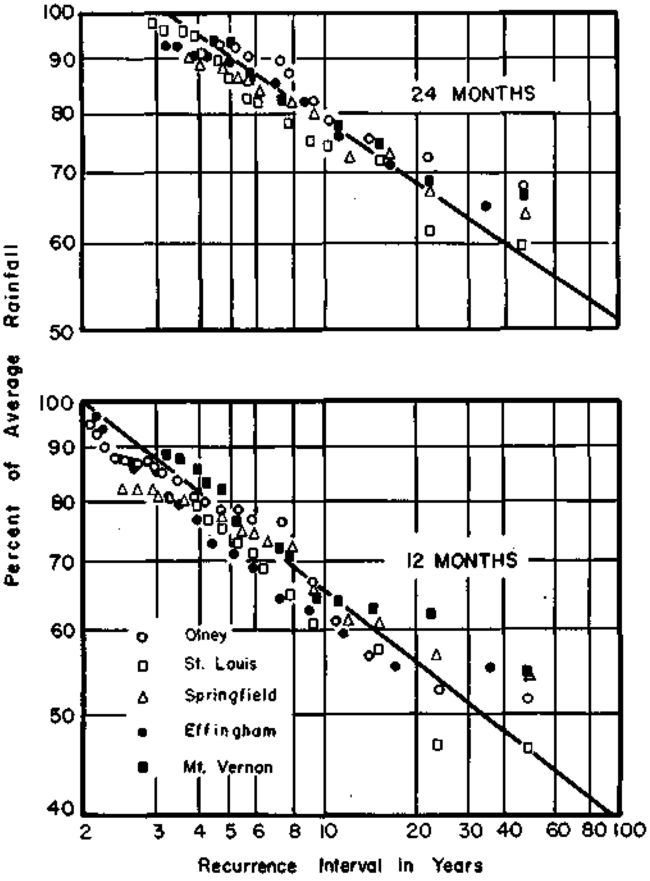


FIGURE 31. LOW RAINFALL FREQUENCY DATA CONSOLIDATED ON BASIS OF PER CENT OF NORMAL.

The mathematical approach might make use of conventional probability methods for determination of the recurrence interval (reciprocal probability) at which curves, such as those in Figure 25, intersect the value of mean flow. The slopes of the lines should be related to the coefficient of variation of the stream under study.

The problem is complicated by the persistent seasonal cyclic variance of both streamflow and rainfall so that simple solutions may possibly be found only for integral multiples of years. Others have dealt with this[17], [26] by separating the statistical approach into two components: annual storage and monthly storage. The former takes care of year-to-year variations and the latter is intended to take into account the seasonal variations. The desirability of this separation, may be questioned and there are reasons to believe that it will be necessary to consider annual and monthly storage together in some fashion, for they seem to be related. In this study, for example, extraordinary seasonal deviations from normal were observed during 1952-55. These seem to have been the result of the unusually low annual flows, rather than independent phenomena.

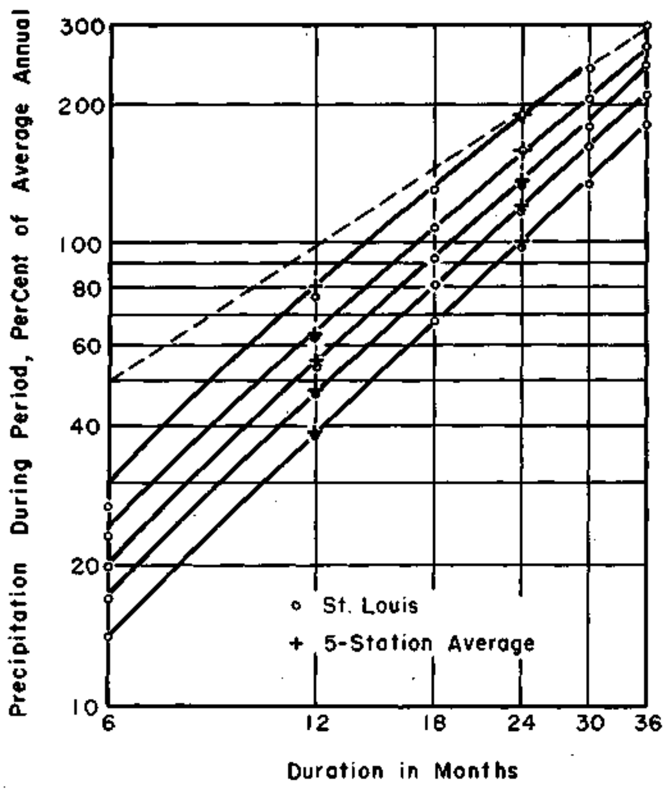


FIGURE 12. GENERALIZED RELATION BETWEEN DURATION AND FREQUENCY OF PERIODS OF LOW RAINFALL (SOUTHERN ILLINOIS).

To return to the possible application of a mathematical approach, Alexander's presentation indicates [24] that there should be a theoretical fixed relation betweenthe probability of occurrence of a one-year drought and those for droughts of other lengths. Assume for example a location for which the recurrence interval is 50 years (probability 0.02) for streamflow of one inch or less in 12 months. Flows lower than one inch could be considered "failures" and higher ones "successes." It would appear possible to calculate the probability of occurrence of flows equal to or smaller than one inch in 2, 3, or "n" successive years from Alexander's, presentation.

<u>Frequency of Periods of Low Rainfall.</u> A method similar to that used for streamflow data was used for unifying the data from the five rain-gaging stations, in which the per cent of normal rainfall was plotted against recurrence interval. Again the result was better than when absolute rainfall amounts were used. The data are shown in Figures 30 and 31.

As has been mentioned above, values of totals for 12- and 24-month duration periods were computed for the five rain-gaging stations, but 6, 18, 30, and 36 month totals were computed only for St. Louis. Average annual rainfall at St. Louis is 37.02 inches. These data have been brought together in Figure 32 (which is similar in construction to Figure 29) in which representative consolidated curves for the five-station rainfall average have been constructed for all periods from six months to 36 months.

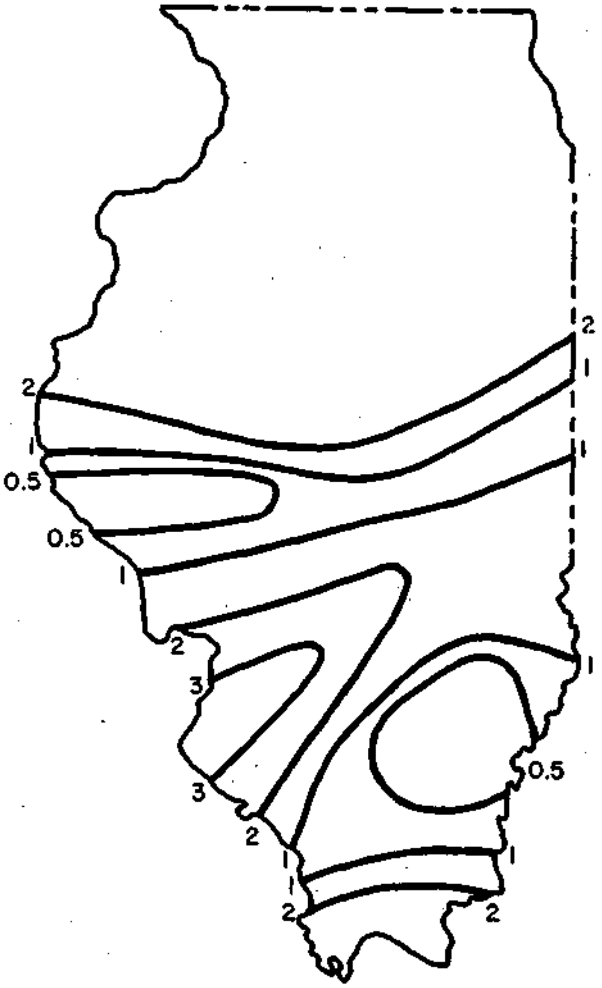


FIGURE 33. PER CENT OF NORMAL RUNOFF, 6 Months Ending January 1954.

The difference in slopes of curves noted for runoff do not seem present in the rainfall frequency consolidated curves.

It should be remembered that the data for the rain-gaging stations are point observations, while those for the stream-gaging stations are measurements that integrate the occurrence of runoff from the areas gaged.

Recurrence Interval of 1952-55 Drought

The data available for the 1952-55 drought enable estimation of the severity of the drought on a basis of rainfall and streamflow. The maps in Figures 13 to 18 show the distribution of runoff during extreme low periods. Since better correlation of the frequency data was obtained using "per cent of normal" as the basis of comparison than by using absolute runoff data, runoff maps for the extreme low periods were prepared showing these values in per cent of normal. These maps were constructed by an overlay procedure using Figure 6 and Figures 13-18 as the bases. The maps are presented as Figures 33 to 38 and no allowance was made for seasonal variations.

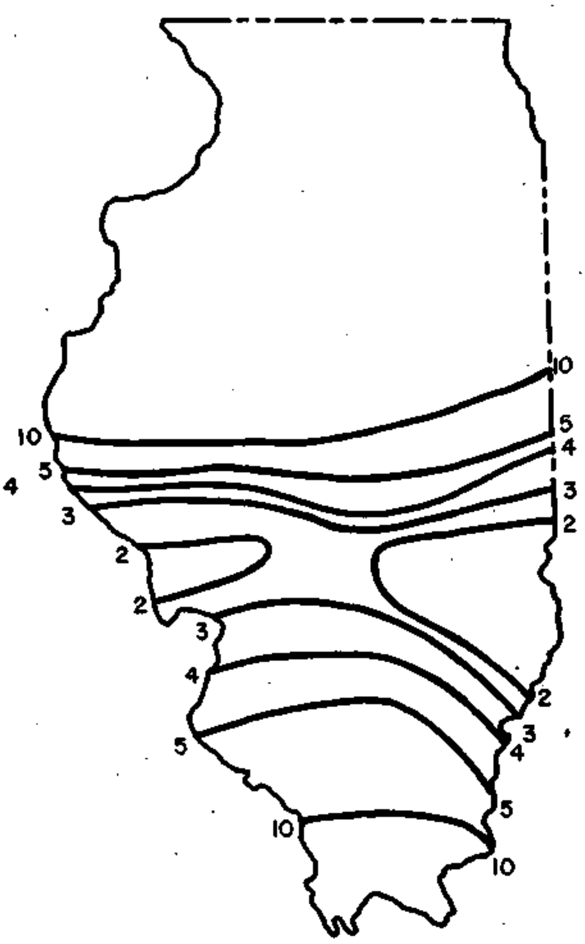


FIGURE 34. PER CENT OF NORMAL RUNOFF, 12 Months Ending December 1954.

