DROUGHT AND GROUND-WATER LEVELS IN NORTHERN WISCONSIN

by

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ABSTRACT

In 1976, much of the United States experienced a serious water shortage caused by a prolonged period of deficient precipitation. One of the areas most severely affected was Wisconsin. Soil moisture was depleted, streamflows were reduced, and levels in lakes, reservoirs, and wells declined. Approximately 500 wells were reported as dry or reduced in productive capacity. That resulted in providing emergency supplies of water in many communities, and in large expenditures for drilling of new wells or deepening and redevelopment of old ones. Many of these problems could have been avoided if wells had been "drought-proof"--had been designed so as to extend below the extremely low water levels. Because humid or subhumid areas are not stricken by drought regularly, people are seldom prepared for declining water levels. Furthermore, no method is presently available for estimating the well depths required to ensure water supplies during droughts. Even though drought periods are not predictable, their effects can be anticipated and a method developed to mitigate them.

Statistical analysis of precipitation records and long-term ground-water level measurements on shallow wells in a glaciated area of northern Wisconsin was made to determine the historical drought periods in Wisconsin and their relation to ground-water levels; and to develop a method for estimating extremely low levels, which can be used for efficient design of wells so that they would not be affected by drought. The analysis has shown that drought periods are quite common in Wisconsin, occurring on the average once in 6 to 7 years statewide. Periods of low ground-water levels closely correlate with drought periods. The most serious declines of water levels were recorded in the late 1940's, the late 1950's, and the middle 1960's. Based on the premise that water levels in given areas with similar hydrogeologic conditions exhibit a normal probability distribution, a relationship was established between record minimum and mean water levels. The results of the analysis indicate that by plotting data from a number of wells, a type curve can be developed from which the required minimum levels can be predicted within selected confidence limits, enabling planners and well owners to anticipate and prepare for declining water levels.

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INTRODUCTION

Project History

In 1976-77, much of the United States experienced a serious water shortage caused by prolonged periods of drought. One of the areas most severely affected was the Upper Midwest, especially Minnesota and Wisconsin (Gilbert and Buchanan, 1977; Upper Mississippi River Basin Commission, 1977). Historical records show that statewide drought occurred in Wisconsin on several previous occasions as well: in 1895, 1910, the 1930's, 1948, 1958, and 1963. The 1976 drought has been considered by many the worst drought in Wisconsin since the 1930's; the Palmer index, used to classify drought severity (Palmer, 1965), dropped to extremes previously unrecorded (-7 to -9).

The runoff pattern reflected the precipitation pattern very closely. The stream discharges approached, and in many cases exceeded, record low flows; and the duration of deficient streamflows reached 16-20 months (Gilbert and Buchanan, 1977; Matthai, 1979). During 1976, approximately 500 wells were reported as dry or reduced in productive capacity (Calabresa, 1977). They were, for the most part, relatively shallow wells (less that 30 ft deep) in a glaciated area, and sensitive to even relatively small lowerings of water level due to the limited storage capacity of shallow Pleistocene aquifers. The drought created an upsurge in deepening and redevelopment of wells, and in replacing inadequate wells with wells of greater capacity. However, drillers from the affected areas reported that many of the wells were dry or near-dry prior to the drought. This indicated that the well failures did not reflect insufficient sources of supply but rather inadequate planning or construction of wells.

Whatever the reason, it was necessary to provide emergency water supplies to affected well owners in northern Wisconsin. This fact created concern on the part of state officials involved in providing emergency supplies, especially the Wisconsin Division of Emergency Government (DEG). It became apparent during the work of the Governor's Drought Task Force (1977) that there was no study available dealing with the extent and cyclic nature of the periods of deficient precipitation, and with the effects of those periods on ground-water levels. Therefore, in May 1977, the author submitted to the National Science Foundation (NSF) Science for Citizens Program a proposal for a research project dealing with the analysis of the periods of deficient precipitation in Wisconsin and their effect on ground water, and with the public perception of this problem.

The grant was awarded to the author in September 1977 in the form of a NSF Public Service Science Residency, and the Wisconsin DEG served as host institution for the duration of the project (June 26, 1978 to June 25, 1979).

Purpose and Objectives of the Project

The main purpose of the project was to develop data that would allow policy makers and state officials to make decisions regarding ground-water problems on the basis of scientific information.

Broad objectives of the project were to

1. establish and document the need for ground-water management and protection in Wisconsin;

2. provide interested public and citizen groups with understandable scientific information that would enable them to address the ground-water issues concerning them; and

3. provide technical information that would help the host government agency cope with the water shortage and to plan emergency measures for drought periods.

The results of the first two parts of the project were summarized in a final report to the NSF (Zaporozec, 1979b).

Specific objectives of the third part, which is presented in this publication, were to

1. analyze existing data on precipitation and ground-water levels for the duration of available records;

2. establish statewide drought years and determine the extent of the 1976 drought relative to other drought years;

3. analyze long-term trends in water-level fluctuations on selected wells in northern Wisconsin, determine periods of low water levels, compare the 1976-77 water levels relative to other below-normal hydrologic years, and document whether the reported ground-water shortages of 1976-77 were caused solely by the drought or by other factors as well; and

4. develop a planning tool that would enable governmental agencies to be prepared for periods of low ground-water levels.

Methods Used

The glaciated area of northern Wisconsin underlain by crystalline rocks of the southern part of the Precambrian Canadian Shield (Figure 1) was selected for the study for several reasons. First, most of the reported cases of ground water problems in 1976-77 came from this area. Second, northern Wisconsin is the largest area of the state with a relatively uniform hydrogeologic environment, which is a necessary prerequisite for achieving comparability of results. And finally, observation wells in northern Wisconsin have the longest records; monitoring of water levels began there at the Forest Ranger Stations in the middle 1930's.

Statistical analysis of existing data on precipitation (USDA, 1910-1969; USDC, 1970-1978) and water-level measurements on observation wells (USGS, 1935-77; 1972-79) was the principal method used for the determination of drought years and their effect on ground-water levels. Precipitation measurements were processed for the whole state. Average annual precipitation data from all

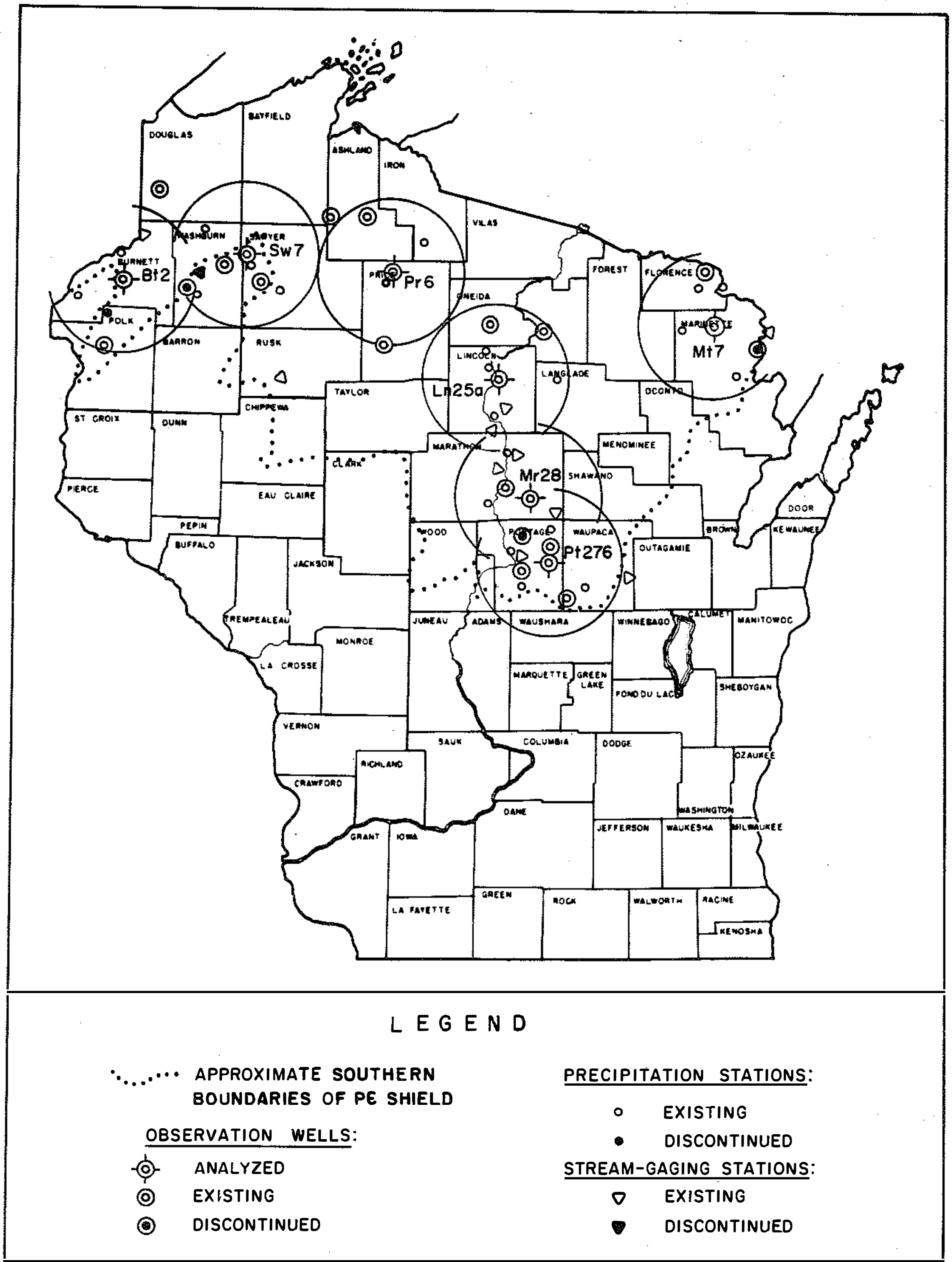

Figure 1. Location of observation wells used in analysis.

stations for each year since 1881 were used for the determination of state averages. In addition, precipitation at the stations nearest the analyzed wells was statistically evaluated (see tables 7 in Appendix B). Weekly water-level measurements were processed for the seven wells in northern Wisconsin for all available hydrologic years. Prior to the actual processing of the statistical set, the measurements were checked for accuracy and completeness. Erroneous values were corrected and missing data supplemented from the records of the closest stations. Statistical methods used in the analysis are described in Appendix A. Streamflow records (USGS, 1958-76; 1972-79) have been used to evaluate the relationship of ground-water levels to stream discharge (see tables 8 in Appendix B). Locations of the closest precipitation and stream-gaging stations are shown in figures 1 in Appendix B.