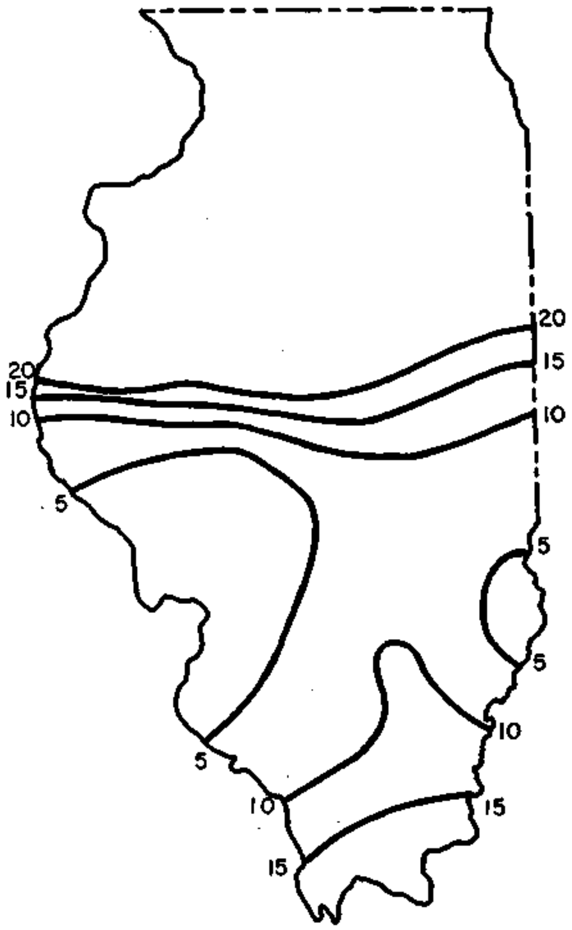


FIGURE 35. PER CENT OF NORMAL RUNOFF, 18 Months Ending December 1954.

The areas within contours and within the Illinois boundaries were planimetered. For purposes of analysis these data were plotted to produce runoff distribution curves from which values of runoff could be taken for areas of various sizes. (Figure 39.)

The consolidated streamflow frequency curves (Figures 25-28) are for drainage basins whose areas range from 550 to 1310 square miles, with a median value of 930 square miles. The frequency curves for the rainfall data (Figure 31) are for point measurements. Accordingly, to estimate the return frequency of the 1952-55 drought, it is necessary to use two different bases for entering the frequency curves. For the runoff frequency estimation, the value of runoff for a drainage area of 1000 square miles was taken off the curves in Figure 39. These, and the recurrence interval values for the 1000 square mile areas of lowest flow are given in Table 10.

Attention is called to the fact that 30-month streamflow was less than that for 24 months, when both were expressed as per cent of normal. This was not true of the actual amounts in inches. This reversal of order is believed due to seasonal effects which are discussed elsewhere in this report. Note that the 36-month period chosen was for the period ending April 1955. The 36-month totals rose in May, declined in June and rose again in July 1955, all hovering close to the April minimum. It was therefore not certain that the 3-year period ending with May 1955 was the lowest during the recent drought, but complete data for August were not available at this writing.

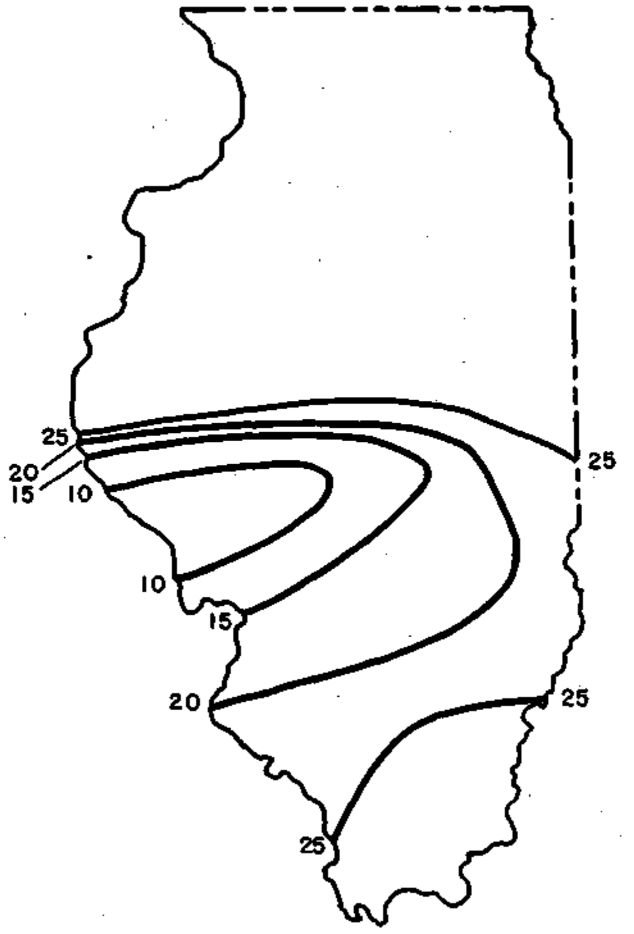


FIGURE 36. PER CENT OF NORMAL RUNOFF, 24 Months Ending December 1954.

For estimation of recurrence interval of the rainfall data, lowest point values for stations in the vicinity of the area of lowest streamflow were determined. In working these out, sliding totals for the individual rain-gaging stations in the area were prepared for 12- and 24-month periods. The lowest 12-month rainfall value found was for Grafton, 16.48 inches which gave 43.7 per cent of normal for the period ending July 1954. The lowest 24-month rainfall value found was for the period ending July 1954 at Grafton, where the rainfall for the two-year period was 39.80 inches or 52.7 per cent of normal. Using these rainfall values, and entering the curves in Figure 31, recurrence intervals for the 12- and 24-month periods of low rainfall were found to be 63 and 87 years respectively.

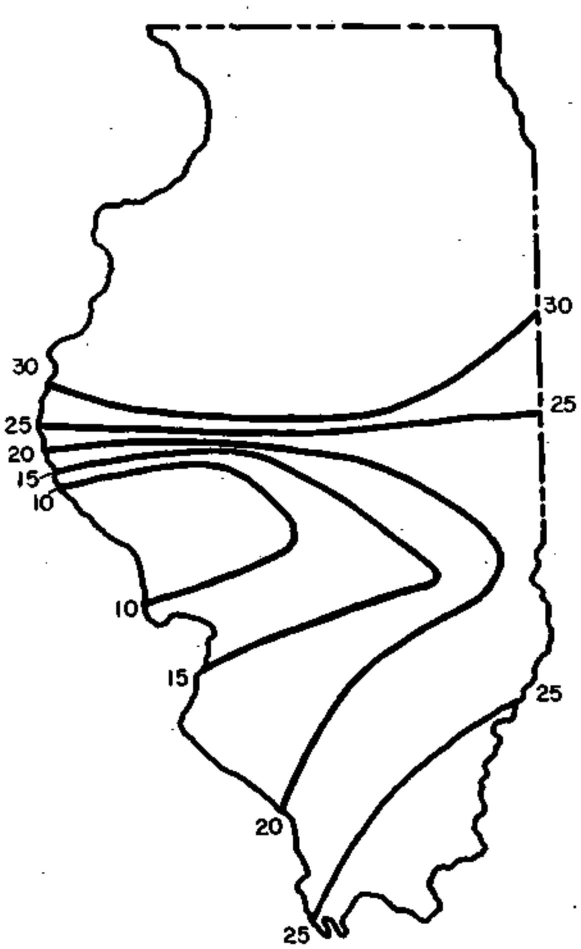


FIGURE 37. PER CENT OF NORMAL RUNOFF, 30 Months Ending December 1954.

Earlier trials of the determination of point rainfall values by the area-distribution graph method used for runoff had indicated that this method yielded recurrence interval values approximately half those obtained when the lowest point observation in the area of low rainfall was used. The use of the lowest point rainfall values obtained gave recurrence interval values that checked closely with those obtained for streamflow by the area-distribution graph method for 1000 square miles.

On the basis of point rainfall data for the period 1906-54 and streamflow data for 1914-54, the drought of 1952-55 appears to have been of a severity that would occur on the average of once in 60 to 100 years. On the basis of streamflow, the 3-year period ending June 1955 appears to have been a more unusual event than the worst periods of a two year or less duration occurring during the period. Estimates of recurrence interval based on streamflow ranged from 75 to more than 100 years.

Median value of the estimates of frequency of the 1952-55 drought gave a recurrence interval of 83 years.

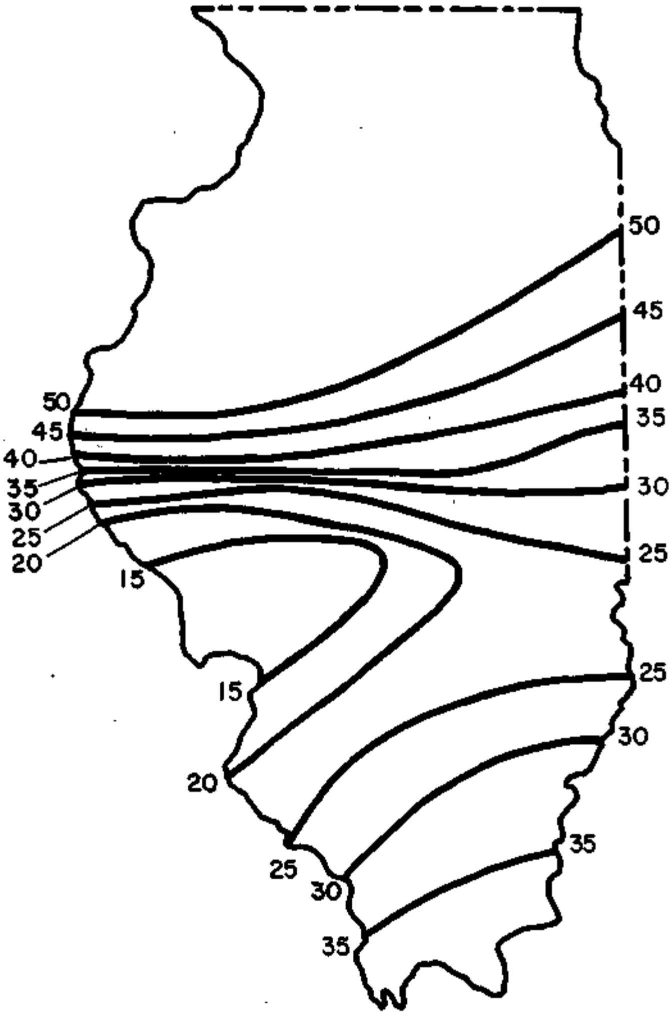


FIGURE 38. PER CENT OF NORMAL RUNOFF, 36 Months Ending April 1955.

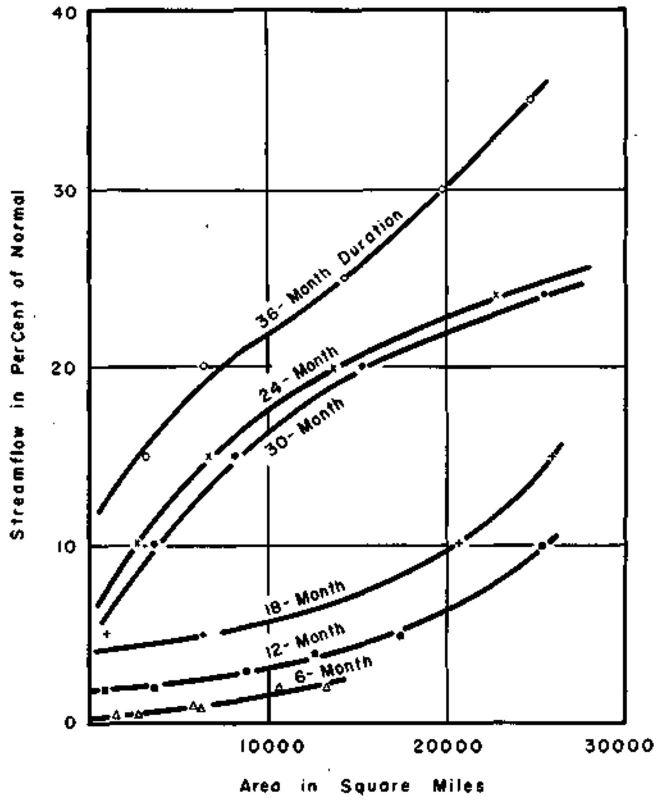


FIGURE 39. AREAL DISTRIBUTION OF RUNOFF IN DROUGHT ZONE IN ILLINOIS. 1952-1955.

TABLE 10

RECURRENCE INTERVALS OF PERIODS OF LOWEST STREAMFLOW OF VARIOUS DURATIONS DURING 1952-1955

SOUTHERN ILLINOIS

Duration in Months	Streamflow in per cent of normal	Recurrence Interval in Years
6	0.35	75
12	1.9	83
18	4.2	82
24	7.4	77
30	6.1	100+
36	12.6	100+

ESTIMATING IMPOUNDING-RESERVOIR STORAGE

INTRODUCTION

Earlier in this report it was brought out that the greatest incidence of shortages of water occurred in communities relying on impounding reservoir sources and that, while unexpected increases in demand for water accounted for more shortages than any other cause, many of the difficulties were attributable to the inadequacy of impounding reservoirs. These findings suggest the desirability of a review of existing practice in design of impoundments in relation to the low-flow frequency data in the preceding section. The low-flow frequency and duration data presented furnish a basis for design of future impoundments.

For municipal or industrial water supply, the controlling considerations in deciding on reservoir capacity are adequacy of supply and cost. While the economics of determining reservoir size is not within the scope of this report, economic considerations confront the designer at a number of points.

The engineer, in evaluating reservoir sources of supply, examines the possible available sites in the vicinity that he believes might be practicable in relation to estimated demand. These will include those locations at which dams (with appurtenances such as spillways) could be built at reasonable cost. This consideration usually requires a narrow section of valley such that the length of dam is not excessive. It also favors the choice of the smaller drainage areas above the dam-site in order to minimize the size of spillway. The engineer will also prefer deep, steep-walled valleys, since they minimize evaporation losses and land-acquisition costs. Deep reservoirs also yield cooler water than shallow ones. Sites at higher elevations will be preferred to those of lower ones in order to minimize pumping costs. Sites closer to the point of use will be preferred to those more remote, in order to minimize length of conduit from the source to the point of use. The influence of distance from point of use to source has in recent years been subject to some noteworthy exceptions in which existing natural waterways were used to convey the water from the source to the point of use. Thus, the cost of constructing a pipeline is saved. However, the use of natural waterways is accompanied by loss of water due to seepage through the channel bottom, through evaporation, and use by riparian vegetation. These losses may range from negligible values to more than 50 per cent of the total(27) (28), depending on local conditions.

Economic considerations for various sites being equal or nearly equal, the engineer then evaluates more precisely the adequacy of each available source. He estimates the amount of water that will be required per unit of time, and establishes a minimum drainage area.

Review of Methods for Calculating Storage

It is desirable to build a reservoir on a watershed of the maximum feasible area in order to obtain adequate runoff, and on the smallest feasible area to minimize silt damage. It is therefore of critical importance to determine a suitable drainage area for which an economical reservoir site is available.

The early surface water reservoirs built for public water supply in Illinois are reported to have been designed on the basis of New England runoff data. This practice probably developed out of the classic studies of Allen Hazen(17) which were published in 1914. Hazen analyzed the desirability of storage provision for water supply from the point of view of low-flow frequency, using data primarily from the New England states. Additional information from other parts of the country was brought together by Hazen in a subsequent publication(23). The methods used by Hazen, while comprehending nearly all the important factors, are complex, and do not seem to have been adapted for use in Illinois design practice.

Instead of working out suitable applications of Hazen's method, designers in Illinois seem to have followed the practice of using rainfall data and applying runoff factors to these for estimation of streamflow. The files of the Water Survey contain a number of engineering reports on reservoir design prepared prior to 1930 for which it was assumed that minimum runoff would be of the order of 10 per cent of the annual rainfall.

As a greater number of Illinois stream-gaging records became available, data from extreme low-flow periods began to be used for design. Synthetic mass curves were sometimes prepared for design purposes, by transposition and adjustment of these records. This latter procedure remained popular until 1950, when W. D. Mitchell made an extensive analysis of streamflow records in Illinois through 1945 by means of residual mass curves, and described improved techniques for determining storage requirements for various draft rates(7).

It might seem possible to obtain a yield from an impounding reservoir equal to the mean runoff from the watershed. In actual practice, since yields must be attained by use of reservoir construction, losses due to seepage and evaporation occur, and these range from a small fraction of the use to an amount exceeding the use, depending upon reservoir surface area and underground conditions at the reservoir.

In addition, much larger reservoirs would be required for use of a high proportion of the streamflow than have generally been built. Mitchell's data for the Little Wabash River at Wilcox for the period 1939 to 1942, indicates that there would be no spillage for a period of 21 months if a reservoir were built to utilize 40 per cent of the average discharge, and that this period would extend to 36 months if it were desired to use 60 per cent of the mean streamflow. These times make no allowance for evaporative or seepage losses, except to the extent that such losses have been included in the draft rates. In Midwest engineering practice, consideration has seldom been given to drawdown periods exceeding three years, although in other parts of the world longer periods of drawdown are expected(29) (30)

The storage requirements indicated by Mitchell's study vary with the demand (draft rate) on the reservoir. To determine this relationship for the southern half of Illinois, averages of the unit storage requirements which he worked out for eight drainage areas have been calculated. These were for the Sangamon River at Monticello, South Fork of the Sangamon River at Kincaid, LaMoine River at Ripley, Macoupin Creek at Kane, Big Muddy River at Plumfield, Embarrass River at Ste. Marie, Little Wabash River at Wilcox, and Skillet Fork at Wayne City. From Mitchell's draft-storage curves for these basins, the storage ratio in million gallons per square mile was determined for each basin for draft ratios (Draft ratio is ratio of demand to average discharge, and may conveniently be expressed in per cent) of 30, 40, 50 and 60 per cent. The means of these data were determined and are represented by the curve in Figure 40.

The data given in Figure 40 are based on the worst conditions that occurred during the periods of record on the eight basins included in the study. The curve therefore represents requirements for an indeterminate return frequency, probably in excess of 20 years, since the records involved in the study ranged from 16 to 34 years in length. The curve gives no information on low-flow duration, but most of the values from which it was determined were for two- to three-year low-flow periods, especially at the higher draft rates. Richard Hazen has pointed out(31) that it would be desirable to construct such curves on a basis of low-flow frequency, but hitherto data in the Midwest have been insufficient to permit this. Inasmuch as Figure 40 does not include consideration of the 1952-55 drought, it should be considered only as a general guide, and storage requirements exceeding those indicated in the curve may occur. The curve does illustrate the necessity for sharply increasing storage capacity as the draft rate is increased.

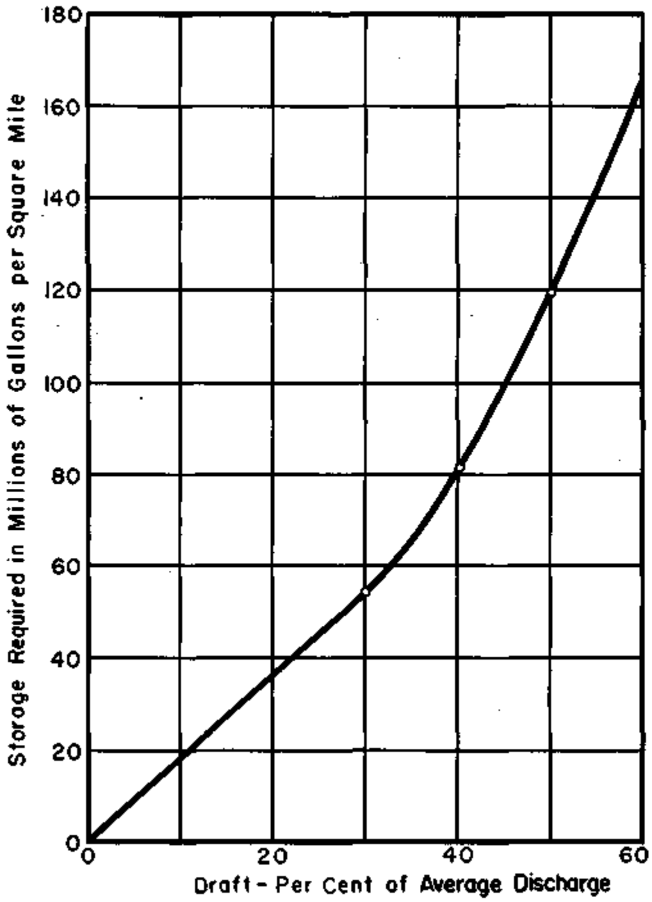


FIGURE 40. DRAFT-STORAGE CURVE FOR SOUTHERN ILLINOIS BASED ON AVERAGE OF 8 GAGING STATIONS.

A simplified version of the Allen Hazen approach to storage computations, published recently(32), explains the allowance for siltation losses, which was not treated in the earlier publication by Hazen. The handling of runoff data was the same as that of Hazen, in that annual deficiencies were computed, and these were subsequently arrayed to determine the frequency of occurrence of annual storage requirements. Smallwood and his colleagues improved on the Hazen approach by using the mass-curve technique, which gives values extending beyond the end of the water year or calendar year. Hazen's method of determination was arithmetic rather than graphic and started from the same month each year in making computations. There is question whether these approaches obtain "independent" values. It is conceivable that several values from within one particular low-flow period might be obtained, particularly under the arithmetic method used by Hazen. The incidence of dependent values could have a profound effect on frequency determinations.