Although the records are readily available, they are not readily usable. Except for data on streamflow and on precipitation for selected stations, the information is not processed or summarized, and no basic statistical characteristics are available. Tabulation and calculation of basic statistical values from the raw data on file required considerable time.

Statistically processed data (published separately in Appendix B--Zaporozec, 1980) were used for the evaluation of long-term trends and cyclicity of water-level fluctuations. The resulting long-term values (mean water levels and record minimum water levels) were used for the development of a type curve that can be utilized as a planning tool for the determination of drought-proof depth of water wells. However, to achieve a higher statistical reliability and to apply the concept to different hydrogeologic conditions, it would be necessary to analyze data from a larger number of wells with long periods of record (at least 20 years) and located in a variety of hydrogeologic environments.

Previous Investigations

General patterns of Wisconsin climate and weather were described by Rosendal (1967). Preliminary evaluation of the frequency and spatial variation of drought in Wisconsin was not done until very recently (Mitchell, 1979); it is based on records at 18 stations for the period 1907-77, and is primarily from the viewpoint of agricultural drought. An overview of drought in Wisconsin was published in the report of the Governor's Drought Task Force (1977) and discussed at the Symposium on Drought in Mid-America (Upper Mississippi River Basin Commission, 1977). However, no in-depth study or analysis of the 1976 drought or previous droughts in Wisconsin has been made. A general summary of the 1976-77 drought and its effects in several parts of the United States, including Wisconsin, was published in 1979 (Matthai, 1979).

The effects of the 1976 drought on water supplies in Wisconsin were surveyed by the Wisconsin Department of Natural Resources (DNR) and Public Service Commission (municipal water supplies), Bureau of Environmental Health (hotel and restaurant supplies), and DEG (private supplies). Well problems reportedly occurred in 19 counties. Low yields and absence of yield made it necessary to truck water from various sources to alleviate problems of supply (Wisconsin DEG, 1977). Several municipal water systems had critical problems: Colby (Marathon County), Greenwood (Clark County), Iron Belt (Iron County), Thorp (Clark County), Sherwood (Calumet County), and Commonwealth Sanitary District

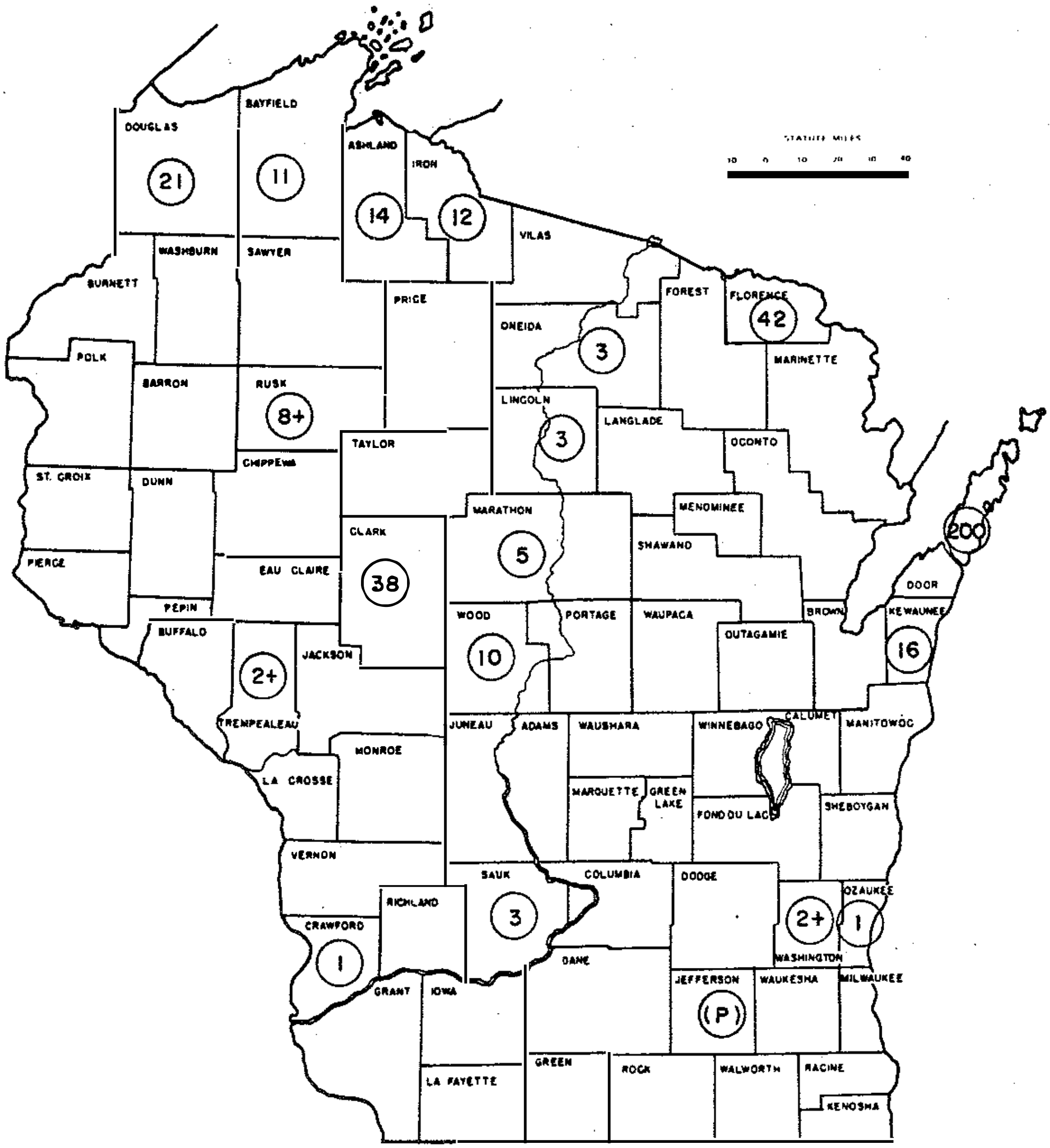

Figure 2. Map showing counties reporting water supply problems. (Source: Wisconsin Division of Emergency Government, 1977)

Numbers indicate the number of township and municipalities reporting health problems due to water supply. (P) indicates unspecified number of private water supplies in Jefferson County reported in FDAA survey. Counties shown in cross-hatching did not qualify for Presidential Emergency Declaration.

(Florence County). Reported problems are summarized in Figure 2. This information is very probably incomplete; the results of the surveys have never been published or summarized, which is unfortunate, as they might provide valuable clues for future studies.

Relatively few ground-water investigations have been made in northern Wisconsin and most of them are of a general nature. General ground-water characteristics were outlined by Cotter (1976), Drescher (1956), and Weidman and Schultz (1915). Ground-water resources of the area are briefly summarized in the USGS Hydrologic Investigations Atlases HA-321 (1968), HA-386 (1972), HA-451 (1973), HA-470 (1973), HA-524 (1974), and HA-536 (1975). A detailed account of the ground-water resources of Portage County was given by Holt (1965), and Weeks and others (1965). Lists of other publications on ground water were compiled by Zaporozec (1974; 1978a; 1978b).

Effects of precipitation on ground water were discussed in general by Drescher (1955), who also correlated the water levels in well Mr 28 with 5-year running average precipitation in Wausau. Relation of water levels in several other wells in the area to precipitation and/or streamflow was graphically expressed by Bell and Sherrill (1974) and in the Hydrologic Investigations Atlases mentioned above.

Ground-Water Monitoring

Wisconsin is one of the few states in which records of ground-water level measurements going back more than 40 years are available (Fishel, 1956). Periodic measurement of water levels began in June 1934 when 13 observation wells were put into service in southwestern Wisconsin (in the Coon Creek area) by the U.S. Soil Conservation Service. All but three of these 13 wells (Mo 2, Mo 10, and Ve 8) have since been discontinued (Table 1). During the years 1935-36, five more wells were added to the observation well program: one in the Coon Creek area and four installed by the Wisconsin Conservation Department (now DNR), in northeastern and central Wisconsin. In 1935, a nationwide observation-well program was initiated by the U.S. Geological Survey (USGS); this program included the 18 Wisconsin wells. In 1935-37, the Wisconsin Conservation Department established observation wells in each of its Forest Protection Districts in northern Wisconsin as a part of the shallow ground-water resources investigation. Five additional wells were installed during that period, bringing the total number of observation wells to 23 in 1938. These additional five wells (Bt 2, Ds 1, Pr 6, Sw 7, and Vi 3) have been in operation ever since. Through 1945, the number of observation wells remained below 30 (Figure 3). The numbering system used to designate wells in Wisconsin is explained in Devaul (1967).