Suggested Design Criteria

In the preceding section, the available procedures and methods for estimating capacity of impounding reservoirs were discussed. It was pointed out that the method most readily available made use of the most extreme periods on record, and computed the storage requirements for these periods(7). This procedure does not tell us the natural risk which the reservoir is prepared to meet; it merely states that the reservoir can meet a situation as adverse as was. experienced during a certain recorded period. It would obviously be desirable to know the probability of occurrence of the "design drought." An analysis of storage requirements that includes the frequency of occurrence of low flows of various durations as a consideration has therefore been made.

This analysis makes use of the unified data on low-flow duration and frequency described in a preceding section, which led to development of a method similar in some respects to that originally used by Hazen(17) in which storage volume requirements, expressed in per cent of average annual discharge, are related to draft rate in per cent of average flow rate.

Stated in general terms, the method developed involves calculation, for fixed low-flow frequencies, of the quantities of water that will be withdrawn from storage at various draft rates for various duration periods. For each given low-flow frequency and draft rate, one value of duration will prove to cause the maximum withdrawal from storage. These maxima may then be used to establish a separate graphic relation between storage required and draft rate for each low-flow frequency. The critical values of duration may also be used to establish the relation between draft rate, storage provided, low-flow frequency, and duration of recession in the reservoir..

For calculating storage required, confusion is avoided by expressing the data in units of streimflow. From Table 4 it was determined that the mean discharge in the region studied was 10.0 inches per year. Draft rates were then expressed in inches, with five inches per year corresponding to a 50 per cent draft rate, etc. A draft rate of five inches per year for a two year period would constitute a total draft of 10 inches. From the total draft was subtracted the value of runoff for the corresponding duration period, obtained from Figure 29 (converted to inches), to yield the volume of flow in inches that must be provided from the reservoir for a given low-flow frequency. Multiplying these values by 10 gave the volume of storage in per cent of mean annual discharge. These data on quantity of storage required for each low-flow duration period, draft rate and low-flow frequency were then plotted in residual mass diagram form, as illustrated in Figure 41, a separate drawing being prepared for each recurrence interval.

The shapes of the curves in Figure 41 and in those for other recurrence intervals were quite similar, although maxima were not always attained within the 60-month period studied. It appears that, in order to work the data out with full precision, it would be desirable to obtain data for low-flow periods longer than 5 years. The curves in Figure 41 show that for a given draft rate the amount of water withdrawn from storage increased to a maximum as the duration of the low flow increased. As duration further increased storage required subsequently declined. It is evident from Figure 41 that, for a 20-year recurrence interval, the duration of the period during which total streamflow is less than 10 per cent of the mean flow is about six months but that, for the same recurrence interval, the duration of the period in which the total flow is less than 90 per cent of the mean flow is approximately 44 months. Increases in streamflow after these duration times account for the subsequent decline of the residual-mass curves.

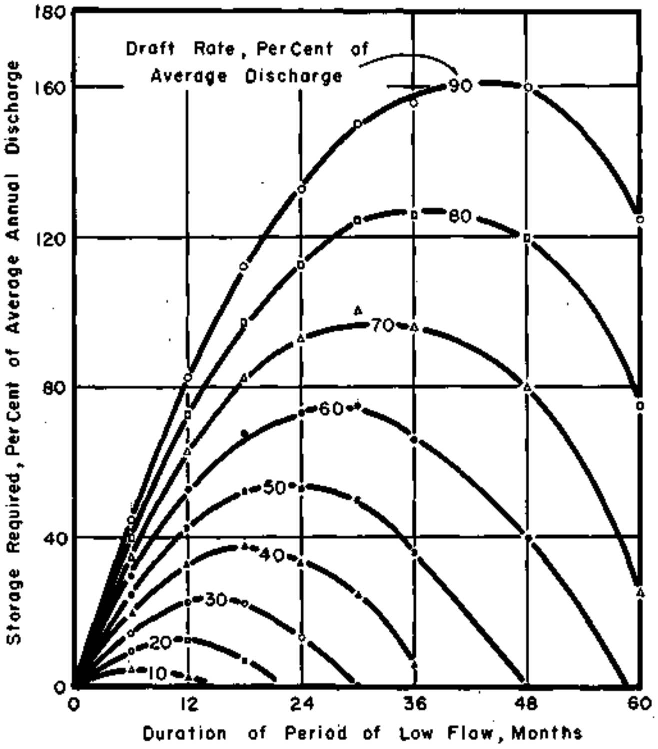


FIGURE 41. RESIDUAL MASS DIAGRAM OF STORAGE REQUIRED FOR PERIODS OF LOW FLOW OCCURRING. ONCE IN 20 YEARS.

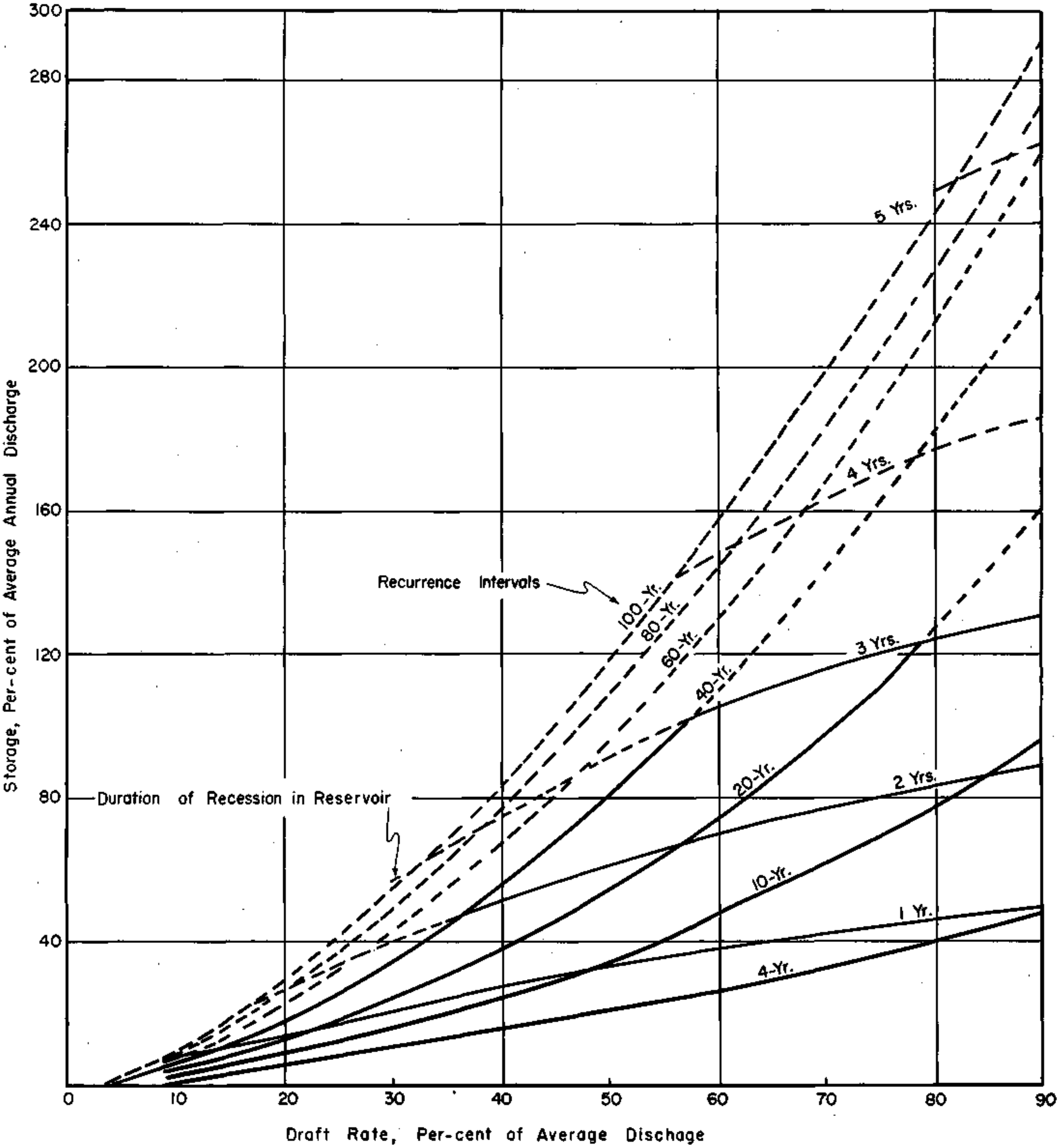


FIGURE 42. STORAGE REQUIRED FOR MAINTENANCE OF VARIOUS DRAFT RATES DURING LOW-FLOW PERIODS OF VARIOUS RECURRENCE INTERVALS AND DURATIONS.

In Figure 41, the location of the apex of each curve determines the amount and time of maximum drawdown in the reservoir. Values for larger periods of duration represent the recovery phase. Computation of these curves to duration periods exceeding 5 years in length could enable determination of the total time of drawdown. The maximal values from Figure 41 and from similar graphs for other recurrence intervals were consolidated in Figure 42 which gives generalized values, for any draft rate of 90 per cent or less and recurrence interval of 100 years or less, of the amount of storage necessary and the duration of the critical low-flow period in the southern half of Illinois.

In Figure 42, those portions of the graph that are based on interpolated values from the low-flow frequency curves are shown as solid lines, while those parts that are extrapolated beyond the period of record are shown as dashed lines. The heavier lines in Figure 42 show the quantity of storage required to sustain various draft rates, while the lighter lines show the duration of the low-flow period that would produce the maximum drawdown in a reservoir of stated capacity at given rates and recurrence intervals.

To illustrate the use of Figure 42, consider the case in which it is desired, at a given site, to develop 60 per cent of the average discharge with assurance that the supply will not fail, on the average, more often than once in 20 years. Figure 42 shows that the necessary volume of storage would be equal to 74 per cent of the mean annual discharge, and that the period during which water levels would decline in such a reservoir under the 20-year low-flow condition would be about 26 months. If, on the other hand, it is desired to develop 60 per cent of the mean discharge of the stream in such a way that the supply would be exhausted only once in 100 years, the volume of storage required would be 158 per cent of the mean annual discharge, and the duration of recession of reservoir levels would be approximately 50 months.

To the storage requirement estimates made in this fashion must be added adjustments for loss in storage due to future sedimentation. Allowances for losses due to evaporation would be subtracted from draft rates to determine net yields.

Figure 42 may also be used to evaluate existing reservoirs. In computing draft rate, the effect of evaporation should be added to the withdrawal. The total, divided by the mean discharge at the site (which may be estimated by use of Figure 6) equals the draft rate. This figure may be used as one value for entering Figure 42. The total volume of storage in the reservoir, divided by the mean annual discharge, gives the storage figure, which is the other value needed for entering the graph. From the point on the graph located by these two values, the capability of the reservoir in meeting demands may be interpolated in terms of low-flow frequency which the reservoir can safely meet. The duration of the recession may also be determined in the same fashion. Assume, for example, a reservoir which is capable of storing one year's normal streamflow. Assume that the draft rate from the reservoir is 50 per cent of the average annual flow. From Figure 42 it may be seen that this reservoir would be capable of maintaining the assumed draft rate for the kind of low-flow period that occurs once in 67 years, and that such a low-flow period could have a duration of approximately 3-1/2 years.

Figure 42 may also be used to evaluate the usefulness of water conservation measures. For example, assume a situation . in which the draft rate is 60 per cent and the storage volume is 100 per cent of the mean annual discharge. Such a reservoir-water shed combination would be estimated from Figure 42 to be capable of meeting a low-flow period of a magnitude that would occur once in 35 years. If means could be found to reduce the draft rate to 50 per cent, the reservoir could be made capable of meeting a low-flow period having a 67-year recurrence interval. To attain a substantial reduction in draft rate requires a considerable reduction in pumpage, for the demands of evaporation continue, unreduced. Inasmuch as the desirability of such a conservation measure could become apparent at the end of 18 months of drawdown, which is approximately half of the anticipated total period of recession, a reduction in pumpage of approximately double the amount estimated would be necessary to achieve the <u>average</u> reduction required. In many communities, such reduction is possible through eliminating leakage, unaccounted-for water, limiting free public use, and through applying restrictions. It therefore appears possible, under certain circumstances, to substantially extend the usefulness of a reservoir through conversation measures. Chief among these measures should be the initiation of continuing leak detection and elimination programs.

Reservoir Sedimentation

Reservoir sedimentation is a factor that was not taken into account in the design of many of the early impounding reservoir supplies in Illinois. This was due to complete lack of data on sedimentation. As a result, many of the older reservoirs in the state have lost storage capacity at surprisingly high rates. These losses of capacity have frequently deprived municipalities of necessary storage space, and thus contributed to supply shortages.

In estimating the watershed area desirable for a reservoir project, the engineer must have two opposing considerations in mind: (1) obtaining sufficient runoff to serve the community's needs, and (2) minimizing the drainage area so as to secure the least sediment damage to the reservoir. While the sediment that reaches a reservoir increases as the drainage area is increased, as shown in other studies(33) this relationship is not one of direct proportion.

For estimating sediment damage rates, it is convenient to use the capacity-watershed (C/W) ratio, which is expressed in acre-feet per square mile. A small C/W ratio usually indicates little space for storage of sediment in respect to sediment yield, and a large ratio indicates great space for storage. Accordingly, reservoirs with low C/W ratios accumulate sediment more rapidly (percentagewise) than those with high ratios. To a small extent this is offset by the effect of

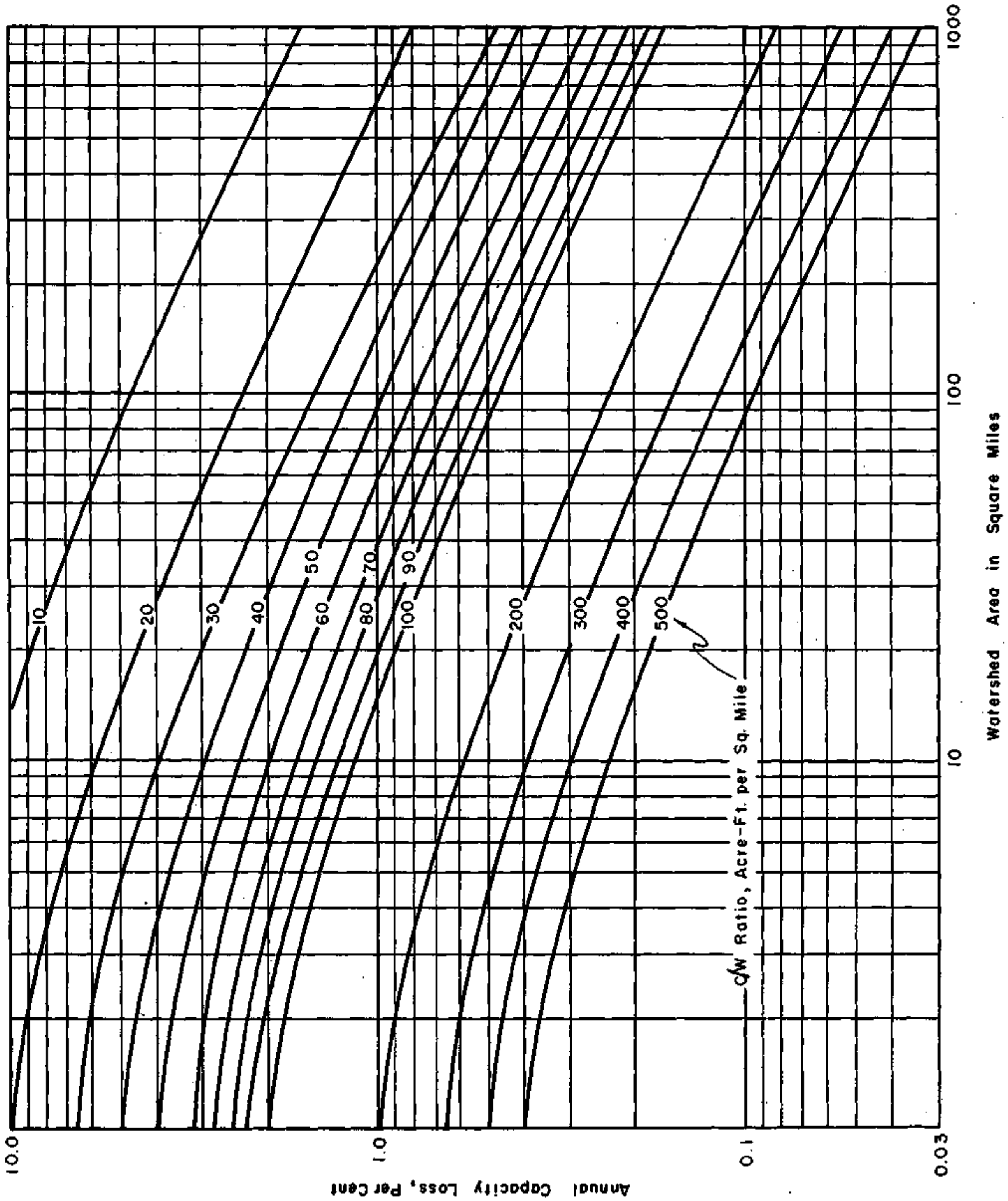


FIGURE 43. LOSS OF CAPACITY RATES DUE TO SEDIMENTATION (ILLINOIS DATA).

"trap efficiency"(34). Reservoirs with C/W ratios below 20 may not halt the majority of the sediment that reaches them.

The data collected from sedimentation surveys in Illinois have been summarized in Figure 43 using a scheme suggested by L. C. Gottschalk(35). This graph may be entered with the value of watershed area that is under consideration. Proceeding vertically along that value to the appropriate C/W value, the rate of capacity loss due to sedimentation may be estimated in per cent per year. A preliminary analysis of the data on sedimentation for 20 impounding reservoirs in Illinois showed the median departure from these estimates to be less than 50 per cent. Greater departures may occasionally occur, as is shown in the original publication of the data(33).

Studies now in progress by the State Water Survey in cooperation with the University of Illinois Agricultural Experiment Station, and the Agricultural Research Service and the Soil Conservation Service of the U. S. Department of Agriculture indicate that rates of sedimentation in reservoirs are dependent on a large number of factors, among which are rainfall intensities and frequencies, soil characteristics, land use, nature of drainage network, slopes, farming practices, drainage area, and reservoir storage capacity. Until these studies are more complete, it is not possible to give a summary statement of the effect of each factor, but present data have enabled estimation of the relationship of rates of sedimentation in reservoirs on the basis of the drainage area and reservoir storage capacity.

The effects of sedimentation losses on capabilities of reservoirs are less simple than they would appear. One would expect to compute the reservoir storage requirements for a chosen life of reservoir, an estimated future demand, and a particular low-flow frequency. To the storage required to meet these parameters, would be added the storage space necessary to provide for sedimentation.

Under such a program, the reservoir would be adequate to meet all conditions until the end of the chosen life. However, because of the initial provision of sediment storage space and because of the lack of immediate attainment of the anticipated demand, the reservoir would, from the time of construction until immediately prior to the end of its life, have excess capacity. In effect, this system of design adds a factor of safety which is present but diminishing until, at the end of the life of the reservoir, the factor of safety is unity.

There is reason to believe that the loss of storage capacity in reservoirs owing to sedimentation occurs in a step-wise fashion, with major increments of sediment entering the reservoir during infrequent periods of very high runoff. For design purposes, lacking information on incidence of future periods of major runoff, it is necessary to assume that the rate of sedimentation will be annually uniform.

As a result of the above considerations, it would appear desirable (a) to design the reservoir for a chosen life, and for certain other chosen parameters, and then (b) to review the situation of the reservoir with regard to sediment damage and changes in demand after approximately one-half the estimated life span of the reservoir. Such a practice would permit advance planning to take care of unusual situations such as accelerated erosion, unexpected increases in demand, or changes in streamflow characteristics.

Evaporative Losses

An additional factor that must be evaluated in reservoir design is the loss of water through evaporation. Evaporation losses may be said to consist of "gross evaporation" which is the total loss of water from the water surface to the atmosphere, and "net evaporative loss" which is the gross evaporation minus the rainfall on the water surface.

Gross Evaporation. Data on evaporative losses from standard Weather Bureau Class A pans in Illinois have been published(36) These data yield values on rates of evaporation only for the warmer months, and further work has therefore been

TABLE 11

EVAPORATION RATES AT CARBONDALE AND URBANA

Month	Rate of Evaporation in Inches per Month			
	Pan and Evaporimeter Data Carbondale and Urbana Stations		Data from Meyer	
	Carbondale	Urbana	Carbondale	Urbana
January	2.48	1.2	0.84	0.63
February	2.52	1.20	1.07	0.80
March	3.31	2.51	1.68	1.25
April	4.96	3.88	3.05	2.30
May	6.06	5.25	3.95	3.20
June	7.05	6.32	5.20	4.50
July	7.11	6.58	6.80	6.10
August	6.37	5.55	6.00	5.50
September	5.04	4.28	5.05	4.60
October	3.18	3.34	3.71	2.90
November	.90	1.96	2.35	1.75
December	.62	1.58	1.10	0.60
Total	49.60	43.57	40.80	34.13

done through the development of an evaporimeter, which records losses of water during the colder months(37). Combining these two sets of data, evaporation values by months can be obtained throughout the year. Table 11 presents the measurements at Urbana and Carbondale for the period April 1 to September 30 for the Class A pans, and October 1 to March 31 for the evaporimeters. The pan data are for the period 1947-54, and the evaporimeter data are for 1953-55. For purposes of comparison, values computed by Meyer(38) have also been tabulated for the same locations. The values taken from Meyer are average values for evaporation from lakes, while the pan measurements give values that are higher than actually occur from lakes. It is customary to reduce pan measurement values by 30 per cent in applying them to lakes(39)(40). Evaporation data for Springfield were not used because they do not appear concordant with those for other nearby stations.