The number of observation well began to increase rapidly in 1946 when the USGS, in cooperation with the Wisconsin Geological and Natural History Survey (WGNHS), began a statewide ground-water monitoring program (Audini and others, 1959). During the period 1946-50, 217 wells were added to the observation network. By 1954 the network had reached its peak of 270 wells and measurements covered 55 counties. In 1956, a substantial number of wells (34) were dropped from the program. By 1957, coverage was extended to 64 counties, although the number of wells dropped to 208. Since 1958, the number of observation wells has stabilized at little over 200 (Figure 3). Not until 1965 did the number of observation wells drop below 200; in that year, measurements were made in 196 wells in 66 of 72 counties (Devaul, 1967). The last information on the Wisconsin observation network was published in 1972 (Erickson, 1972). In 1978, according to the USGS files, measurements were made in 204 wells in 67 counties (Eau Claire, Iron, LaCrosse, and Washington Counties were not covered). Twenty-six of these wells were equipped with recording gages; 17 were measured weekly and 161 were measured monthly (Table 1).

Table 1. Summary of existing observation wells as of December 31, 1978

Period of Continuous Record	Number of Wells	Frequency of Measurement		
		Monthly	Weekly	Recording
45 years	3	3	--	--
41-44	4	--	4	--
31-40	47	32	7	8
21-30	52	38	4	10
11-20	56	52	--	4
10 or less	42	36	2	4
TOTAL	204	161	17	26

Cooperation and Acknowledgments

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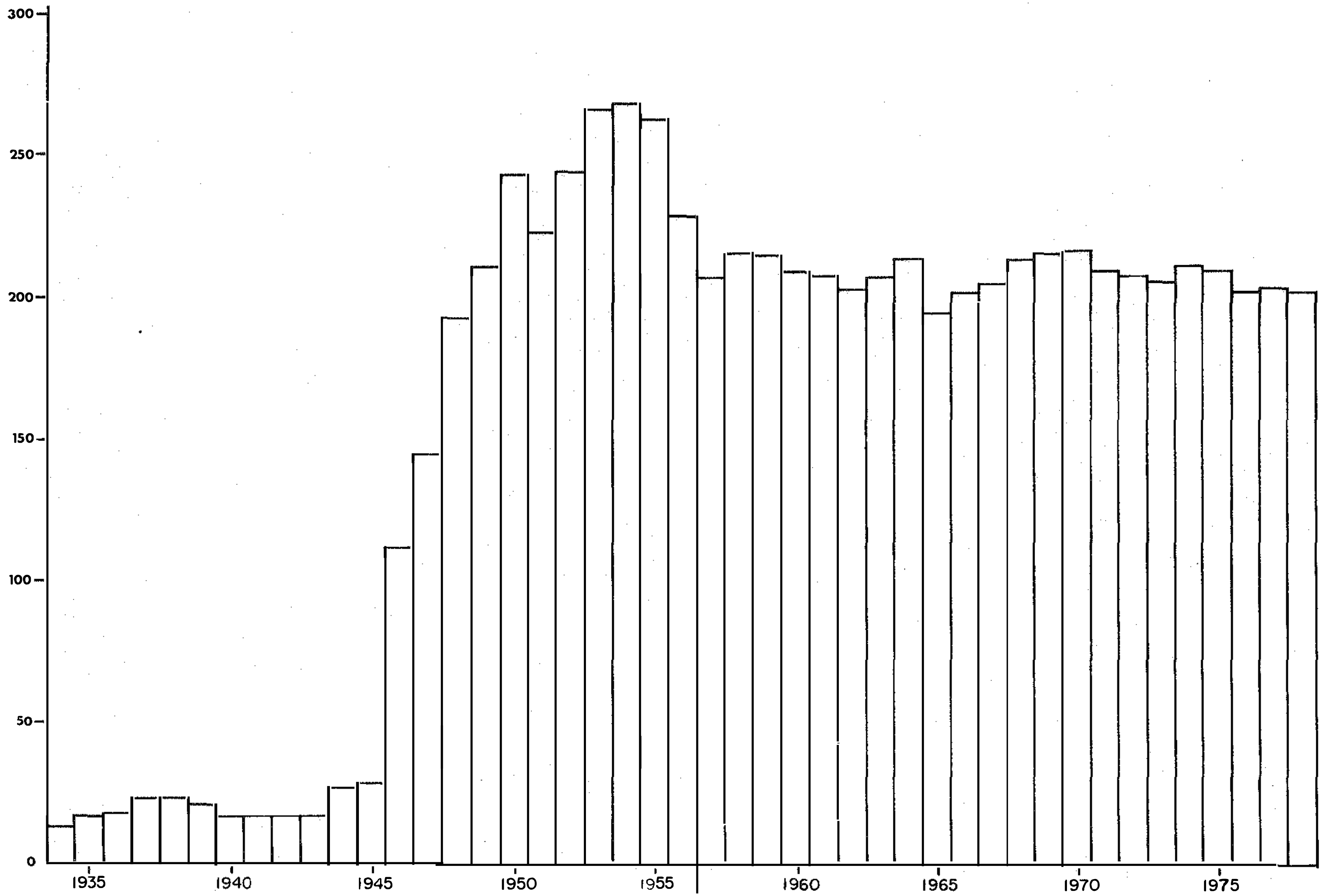

Figure 3. Number of observation wells in Wisconsin by year. The major addition of wells in 1946 represents the beginning of organized monitoring of ground water.

Wisconsin DNR; by District Engineers of the DNR Northwest, North Central, and West Central Districts; and by the USGS Reports Section and Northeastern Region.

Special appreciation is due to the Wisconsin Geological and Natural History Survey and the U.S. Geological Survey District Office in Madison for providing access to data on observation wells, ground-water levels, and streamflows in their files. Special thanks go to William B. Mann, District Chief; R.D. Cotter, Assistant District Chief; R.M. Erickson; and L.C. Trotta. Dale Cotter and Jack Green were kind enough to review the report and make valuable suggestions. Dr. V.L. Mitchell, State Climatologist, and his staff were extremely helpful in providing all necessary data on precipitation. Data on precipitation in neighboring states were supplied by the offices of the state climatologist in Michigan, Minnesota, Illinois, and Iowa.

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PHYSICAL SETTING OF STUDY AREA

Location and Physiography

The study area is approximately bounded by the southern edge of exposed Precambrian Canadian Shield, which projects into 14 counties and parts of another 14 counties in northern and central Wisconsin (see Figure 1). It includes all of Ashland, Bayfield, Douglas, Florence, Forest, Iron, Langlade, Lincoln, Marathon, Menominee, Oneida, Price, Taylor, and Vilas Counties; most of Burnett, Marinette, Portage, Rusk , Sawyer, Shawano, Waupaca, and Wood Counties; portions of Chippewa, Oconto, Polk, and Washburn Counties; and negligible portions of Barron and Clark Counties. Physiographically, it belongs to the Superior Upland Province (Northern Highland of Martin, 1932)--an undulating upland characterized by irregularities and low to moderate relief averaging 200 ft. It also contains the highest point in Wisconsin: Timms Hill in Price County, 1,951.50 ft above mean sea level (msl).

Climate

The location of Wisconsin near the center of the North American continent provides a typical temperate, subhumid to humid, continental climate. It is characterized by regular alternation of four climatic seasons, with very cold winters and rather hot summers and by moderate amounts of rainfall. Precipitation is normally adequate for the vegetation and the economy of the state. Long-term average annual precipitation is about 31 in., with the greatest amount (69% of the total) concentrated in the six monts of the growing season (April-September).

Drainage

The area is situated on the subcontinental divide between the Atlantic Ocean (St. Lawrence River basin) on the north and the Gulf of Mexico (Mississippi River basin) on the south. It is the headwater region for all major river systems in Wisconsin: the St. Croix, Chippewa, Wisconsin, Menominee-Peshtigo-Oconto, and Fox-Wolf river basins. Water is stored in numerous lakes, swamps, and marshes, and flows out in all directions approximately from a center near Land O'Lakes. Due to the relatively recent retreat of the continental glacier (about 10,000 years ago), streams have accomplished very little in draining this area. The drainage system is poorly developed and approximately 40 percent of the area is either water or swamp. Glacial activity is also responsible for the high density of lakes and swamps (Figure 4). Taking into account all named lakes and the unnamed lakes over 20 acres in size (Wisconsin DNR, 1978), the average number of lakes per square mile is 0.49 in comparison to 0.08 in the rest of the state. This is more than double the state average of 0.23 lakes per square mile. The greatest concentration is in Vilas County which has 1.53 lakes per square mile. The area features the largest springs in the state, with a discharge of 3.5 or more cubic feet per second (cfs). These springs are concentrated along a large tectonic zone of the Lake Owen and Douglas faults in the northwestern part, especially in Washburn County (Zaporozec 1975).