It may be seen from Table 11 that there are large seasonal variations in evaporation rates. Inspection of the data and. comparison with Figure 7 indicate that these maximum rates of evaporation coincide with the annual periods of minimum streamflow. The Illinois data are not sufficient to determine annual variations in gross evaporation. It therefore appears advisable to estimate gross evaporation by a conservative method in order to take into account the possible occurrence of. high gross evaporation rates during years of extremely low streamflow. This method will, of course, be subject to considerable refinement as evaporation data are improved.

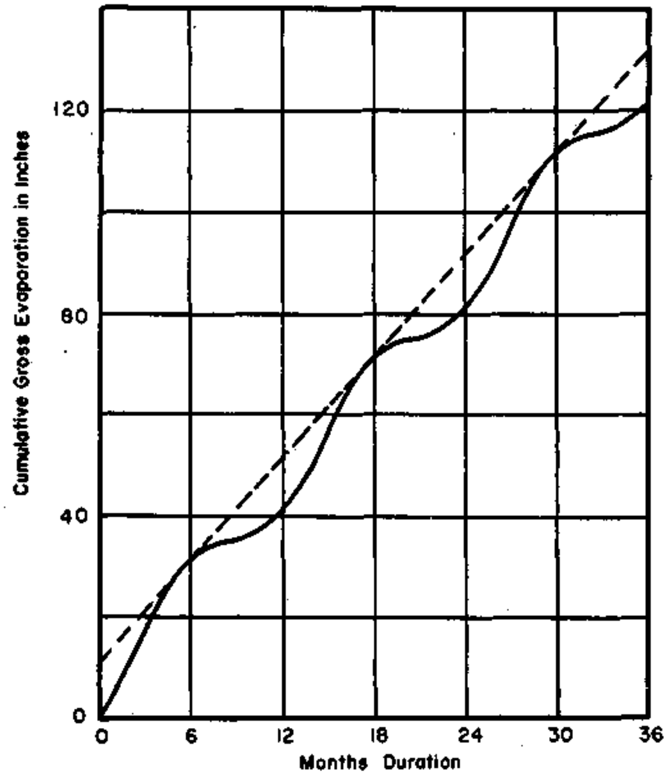


FIGURE 44. CUMULATIVE EVAPORATION AT VANDALIA.

A mass curve presentation of evaporation rate data, assuming equal monthly rates of evaporation for each of several successive years has been prepared, as shown in Figure 44. This curve is based on evaporation from lakes estimated by Meyer's method for the vicinity of Vandalia, which is approximately in the center of the area covered by this report. From this curve it may be seen that the most critical duration periods for evaporation losses are 6, 18, and 30 months. For the intervening periods, less rigorous values of evaporation would apply. It is believed desirable to ignore these less rigorous values in order to make allowance for variations in evaporation rates that may occur from year to year, and which may occur during a period of extreme flow. Accordingly, the dashed line in Figure 44 has been constructed to define evaporation losses for various duration periods.

Evaporation data for Carbondale, Quincy, Springfield, Urbana and Vandalia estimated from the maps of Meyer were studied. In each case it was clear that the maximum six months' evaporation occurred in the period from April through October. For estimating the most extreme values of evaporation that might be obtained during any duration period, the following formula yields conservative results;

$A = B + CD$, in which

A = Total gross evaporation for the duration period, inches

B = The maximum gross evaporation for the area under study for a six-month period, less 1/2 the annual gross evaporation, inches

C = Annual gross evaporation, inches, and

D = Duration period in years

Values of B and C are given in Table 12.

TABLE 12

ESTIMATED GROSS EVAPORATION RATES

Location	Average Annual Precipitation Inches	Max. 6-Month Evaporation in Inches	Max, 6-Month Evaporation Minus 1/2 Annual, Inches (B)	Annual Evaporation in Inches (C)
Carbondale	43.45	30.9	10.5	40.8
Quincy	35.86	30.6	11.2	38.8
Springfield	36.45	30.6	11.3	38.6
Urbana	36.05	28.9	10.6	36.6
Vandalia	38.36	30.8	10.9	39.8

Area Exposed to Evaporation. A review of the literature indicates that no simple but comprehensive method has been published for taking into account evaporative losses from reservoirs prior to the detailed computation of losses for each particular proposed project. At the time that Allen Hazen published his original studies on storage to be provided in impounding reservoirs(7), allowances for evaporation were discussed by Marsh and others(41). Hazen had estimated that evaporation losses should be calculated on a reservoir surface area which was 90 per cent of the area of the reservoir when full. Marsh suggested using the water area corresponding to a storage of two-thirds of the maximum quantity stored. Cory(42), suggested that evaporation should be considered as one part of the total draft, just as net draft is the other part. Cory did not suggest any method for accomplishing this, however.

Hazen found no way of accomplishing Cory's suggestion of including evaporation in the draft, owing to the variability in reservoir characteristics and in net evaporation losses from one location to another.

In the discussion of the Hazen paper the topic of relation of water area to land area is also analyzed. Several of the discussers point out that, when the lake has a very large surface area in comparison to the total watershed area, a reduction in estimated runoff is necessary in order to compensate for the reduction in available land surface. This is to some extent offset by gains due to rainfall on the lake surface, but where evaporation exceeds annual precipitation, a net loss may be obtained by making the lake larger. This influence has been ignored in these studies as being a minor one.

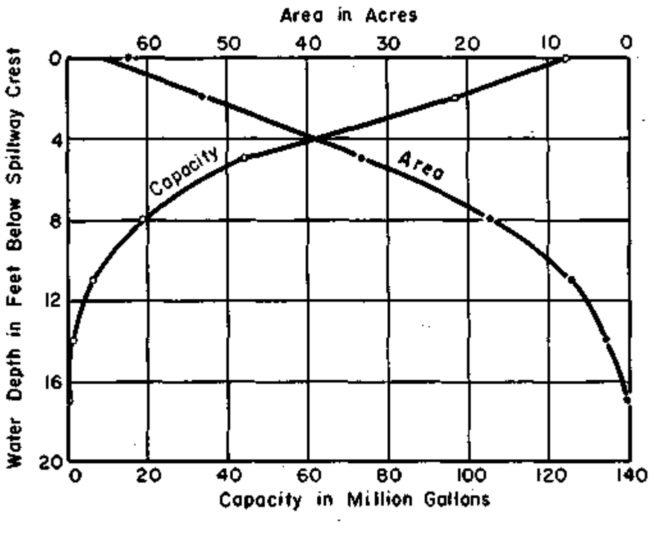


FIGURE 45. AREA AND CAPACITY CHARACTERISTICS.
Johnston City Reservoir.

It is expected that, during the design low-flow period, a reservoir will recede (at the design draft rate) from spillway level to a completely empty state at the end of the low-flow period. For purposes of simplification it may be assumed that, except at the end of the low-flow period, inflow into the reservoir will be immaterial, and that withdrawals of water from the reservoir will take place at a uniform rate during the entire period of recession. Thus the rate of removal of water from storage will be uniform with respect to time.

Figure 45 shows a typical set of area-depth and depth-capacity curves for a water supply reservoir. From such a pair of curves an "area-capacity" curve may be constructed. Area-capacity curves have been constructed for 15 municipal water supply reservoirs in Illinois which were surveyed in 1954 for which area-depth and depth-capacity curves were prepared. Areas and capacities have been expressed in per cent of the values obtained when the reservoirs were full. The reservoirs used for this determination and their characteristics are listed in Table 13. The results are summarized in Figure 46.

TABLE 13

CHARACTERISTICS OF RESERVOIRS SURVEYED IN 1954

Community	Year of Construction	Capacity, Million Gallons	Surface Area, Acres	Average Depth, Feet	Watershed Area, Square Miles
Ashley	1941	45.0	18.0	7.6	1.24
Bunker Hill	1937	12.0	17.0	2.2	7.19
Coulterville	1940	64.7	26.7	7.4	1.22
DuQuoin	1937	543.5	244	6.8	10.73
Gillespie	1923	226	70.3	9.8	5.73
Johnston City	1922	119	65.5	5.6	3.85
Nashville	1936	94	39.5	7.3	1.39
Norris City	1937	39.9	15.7	7.8	0.83
Oakland	1937	32.7	25.0	4.0	14.3
St. Elmo	1935	39.4	20.0	6.0	3.0
C.&E.I. (St. Elmo)	Prior to 1934	7.4	9.0	2.5	2.93
Staunton	1926	371	89.6	12.7	3.68
Virginia	1933	36.9	18.9	6.0	0.828
Waverly	1938	78.9	38.9	6.2	13.8
White Hall	1897	112.2	37.2	9.2	0.97

The solid line in Figure 46 represents the arithmetic mean of area values determined for capacity values of 20, 40, 60 and 80 per cent of full capacity. The dashed lines in the figure were drawn through the extreme values obtained from the 15 reservoirs used. The departures (of area) from the mean curve were small except in the case of the area for 80 per cent of capacity, for which one value (67 per cent) for one of the lakes fell well outside the envelope curve. It will be noted by inspection of the curves in Figure 46 that departures from the mean curve generally did not exceed 10 percentage points. This concordance of the data indicates that there is a general similarity in the geometry of reservoir sites in the areas studied, and that it is therefore reasonable to use the mean curve for purposes of estimating the effective area exposed to evaporative action.

The area under the solid curve in Figure 46, divided by 100, will equal the mean surface area with respect to time when draft from the reservoir is continuous and uniform. The mean value of this area was found to be 64.4 per cent of the surface area with water level at spillway crest. The 15 cases studied indicate that values ranging from 55 to 70 per cent may occur. This method of approach makes no allowance for changes in surface area produced by sedimentation with time.

It is concluded that, for southern Illinois water supply reservoirs, it would be reasonable to apply evaporation estimates to an area which is 64 per cent of the design surface area of the reservoir.

The surface area of a reservoir is equal to the volume divided by its average depth. Table 3 gives data on the average depth of 40 impounding reservoirs for municipal water supplies in Illinois. These figures were obtained by dividing the original total capacity of the reservoir by the original surface area. It was noted that the median of the average depths of these reservoirs is 8.7 feet, and that the extreme values are 4 feet and 20 feet.