Geology

Rocks in the study area belong to the opposing end members of the geologic time scale, Precambrian and Pleistocene. The bedrock is composed mainly of metamorphic and igneous rocks of Precambrian age (more than 600 million years old), which are covered by glacial sediments of variable thickness of Pleistocene age. The basement rocks were intensively folded, faulted, and subjected to igneous and metamorphic activity during a long and complex history, and finally were extensively eroded by continental glaciers and other agents. Major continental ice sheets advanced to and retreated from this area about 10,000 to 30,000 years ago, leaving behind a variety of unconsolidated deposits called glacial drift. Generally, two types of drift are recognized--outwash and till. Outwash is generally stratified sand and gravel, with varying amounts of silt, sorted and deposited by meltwaters associated with the glacier. Till is generally unstratified and is composed of an unsorted mixture of cobbles, gravel, sand, silt, and clay deposited by glacial ice.

Other special features of the area include scenic waterfalls and rapids; quartzite monadnocks (isolated, resistant bedrock hills protruding above the old erosional surface); mineral deposits (iron, copper, zinc); and state and national forests and recreational areas.

Ground-Water Supplies

Ground water is a very important source of water supplies in Wisconsin. Almost half of the total amount of water used in Wisconsin for municipal, industrial, and rural supplies comes from ground-water sources (Zaporozec, 1975). Ninety percent of the communities served by central water-supply systems use ground water from wells and springs; and almost all the water (over 80%) consumed

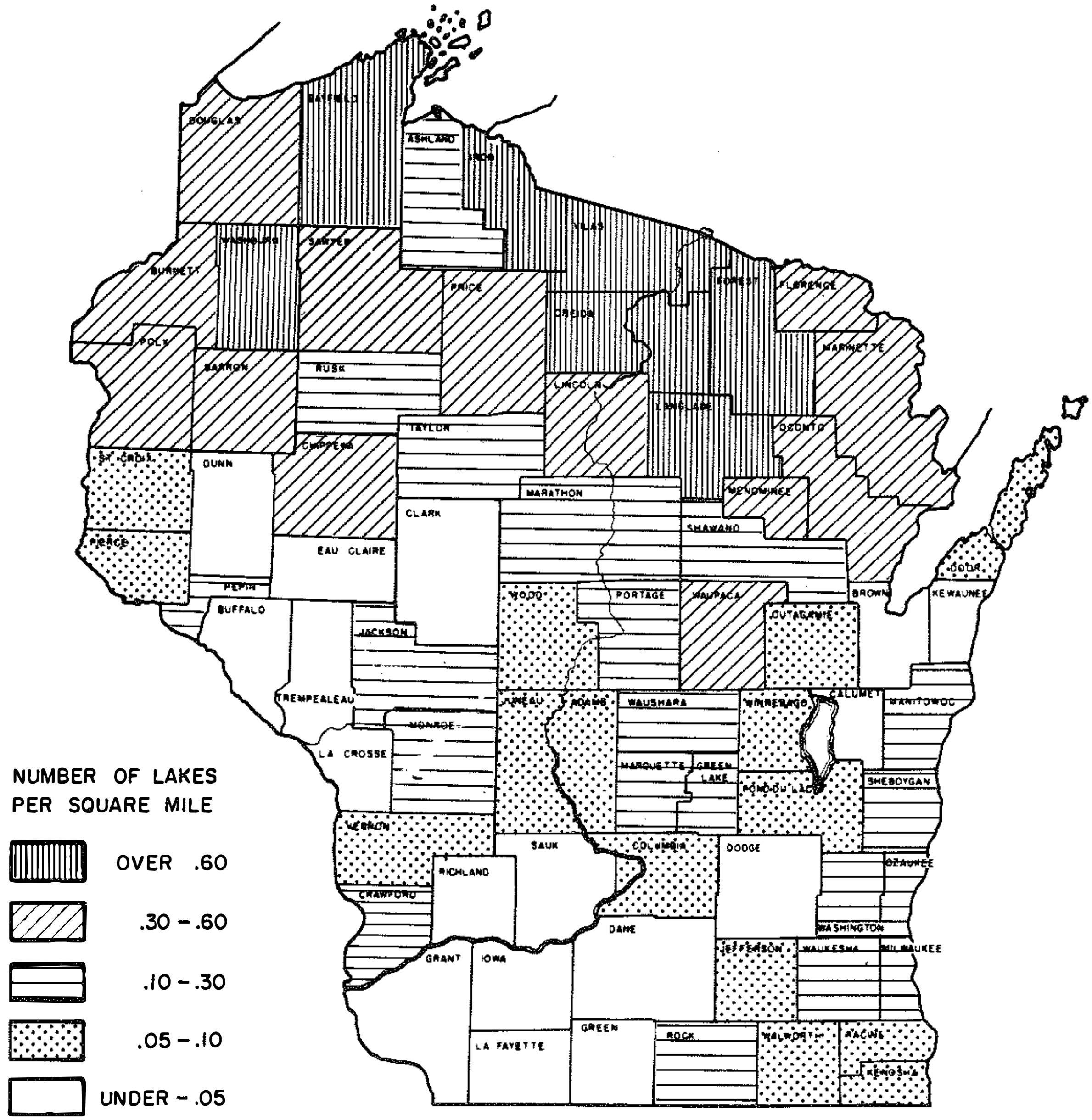


Figure 4. Map showing the relative density of lakes in Wisconsin by county (Source of data: Wisconsin Department of Natural Resources, Publ. 7-3600 [78]).

for rural uses (domestic supplies, stock watering, and irrigation) comes from ground-water sources. An analysis of ground-water use patterns (Zaporozec, 1979a) indicates that the ground-water portion of total water use (excluding water used for cooling in power production) is steadily increasing, rising from 43 percent in 1960 to 47 percent in 1975.

Wisconsin ground-water resources are plentiful, and adequate amounts are generally available throughout the state. Precipitation annually brings about 31 in. of water to the land surface. In most areas, soil and rock properties are favorable for storage of the excess water (approximately 17 percent of the annual precipitation) which remains after loss from evapotranspiration, saturation of the soil, and runoff to streams (Cotter, 1976). However, this excess water (the ground-water recharge) varies from place to place depending upon geological conditions, and from year to year in accordance with variations in precipitation. In some years there is no water available for ground-water recharge, and ground water has to be withdrawn from storage. Even though the exact amount of water in storage changes from year to year, over the long run, increases and decreases balance out and the net change is zero. However, periodic changes are reflected in fluctuations of ground-water levels.

Ground-Water Movement

Water from precipitation infiltrates into the ground and then, under the influence of gravity, moves toward the water table, which is the upper surface of the zone of saturation (Figure 5). In this zone, all spaces are filled with ground water. The water table is actually a free surface of water because the ground water is under pressure equal to atmospheric pressure. In confined (artesian) aquifers, ground water is not free; it is confined under pressure greater than atmospheric by overlying, relatively impermeable layers. The water level in a confined aquifer is represented by piezometric surface, an imaginary surface coinciding with the hydrostatic pressure level of the water in the aquifer. The piezometric surface can be both above the ground surface, as in the case of flowing wells, or below it.

Depth of the water table below the surface of the ground is controlled by the configuration of terrain, frequency and intensity of precipitation, and permeability of earth materials. The water table tends to be closer to the surface in relatively impermeable materials and in lowlands (discharge areas). It is deeper in relatively permeable materials and beneath topographic elevations (uplands, recharge areas). The water table usually resembles a flattened form of the surface relief, with elevations under hills and depressions below valleys. In Wisconsin, the depth to water table in shallow aquifers generally is from a few tens of feet to 50 ft below ground surface; piezometric surface varies from several feet above surface to 300 ft below surface (Zaporozec, 1975).

Contours on the water table indicate its slope. Ground water moves downslope, perpendicular to the contours. Natural movement of ground water is from areas of higher ground-water potential (recharge areas) to areas of lower potential (discharge areas) (Figure 5). The distance that the ground water travels from a recharge to a discharge area depends upon the size of the basin and is generally only a few miles.

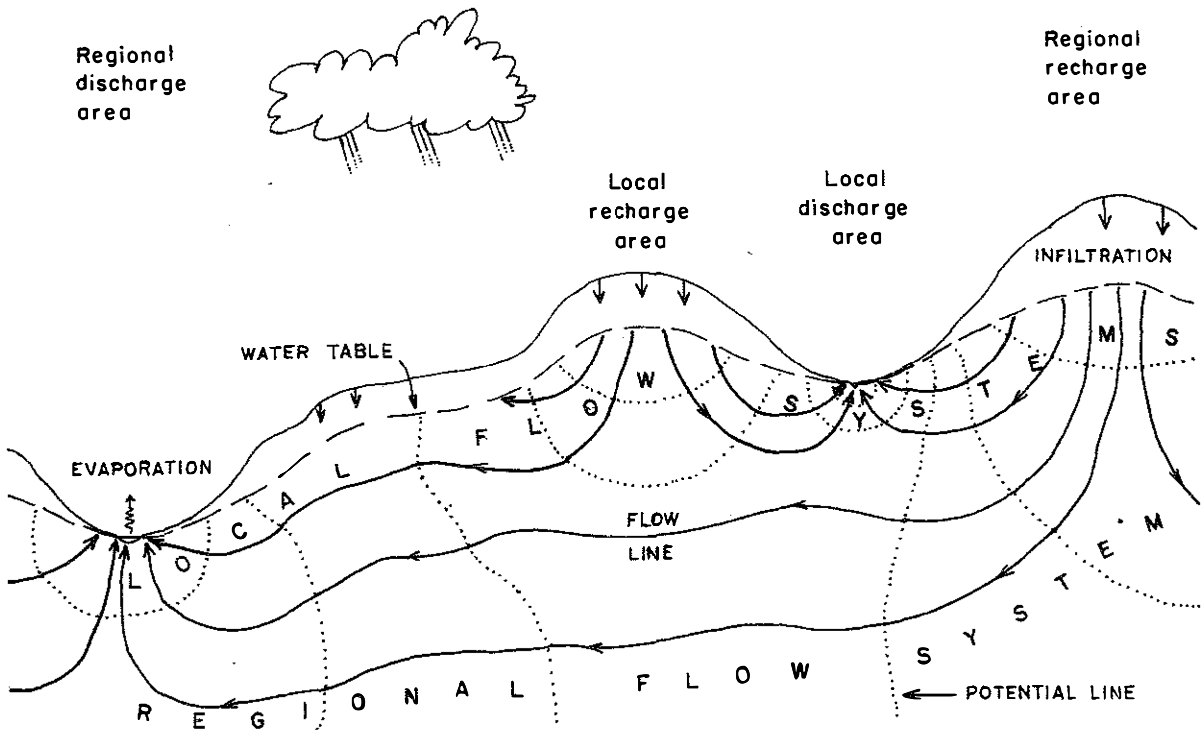


Figure 5. Idealized ground-water flow system.

Ground-Water Availability

Each geographic area of Wisconsin has unique soil-rock-water relationships because geology, topography, and climate vary regionally. On the basis of these three parameters, the state has been divided into three major hydrogeologic provinces (Meinzer, 1923) within which conditions are broadly similar: Drift-Crystalline (northern); Drift-Paleozoic (west central and eastern); and Paleozoic (southwestern). Usually, two other areas are also designated as hydrogeologic provinces (Drescher, 1956): Sand Plain (central) and Valley Alluvium (bordering the Mississippi, St. Croix, Chippewa, Wisconsin, and Rock-Sugar rivers). The term province in this case is somewhat misleading, since it implies a large area of uniform character. More appropriate would be the term district (or region) as a subdivision of province. In fact, the district (or region) should be the fundamental hydrogeologic unit, since it is small enough to show regional variations and large enough to allow regional generalizations for planning purposes (Zaporozec, 1972). The State of Wisconsin can be subdivided into approximately 17 major hydrogeologic units. Preliminary subdivision is indicated in Figure 6.

The study area belongs to the Drift-Crystalline Province, a large hydrogeologic unit extending into Wisconsin from Minnesota and Canada. Ground water is generally available from unconsolidated deposits of glacial origin (outwash

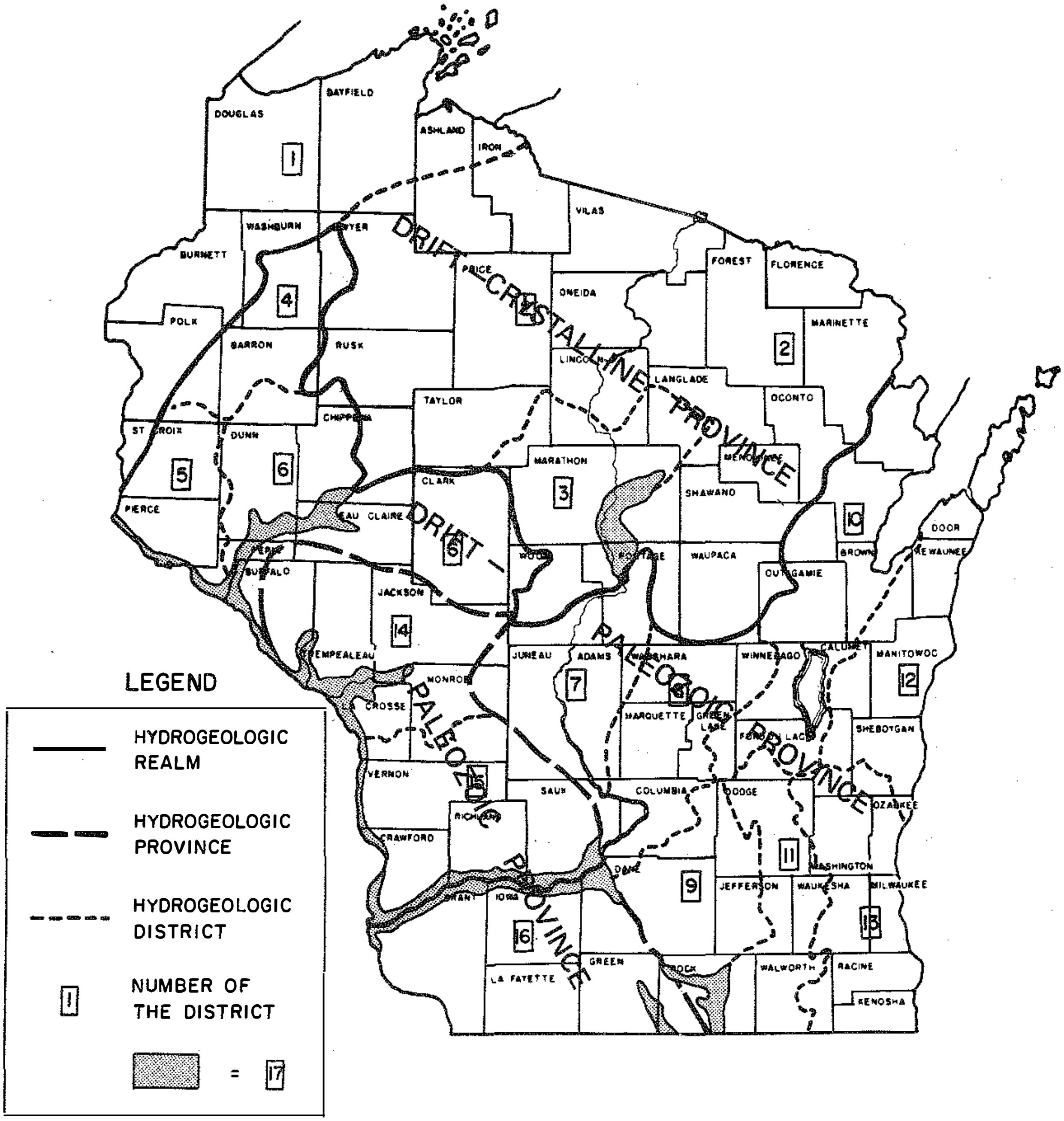


Figure 6. Map showing hydrogeologic units in Wisconsin. The stipple pattern includes gravel-based aquifers (river valley alluvium and outwash).

and till), and to a limited extent from river valley alluvium, in small (5-10 gallons per minute - gpm) to adequate (10-100 gpm) amounts (occasionally up to 400 gpm). Locally, Precambrian bedrock serves as a source of water supplies; fractures or weathered zones in crystalline rocks yield limited amounts of less than 2 gpm and sandstones have adequate yields of 10-100 gpm. Precambrian sandstones are limited to the northwestern part of the province (Lake Superior Syncline). In the south central part of the province, the Precambrian intrusive rocks are either exposed or thinly covered by glacial till and yield very little water. Principal sources of water here are buried bedrock channels filled with Pleistocene and Holocene sand and gravel.

The Drift-Paleozoic Province is a part of Meinzer's North-Central Drift-Paleozoic Province, which covers parts of Minnesota, Iowa, Missouri, Illinois, Indiana, Michigan, Ohio, Pennsylvania, and New York. Ground water occurs in both unconsolidated glacial deposits of Pleistocene age and consolidated rocks of Paleozoic age. Throughout the entire province good aquifers, either glacial or bedrock, supply water in adequate quantity (Devaul, 1975a; 1975b; 1975c). For convenience, the bedrock aquifers are subdivided into two groups: upper aquifers and sandstone aquifers. The subdivision is based on well-construction practices, which generally reflect hydrogeologic conditions. The boundary between the two aquifers is set at the base of the Tunnel City Group of Cambrian age.

The Drift-Paleozoic Province is separated by the Paleozoic Province into two parts. The west central part relies mostly on bedrock aquifers consisting of Cambrian sandstones. The eastern part has a variety of aquifers including Pleistocene sand and gravel, Silurian Niagara dolomite, Cambrian-Ordovician sandstones and dolomites, and Cambrian sandstones. The sandstone aquifer is the most heavily pumped aquifer in the state. Heavy pumping has resulted in regional decline of ground-water levels in the Milwaukee-Waukesha, Green Bay, and Madison metropolitan areas.

The Paleozoic Province is a part of the glaciated area of the United States not covered by glacial deposits (the so-called Driftless Area of Wisconsin, Illinois, Iowa, and Minnesota). Sedimentary rocks of Cambrian and Ordovician age (sandstones, dolomites, and shales) overlie Precambrian crystalline rocks in this province. The entire sequence may act as a single aquifer or, when separated by less permeable layers, as several aquifers of moderate to large yields. The mantle covering the bedrock is generally very thin and unsaturated.