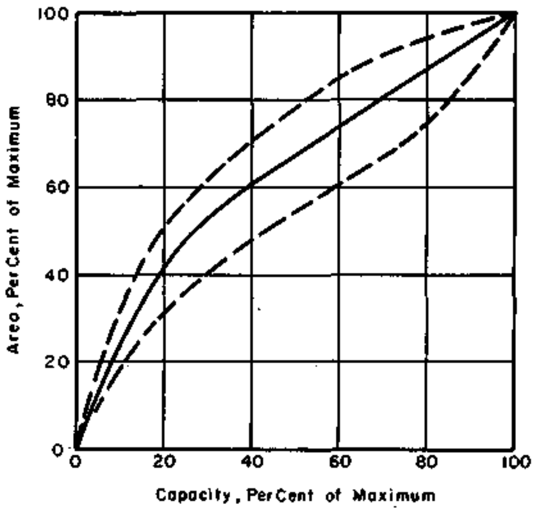


FIGURE 46. AREA-CAPACITY RELATIONSHIPS FOR ILLINOIS RESERVOIRS. 1954 Area-Depth Curves.

While most of the reservoirs studied were small, detailed examination of the data for the two larger ones (DuQuoin and Staunton) showed them to be in close agreement with the average curve given in Figure 46. Additional data on characteristics of reservoirs in Illinois were assembled in Table 14, covering the largest reservoirs in the State. Area and capacity-depth curves are not available for all of these reservoirs, but the data given indicate that their average depths are not greatly different from those of the smaller reservoirs shown in Table 13. The average depths of the larger reservoirs are greater than those of the smaller ones. In estimating average depth for a reservoir, it would therefore be desirable to proceed on the basis that the average depth of a reservoir storing more than one billion gallons could very well be of the order of 15 feet, while the average depth for reservoirs storing 500 million gallons or less might be 10 feet or less.

TABLE 14

CHARACTERISTICS OF LARGE IMPOUNDING RESERVOIRS IN ILLINOIS

	Year of Construction	Capacity, Million Gallons	Surface Area, Acres	Average Depth, Feet	Watershed Area, Square Miles
Bracken **Near Galesburg**	1923	802	181	14.5	8.91
Bloomington **Near Bloomington**	1929	1,927	487.2	13.2	61
Carlinville **Near Carlinville**	1939	465	167	9.1	26.1
Charleston **Near Charleston**	1947	860	400	7.0	800
Crab Orchard **Near Carterville**	1940	21,938	6,965	10.3	196
Decatur **Near Decatur**	1922	4,763	2,604	6.0	906
Hillsboro **Near Hillsboro**	1918	500	96	17.0	7.5
Jacksonville **Near Jacksonville**	1939	2,240	469	15.6	10.8
Mauvaise Terre **Near Jacksonville**	1921	396	223	5.8	32.6
Little Grassy **Near Makanda**	1942	8,417	1,000	27.5	15.1
Springfield **Near Springfield**	1934	19,089	4,234	14.7	258
Vermilion **Near Danville**	1902	2,600	900	9.5	267

NOTE: Capacity and area values based on most recent survey data.

Average depth data may be used for making preliminary estimates of reservoir surface areas. For the region studied, it would appear desirable to calculate such areas for average depths of 5 to 20 feet. Data covering this range of average depth would take into account variances in topography from place to place. At some locations reservoirs with small average depths may be necessary, and at others, greater average depths may be attained. These variations depend on the topography and on dam height. Inasmuch as this study indicates a need for more storage than has hitherto been provided, average depths of 10 feet or more may be expected in future reservoirs.

To sum up, the evaporative losses may be seen to be a function of the average depth of reservoirs. When the storage volume is known, use of an average depth figure enables estimation of the surface area of the reservoir. To this may be applied the factor 0.644. To the resulting reduced area value, may be applied net evaporative loss rates (discussed below). As will be pointed out, this process can be combined with the process of estimating storage for any stated draft rate.

Net Evaporative Rates. In order to obtain net evaporation rate values, appropriate values for rainfall on the water surface must be subtracted from the values of gross evaporation. Such rainfall values, for various duration periods and for various frequencies of occurrence have been prepared and are given elsewhere (Figure 32). It would be convenient if it should turn out that, throughout a given region, net evaporative loss rates were uniform. Studies were made of calculated net evaporative loss rates at Quincy, Springfield, Urbana, Vandalia, and Carbondale. These studies indicated that the evaporation and precipitation patterns in the southern half of Illinois are sufficiently different that net evaporative loss values are not uniform throughout central and southern Illinois. Departures of as much as 20 per cent from a mean curve were noted, but the mean for each of five different dry-weather frequency periods tested was quite well represented by the data for the region of Vandalia. The Vandalia values for net evaporative loss appeared to check those for the other locations within five per cent for duration periods up to two years, and the more severe errors occurred for the 2 1/2 and 3-year duration periods.

The computed results for the vicinity of Vandalia are shown in Figure 47, which gives the net loss due to evaporation for dry periods of various durations and frequencies.

Net Yield of Reservoirs

In the preceding material on reservoir capabilities, storage requirements have been related to the draft rate on the reservoir. The draft rate is the total withdrawal from the reservoir, and includes (a) water supply requirements, (b) evaporative losses and (c) seepage losses. Noinformation is available for determination of seepage losses quantitatively at this time. Attempts to secure evaluations of seepage loss have indicated that this quantity, with properly constructed dams, is negligible.

It would obviously be desirable to be able to estimate net yield of reservoirs by taking into account evaporative losses as well as water supply requirements. This may be done by estimating the lake surface areas exposed to evaporation, and applying appropriate evaporation rates to the area values. Draft rates are then reduced by the amount of the evaporative loss (which may be expressed in per cent of mean flow rate and called the evaporative draft rate) to obtain "net yield" values.

In calculating draft rates, consideration should be given to the demand during the low-flow duration period that is expected to control the reservoir design. For low-flow periods in excess of one year, it would seem proper to use the average annual water requirement from the lake plus net evaporative loss to estimate draft. For those situations in which short low-flow duration periods are expected to control or in which unusual variations in demand are expected, it may be desirable to use (a) a draft rate based upon summertime pumping rates plus summertime evaporation losses or (b) a draft rate based on other special local conditions. Inasmuch as those situations in which short-term low-flow periods may control will probably be avoided through the desire to reduce sediment damage, in general the average annual withdrawal rate may be used.

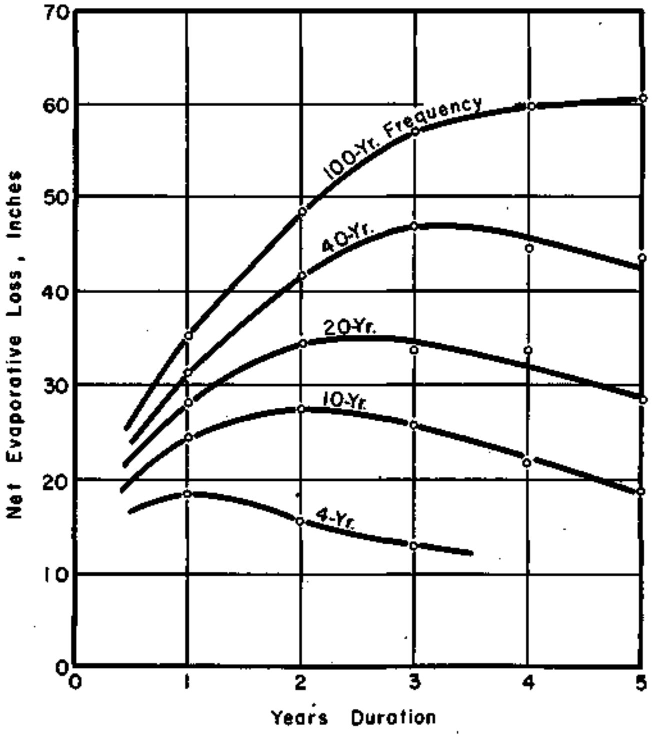


FIGURE 47. ESTIMATED NET EVAPORATIVE LOSSES FOR PERIODS OF LOW RAINFALL OF VARIOUS FREQUENCIES AND DURATIONS.

For the calculation of net yield, it is necessary to make correction for evaporative losses for fixed duration periods. Accordingly, from Figure 42, values of storage and draft rate (expressed in per cent of mean annual flow) were tabulated for 1, 2, 3, 4 and 5-year duration periods for 4, 10, 20, 40 and 100-year recurrence intervals.

For the computations of net yield that follow, mean annual streamflow in the area was taken as 10 inches per year. Storage volume values were converted into acre-feet. These values - divided by an assumed average depth for the reservoir of 10 feet - yielded reservoir surface area values in acres. Each of these was reduced to 64.4 per cent of its value in accordance with the findings above. Appropriate values for net evaporative loss obtained from Figure 47 were then applied to obtain the evaporative drafts for each of the surface area values. These were then expressed in per cent of mean flow, producing values of the "net evaporative draft rate", which may be defined as the ratio, expressed as a per cent of the net evaporative loss rate to the mean discharge rate for the site under consideration. Actually this process does not require consideration of the mean streamflow, and the same net evaporative draft rate values, expressed in per cent of mean flow, are obtained regardless of the streamflow assumed.

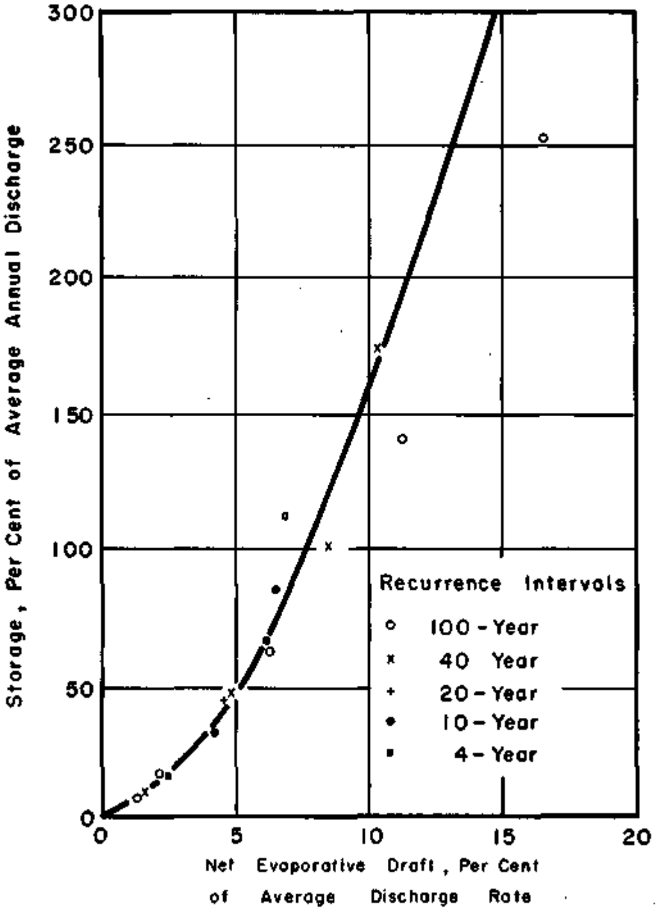


FIGURE 48. NET EVAPORATIVE DRAFT FROM RESERVOIRS.