PATTERNS OF PRECIPITATION IN WISCONSIN

Definition of Drought

A large part of the United States was more severely affected by the 1976-77 drought than by other droughts in at least the preceding 50 years (Matthai, 1979). Before the rains came in the summer of 1977, severe drought covered most of the western states and the Upper Midwest, including Wisconsin. As is usually the case, it started rather inconspicuously, and many people were not convinced that drought conditions existed. The existence of drought is difficult to recognize because its onset is usually a subtle process--certainly it is not as cataclysmic as other natural disasters such as floods and earthquakes--and because it produces effects in a scattered or random pattern (Matthai, 1979). Thus any definition of drought must be tailored to conditions in an area at a given time. Even so the definition must be general, because any definition other than one in very general terms is too restrictive.

A drought is primarily a natural event resulting from a prolonged and abnormal moisture deficiency. Drought means various things to various people, depending upon their specific interests. Numerous definitions of drought have been proposed and used during the past 60 years (Changnon, 1979). No completely adequate or even generally accepted definition is available (Warrick, 1975). Moreover, a precise definition is not practical because a drought is the result of many complex factors (Matthai, 1979). Drought is not strictly a physical phenomenon but rather represents an interplay between the natural system, the available precipitation, and the human and plant systems that are related to precipitation variations (Changnon, 1979). In arid or semiarid areas, water deficiencies are chronic. In humid or subhumid areas, drought conditions mean insufficient moisture in the soil to maintain plant life or meet established human needs.

The World Meteorological Organization has defined six categories of drought (Subrahmanyam, 1967):

1. meteorologic drought,
2. climatological drought,
3. atmospheric drought,
4. agricultural drought,
5. hydrologic drought,
6. water-management drought.

Palmer (1965) defines meteorologic drought as a prolonged period, generally on the order of months or years, during which the actual moisture supply at a given place rather consistently falls short of the climatically expected or climatically appropriate moisture supply. Climatological drought is defined in terms of precipitation deficiences--not as to specific quantities, but as a ratio to mean or normal values. Definition of atmospheric drought involves not only precipitation but also temperature, humidity, and wind speed. Agricultural drought is any shortage of moisture in the root zone of crops which can cause serious crop damage over a sizable area. Hydrologic drought is drought of the type that affects, besides soil moisture, streamflows, levels in lakes and reservoirs, and ground-water levels.

In this report, only the impact of hydrologic drought on ground-water levels is considered. In the literature, the term hydrologic drought is commonly reserved for a succession of dry years in which the cumulative deficiency in precipitation is sufficient to be reflected in depleted storage in surface- or ground-water reservoirs. It is usually not applied to a few rainless weeks or even a year of deficient precipitation. Such events are commonplace and expected, and are ameliorated by water previously accumulated in the reservoirs. Using the definitions described above we must conclude that the 1976-77 drought was a significant meteorologic and agricultural drought in Wisconsin but only a marginal hydrologic drought. Its effects on streamflows and ground-water levels were not long lasting. The water levels of wells directly related to precipitation were below normal for nine to 13 months. The wells with longer response to precipitation (Bt 2, Mr 28, Pt 276) had low water levels lasting from 16 to 22 months.

Because droughts result from a combination of events, there is no direct measure of their magnitude. Two measures most commonly used are deficiencies in precipitation and extent of area affected (W.G. Hoyt, 1942). A useful measure of moisture deficiency, and the most meaningful quantified presentation of drought-related information for most users, is the percent of normal precipitation. According to various studies (J.C. Hoyt, 1936; 1938; Nace and Pluhowski, 1965), in humid areas serious drought effects do not occur unless the annual precipitation deficiency is 15 percent or more. Even though deficiency in precipitation is not the sole cause of drought, this somewhat arbitrary definition (85 percent of normal percipitation) has been used for the classification of drought years in this study.

Statistical Analysis of Wisconsin Precipitation

Even though the recent publications (Calabresa, 1977; Mitchell, 1977; Wis. Gov. Task Force, 1977) have listed several years as statewide drought years in Wisconsin (1895, 1910, 1939, 1948, 1958, 1976), these findings were based on the records of only a few stations. Therefore, it was necessary first to determine which years would qualify as statewide drought years using 85 percent of normal precipitation as a limit. Because no summarizing publication on Wisconsin precipitation data is available, statewide averages of all stations for a given year were compiled for the period 1881-1978 (Table 2), and graphically expressed in Figure 7. The years were then arranged in order of decreasing magnitude, and the corresponding percentage of normal precipitation was calculated. Although the emphasis of this study is on the pattern of dry years, statistical analysis included both dry and wet years. The ratio of dry years to wet years is almost equal: 47:50, one year being an average. The driest years (those with a deficiency of 15% or more) and the wettest years (those with an excess of 14% or more) are summarized in Table 3.

In the analysis, normal annual precipitation of 30.73 in. for the period of the last 90 years (1889-1978) has been used rather than the long-term average (1881-1978) of 31.20 in. because the number of precipitation stations in the decade 1881-1890 was not high enough to give a reliable statewide average. In 1881, measurements were made in only 8 stations (Beloit, Dubuque, Duluth, Embarrass, LaCrosse, Madison, Manitowoc, and Milwaukee), as opposed to 27 stations in 1891.

The graph of average annual precipitation (Figure 7) indicates that annual fluctuations are relatively large in amount but comparatively small in percentage of normal, seldom exceeding 15 percent (Table 3). The amplitudes of annual fluctuations are mostly smaller than 20 percent (6.1 in.), the largest being little over 50 percent (15.6 in. in 1910-11). The amplitudes of 30 percent or more (9.2 in.) are characteristic for extremely wet or dry years.

Table 2. Average annual precipitation in Wisconsin, 1881-1979
(90-year normal = 30.73 inches; mean = 31.20 inches)

Year	Precipitation		Year	Precipitation		Year	Precipitation		Year	Precipitation		Year	Precipitation	
	inches	percent of normal		inches	percent of normal		inches	percent of normal		inches	percent of normal		inches	percent of normal
1881	46.38	150.9	1891	26.12	85.8	1901	26.34	85.7	1911	37.00	120.4	1921	30.73	100.0
1882	37.15	120.9	1892	34.98	113.8	1902	32.59	106.1	1912	32.51	105.8	1922	31.42	102.2
1883	35.38	115.1	1893	29.80	97.0	1903	35.81	116.5	1913	32.81	106.8	1923	26.39	85.9
1884	40.86	133.0	1894	27.96	91.0	1904	31.55	102.7	1914	32.30	105.1	1924	33.06	107.6
1885	34.48	112.2	1895	22.45	73.1	1905	35.10	114.2	1915	32.79	106.7	1925	27.62	89.9
1886	33.74	109.8	1896	32.21	104.8	1906	34.20	111.3	1916	33.79	110.0	1926	35.05	114.1
1887	32.66	106.3	1897	27.77	90.4	1907	30.14	98.1	1917	27.35	89.0	1927	30.94	100.7
1888	31.02	100.9	1898	28.04	91.2	1908	29.36	95.5	1918	29.69	96.6	1928	33.09	107.7
1889	27.04	88.0	1899	30.54	99.4	1909	31.43	102.3	1919	33.22	108.1	1929	28.09	91.4
1890	37.04	120.5	1900	35.07	114.1	1910	21.41	69.7	1920	29.99	97.6	1930	25.08	81.6
1931	29.68	96.6	1941	34.00	110.6	1951	38.24	124.4	1961	32.44	105.6	1971	31.95	104.0
1932	25.37	82.6	1942	35.26	114.7	1952	28.75	93.6	1962	27.73	90.2	1972	35.81	116.5
1933	27.11	88.2	1943	29.51	96.0	1953	29.96	97.5	1963	23.78	77.4	1973	35.87	116.7
1934	30.55	99.4	1944	29.10	94.7	1954	36.07	117.4	1964	27.75	90.3	1974	29.65	96.5
1935	30.39	98.9	1945	35.16	114.4	1955	27.03	87.9	1965	38.50	125.3	1975	31.89	103.8
1936	25.41	82.7	1946	29.69	96.6	1956	27.45	89.3	1966	26.30	85.6	1976	21.71	70.6
1937	27.41	89.2	1947	29.99	97.6	1957	28.39	92.4	1967	30.89	100.5	1977	35.31	114.9
1938	41.64	135.5	1948	24.64	80.2	1958	23.28	75.8	1968	36.62	119.2	1978	35.71	116.2
1939	26.37	85.8	1949	27.62	89.9	1959	37.53	122.1	1969	28.78	93.7	1979	32.29*	105.1
1940	32.81	106.8	1950	30.54	99.4	1960	34.43	112.0	1970	31.78	103.4			

Data for 1881-1934 taken from J.C. Hoyt (1936) and for 1935-1953 from Climatological Data for the United States - Wisconsin Section. Annual averages for 1954-1978 were calculated from divisional averages. * Preliminary value.

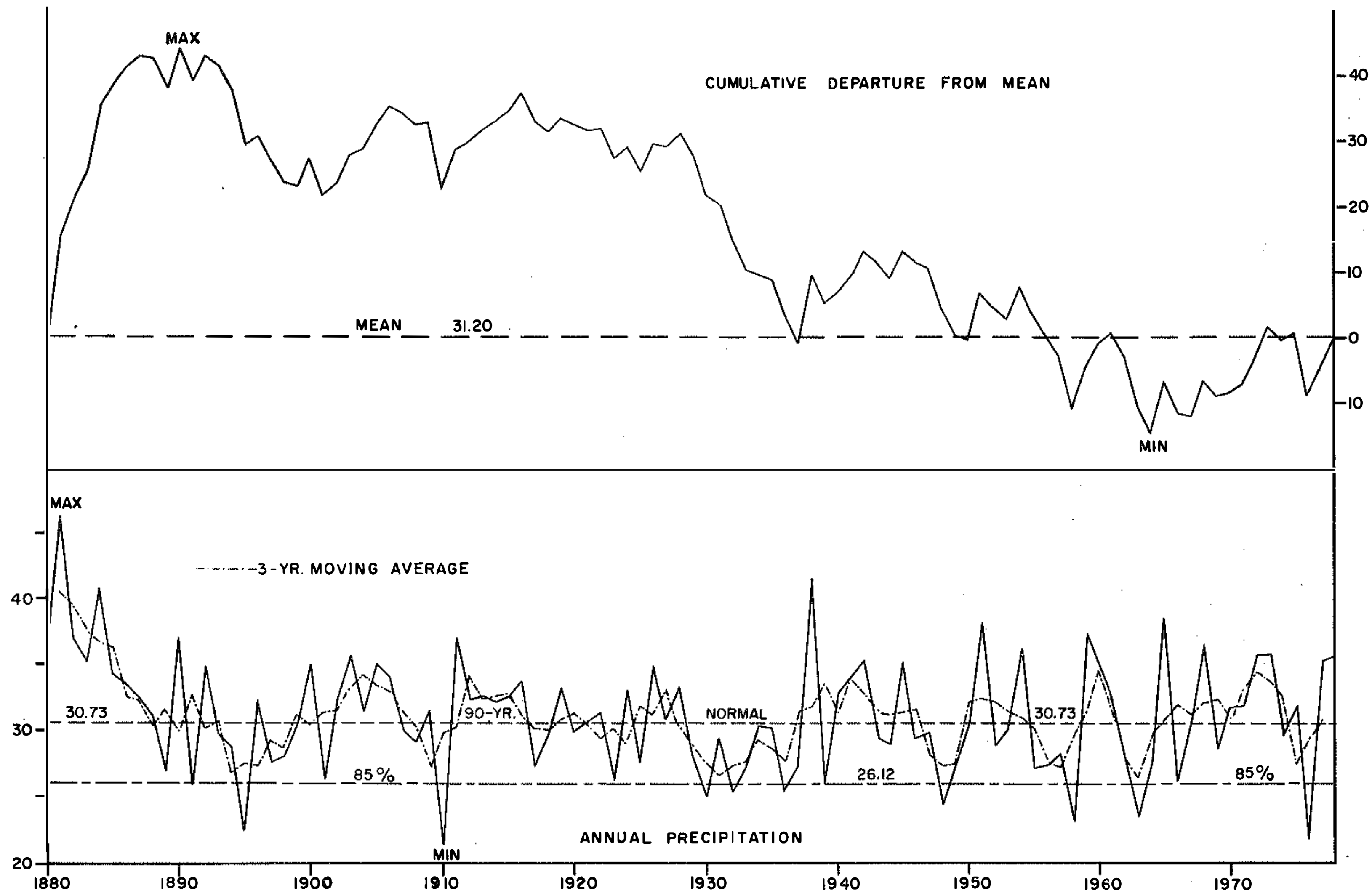


Figure 7. Diagram showing average annual precipitation in Wisconsin in inches. Upper diagram is cumulative departure from mean precipitation of 31.20 inches since 1880. The dash-dot line in the lower diagram shows 3-year moving average of the precipitation.

Table 3. Tabulation of driest and wettest years

No.	Driest Years (below 90%)			Wettest Years (above 114%)		
	Year	Average Precipitation		Year	Average Precipitation	
		inches	percent of normal		inches	percent of normal
1.	1910	21.41	69.7	1881	46.38	150.9
2.	1976	21.71	70.6	1938	41.64	135.5
3.	1895	22.45	73.1	1884	40.86	133.0
4.	1958	23.28	75.8	1965	38.50	125.3
5.	1963	23.78	77.4	1951	38.24	124.4
6.	1948	24.64	80.2	1959	37.53	122.1
7.	1930	25.08	81.6	1882	37.15	120.9
8.	1932	25.37	82.6	1890	37.04	120.5
9.	1936	25.41	82.7	1911	37.00	120.4
10.	1891	26.12	85.0	1968	36.62	119.2
11.	1966	26.30	85.6	1954	36.07	117.4
12.	1901	26.34	85.7	1973	35.87	116.7
13.	1939	26.37	85.8	1903	35.81	116.6
14.	1923	26.39	85.9	1972	35.81	116.5
15.	1955	27.03	87.9	1978	35.71	116.2
16.	1889	27.04	88.0	1883	35.38	115.1
17.	1933	27.11	88.2	1977	35.31	114.9
18.	1917	27.35	89.0	1942	35.26	114.7
19.	1937	27.41	89.2	1945	35.16	114.4
20.	1956	27.45	89.3	1905	35.10	114.2
21.	1925	27.62	89.9	1900	35.07	114.1
22.	1949	27.62	89.9	1926	35.05	114.1

Table 4. Probability of exceedance of annual precipitation (median = 30.92 in.; p = probability in percent)

No. (m)	Year	Avg. Precip. (in.)	p (%)	Class. (See Tab.5)	No. (m)	Year	Avg. Precip. (in.)	p (%)	Class. (See Tab.5)
1.	1881	46.38	.71	WWWW	50.	1967	30.89	50.51	N
2.	1938	41.64	1.73	WWWW	51.	1921	30.73	51.52	N
3.	1884	40.86	2.74	WWWW	52.	1934	30.55	52.54	N
4.	1965	38.50	3.76	WWWW	53.	1899	30.54	53.57	N
5.	1951	38.24	4.78	WWWW	54.	1950	30.54	54.57	N
6.	1959	37.53	5.79	WWWW	55.	1935	30.39	55.59	D
7.	1882	37.15	6.81	WWWW	56.	1907	30.14	56.61	D
8.	1890	37.04	7.82	WWWW	57.	1920	29.99	57.62	D
9.	1911	37.00	8.84	WWWW	58.	1947	29.99	58.64	D
10.	1968	36.62	9.86	WWWW	59.	1953	29.96	59.65	D
11.	1954	36.07	10.87	WWW	60.	1893	29.80	60.67	D
12.	1973	35.87	11.89	WWW	61.	1918	29.69	61.69	D
13.	1903	35.81	12.91	WWW	62.	1946	29.69	62.70	D
14.	1972	35.81	13.92	WWW	63.	1931	29.68	63.72	D
15.	1978	35.71	14.94	WWW	64.	1974	29.65	64.74	D
16.	1883	35.38	15.95	WWW	65.	1943	29.51	65.75	D
17.	1977	35.31	16.97	WWW	66.	1908	29.36	66.76	DD
18.	1942	35.26	17.99	WWW	67.	1944	29.10	67.78	DD
19.	1945	35.16	19.00	WWW	68.	1969	28.78	68.80	DD
20.	1905	35.10	20.02	WW	69.	1952	28.75	69.82	DD
21.	1900	35.07	21.04	WW	70.	1957	28.39	70.83	DD
22.	1926	35.05	22.02	WW	71.	1929	28.09	71.85	DD
23.	1892	34.98	23.07	WW	72.	1898	28.04	72.87	DD
24.	1885	34.48	24.08	WW	73.	1894	27.96	73.88	DD
25.	1960	34.43	25.10	WW.	74.	1897	27.77	74.90	DD
26.	1906	24.20	26.12	WW	75.	1964	27.75	78.91	DD
27.	1941	34.00	27.13	WW	76.	1962	27.73	76.93	DD
28.	1916	33.79	28.15	WW	77.	1925	27.62	77.95	DD
29.	1886	33.74	29.17	WW	78.	1949	27.62	78.96	DD
30.	1919	33.22	30.18	WW	79.	1956	27.45	79.98	DD
31.	1938	33.09	31.20	WW	80.	1937	27.41	81.00	DDD
32.	1924	33.06	32.12	WW	81.	1917	27.35	82.01	DDD
33.	1913	32.81	33.23	W	82.	1933	27.11	83.83	DDD
34.	1940	32.81	34.25	W	83.	1889	27.04	84.04	DDD
35.	1915	32.79	35.26	W	84.	1955	27.03	85.06	DDD
36.	1887	32.66	36.28	W	85.	1923	26.39	86.08	DDD
37.	1902	32.59	37.30	W	86.	1939	26.37	87.09	DDD
38.	1912	32.51	38.30	W	87.	1901	26.34	88.11	DDD
39.	1961	32.44	39.33	W	88.	1966	26.30	89.13	DDD
40.	1914	32.30	40.35	W	89.	1891	26.12	90.14	DDDD
41.	1896	32.21	41.36	W	90.	1936	25.41	91.16	DDDD
42.	1971	31.95	42.38	W	91.	1932	25.37	92.17	DDDD
43.	1975	31.89	43.39	W	92.	1930	25.08	93.19	DDDD
44.	1970	31.78	44.41	N	93.	1948	24.64	94.21	DDDD
45.	1904	31.55	45.43	N	94.	1963	23.78	95.22	DDDD
46.	1909	31.43	46.44	N	95.	1958	23.28	96.24	DDDD
47.	1922	31.42	47.46	N	96.	1895	22.45	97.26	DDDD
48.	1888	31.02	48.48	N	97.	1976	21.71	98.27	DDDD
49.	1927	30.94	49.49	N	98.	1910	21.41	99.29	DDDD

The individual values of precipitation can be regarded as elements of a statistical set. In their processing and analysis, conventional methods of mathematical statistics were used, as described in Appendix A.