It was found that, for the location studied, there appears to be an approximate general relationship between storage volume and the net evaporative draft rate from the reservoir. The data establishing this relationship are shown in Figure 48 for a 10-foot average depth of reservoir. For any other average depth, these values may be increased or reduced in inverse proportion to the average depth. The adjusted values of net evaporative draft rate may then be subtracted from the draft rate values obtained from Figure 42 to obtain values of "net yield" in per cent of mean streamflow.

The values given in Figure 48 are for the vicinity of Vandalia and, while they are probably fairly trustworthy throughout southern Illinois, should not be relied on for design computations elsewhere, without checking them against local data. The correlation between storage volume and net evaporative draft should also be checked before application to other locations.

From Figure 48 it will be noted that, except for very high storage volumes, the net evaporative draft rate is relatively small. In no case does it reach 20 per cent of the mean discharge rate. The most serious effects of the net evaporative draft rate will be felt in those situations which require high storage values, especially when particularly shallow lakes are necessary.

To complete the portrayal of effects of net evaporative losses, Figure 49 has been prepared. It shows the relationship between net yield and storage required, assuming an average depth of 10 feet. For any particular site, a different relationship would hold, since average depth would vary with reservoir capacity.

Limitation of Method

Although the results obtained in this study have been generalized, it is believed that they will yield satisfactory approximations for preliminary evaluation of reservoirs in the southern half of Illinois. The results obtained should not be regarded as a final basis for design of any specific reservoir. For design, there is no substitute for thoughtful, intensive analysis of hydrologic records collected in the vicinity of the proposed project. The designer may find the methods used in preparing this study helpful in analysis of local records for design.

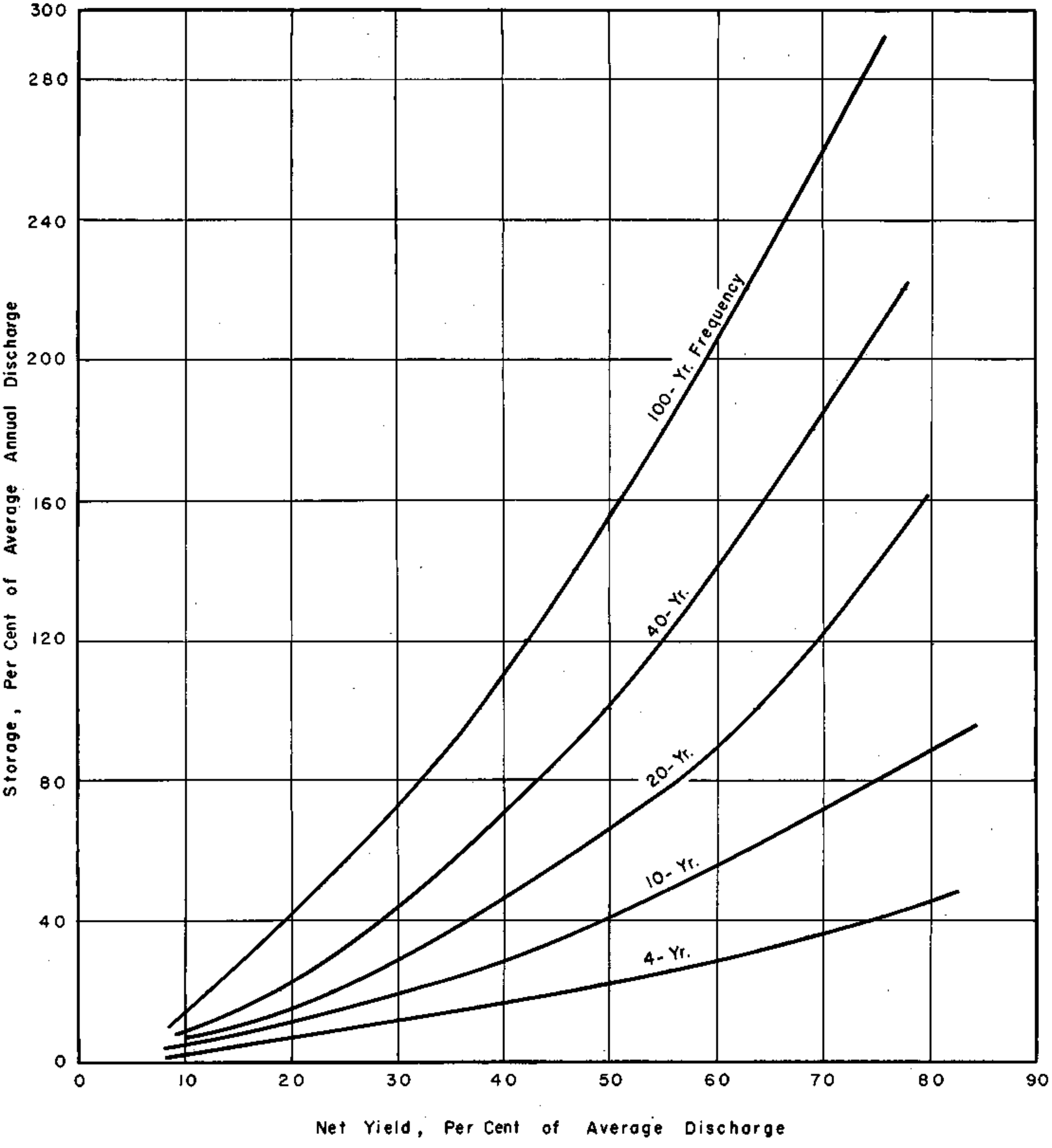
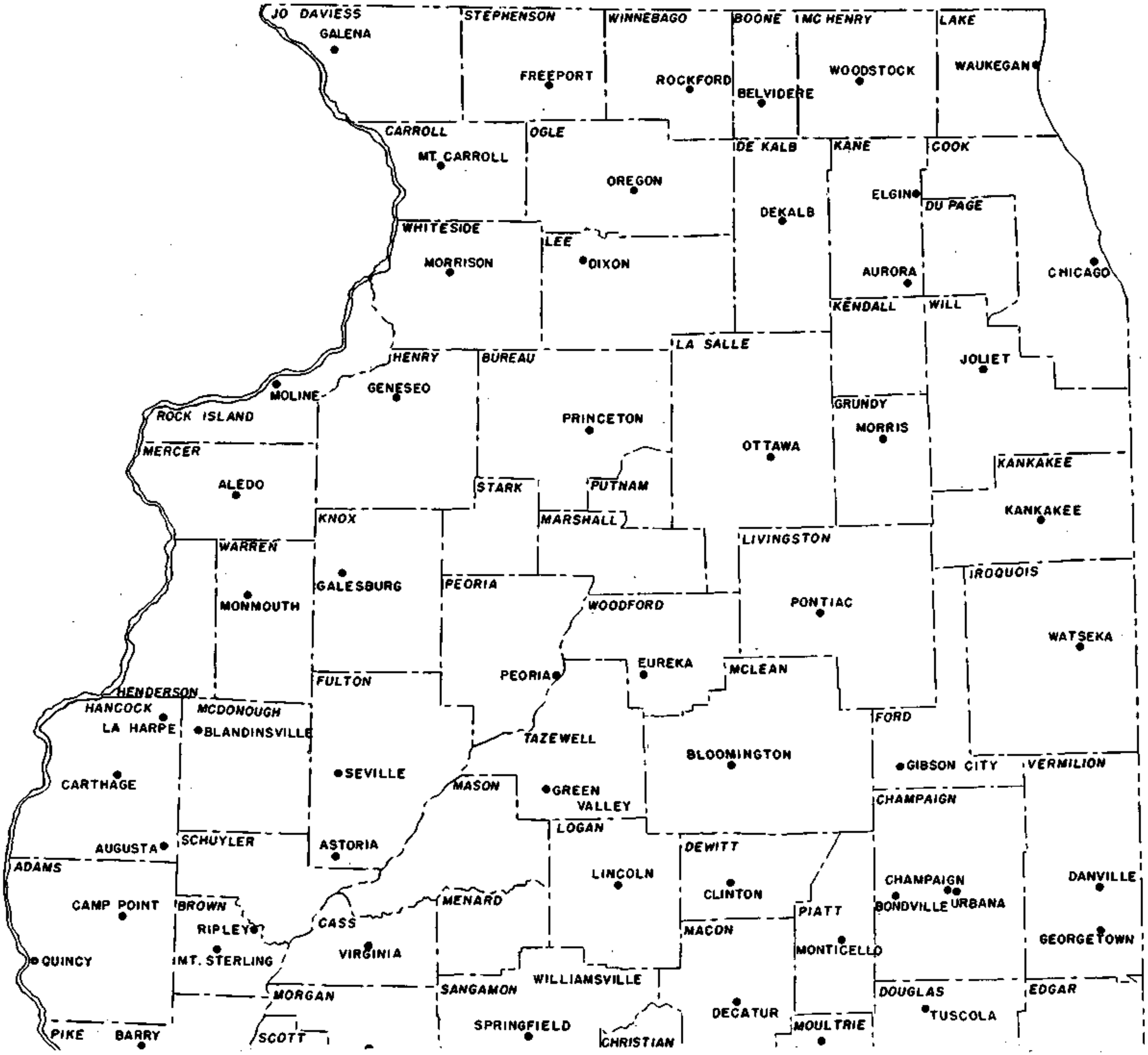


FIGURE 49. NET YIELD OF RESERVOIRS HAVING 10-FOOT AVERAGE DEPTH, Southern Illinois.


JO DAVIESS
GALENA
STEPHENSON
FREEPORT
WINNEBAGO
ROCKFORD
BOONE
BELVIDERE
MC HENRY
WOODSTOCK
LAKE
WAUKEGAN
CARROLL
MT. CARROLL
OGLE
OREGON
DE KALB
DEKALB
KANE
ELGIN
COOK
DU PAGE
AURORA
CHICAGO
WHITESIDE
MORRISON
LEE
DIXON
KENDALL
WILL
JOLIET
LA SALLE
HENRY
GENESEO
BUREAU
MOLINE
ROCK ISLAND
PRINCETON
OTTAWA
GRUNDY
MORRIS
MERCER
ALEDO
STARK
PUTNAM
KANKAKEE
KANKAKEE
KNOX
MARSHALL
WARREN
LIVINGSTON
GALESBURG
MONMOUTH
PEORIA
WOODFORD
PONTIAC
IROQUOIS
WATSEKA
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SCHUYLER
ASTORIA
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DEWITT
LINCOLN
CLINTON
CHAMPAIGN
DANVILLE
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CAMP POINT
BROWN
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PIATT
RIPLEY
CASS
MACON
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MT. STERLING
VIRGINIA
MONTICELLO
GEORGETOWN
WILLIAMSVILLE
MORGAN
SANGAMON
DOUGLAS
EDGAR
TUSCOLA
DECATUR
PIKE
BARRY
SCOTT
SPRINGFIELD
CHRISTIAN
MOULTRIE

FIGURE 50. ORIENTATION MAP OF ILLINOIS.

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