The data for the average annual precipitation arranged in chronological order in Table 2 were transferred to Table 4 and rearranged in order of descending amount; each value was assigned a serial number (m) from 1 to 98. From Table 4 it is evident that the highest value (46.38 in.) was attained, and thus occurred, only once; and therefore its m = 1. The second highest value (41.64 in.) was attained (was exceeded) twice, hence m = 2. The lowest value (21.41 in.) was exceeded in every occurrence and its m = 98. The values in column 4 give, in percent, probability of exceedance of average annual precipitation. The values correspond to the percent of observed events that were equal to, or larger than, a given event within the period of record under observation. They were calculated using the Chegodayev formula (Nemec, 1972): $p = (m - 0.3)/(n + 0.4) \times 100$. In the evaluation of the wetness of individual years, a nine-part classification scale (Table 5) was used (Dub, 1963).

Table 5. Classification scale of wetness based on probability of exceedance (Dub, 1963)

Probability (%)	Category	Symbol
0.00- 10.00	Extremely Wet	WWWW
10.01- 20.00	Very Wet	WWW
20.01- 33.33	Moderately Wet	WW
33.34- 44.99	Slightly wet	W
45.00- 55.00	Near-normal	N
55.01- 66.66	Slightly dry	D
66.67- 79.99	Moderately dry	DD
80.00- 90.00	Very dry	DDD
90.01-100.00	Extremely dry	DDDD

Table 4 can be used for calculating the average interval of time within which the magnitude of the event will be equaled or exceeded once on the average (recurrence interval, T). The recurrence interval (return period) is the reciprocal of the probability of occurrence of an event (p): $T = 1/p$. Since in our case we are not interested in high values of precipitation or in how often the event will occur but rather in low values, reciprocal relationship or probability of not being equaled or attained can be used: $T = 1/(1 - p)$. For example, there is a probability of 90 percent that precipitation in the amount of 26.12 in. will be attained. The recurrence interval for this value will be $T = 1/(1 - 0.9014) = 10.1$ years. The median value of 30.92 in. has a probability of 50 percent, hence the recurrence interval is 2 years. Similarly, the recurrence interval of the minimum precipitation of the annual series will be 140.8 years, which means that this extremely low precipitation of 21.41 in. (recorded in 1910) will occur on the average once every 141 years.

Probability values can be plotted against the corresponding average annual precipitation to obtain a probability curve that can be used for prediction of precipitation in the future. However, the return period obtained from the period of observation (98 years) is quite long--141 years--and the use of the probability curve is not necessary.

A frequency distribution analysis was made to evaluate the distortion of observed values. The range of values for the period of record (21 to 47 in.) was divided into 13 classes (intervals) of equal length of 2 in. and summarized in Table 6. The number of occurrences in each of the intervals was plotted to obtain a frequency distribution graph (histogram) in Figure 8. The shape of the broken line connecting the midpoints of the tops of the successive columns in the graph indicates an irregular character of data. The distribution is asymmetric and negatively skewed; distinct bimodal distribution indicates nonhomogeneous data with one peak between 29-31 in. and another between 35-37 in.

Table 6. Frequency of average annual precipitation in Wisconsin

Interval (inches)	Frequency (n)		Cumulative Frequency (duration)	
	Absolute (n)	Relative ($\frac{n}{N}$)	Absolute (Σn)	Relative ($\frac{\Sigma n}{N}$)
45.01-47.00	1	1.02	1	1.02
43.01-45.00	0	0	1	1.02
41.01-43.00	1	1.02	2	2.04
39.01-41.00	1	1.02	3	3.06
37.01-39.00	5	5.10	8	8.16
35.01-37.00	14	14.29	22	22.45
33.01-35.00	10	10.20	32	32.65
31.01-33.00	16	16.33	48	48.98
29.01-31.00	19	19.39	67	68.37
27.01-29.00	17	17.35	84	85.72
25.01-27.00	8	8.16	92	93.88
23.01-25.00	3	3.06	95	96.94
21.01-23.00	3	3.06	98	100.00
	N = 98	100.00%		

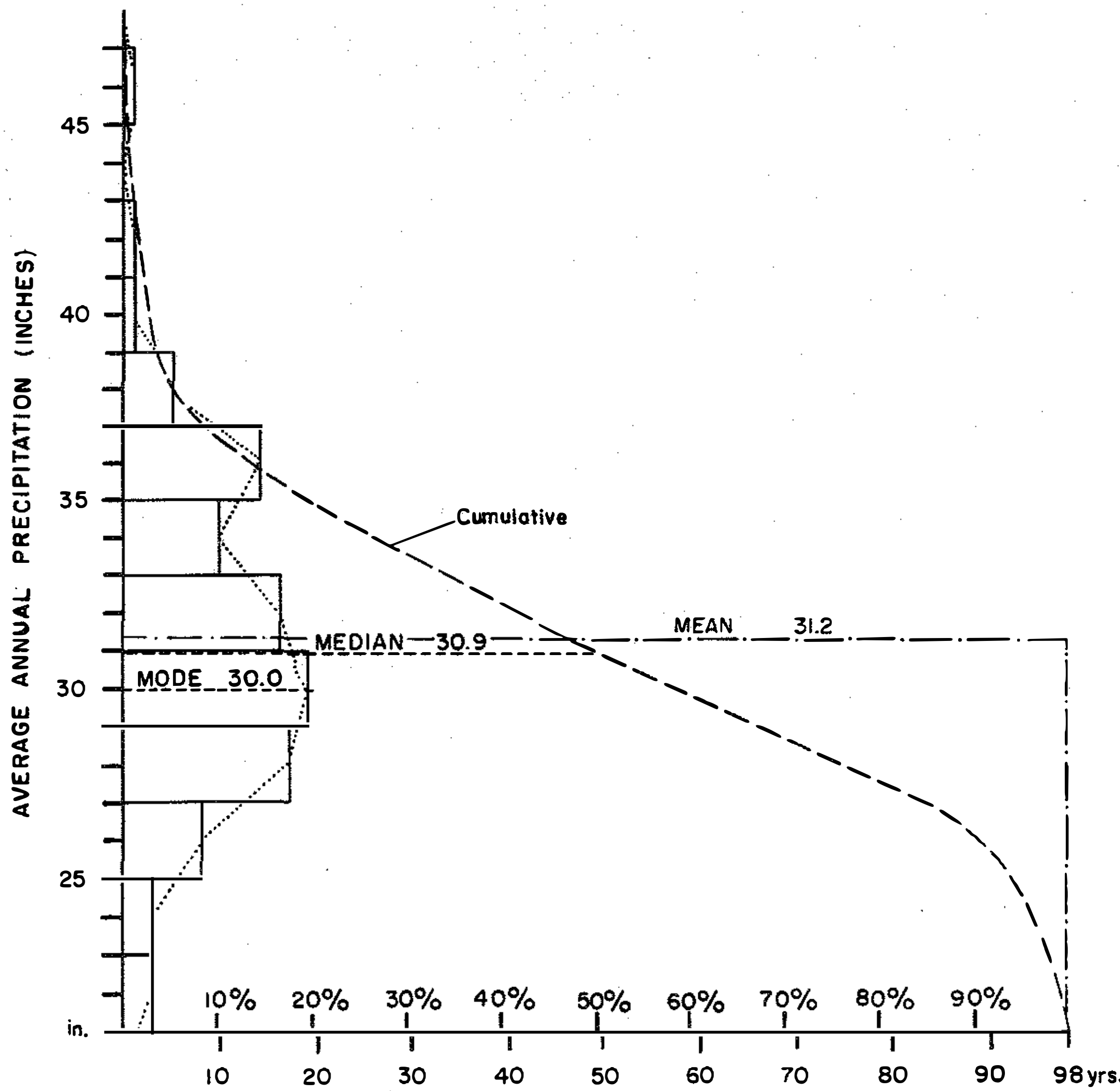


Figure 8. Frequency distribution of average annual precipitation in Wisconsin. The dotted line represents a frequency polygon. The dashed line is a cumulative plot of frequencies. See page 75 for a discussion of "mean", "median", and "mode".

Frequency values were summed up to obtain cumulative frequency distribution, which was plotted in an ogive in Figure 8. The resulting frequency distribution curve indicates several characteristics. The value having a 50 percent cumulative frequency is the median of the series: 30.9 in. The value having the highest frequency (30.0 in.) is the mode. Finally, the arithmetic mean may also be determined from a line dividing the area of the curve in two halves.

Drought Periods

From the preceding discussion it follows that Wisconsin is not located in an arid zone; neither is it a typical drought-stricken state. Nevertheless, drought periods (or prolonged periods of moisture deficiency) are quite common, causing problems in agriculture and water supply by depleting soil moisture, ground-water and lake levels, and streamflows. Based on the criteria given at the beginning of this chapter, in the 98-year period 1881-1978, Wisconsin had 10 drought years when statewide average precipitation was 85 percent or less of normal (see Table 3): 1891, 1895, 1910, 1930, 1932, 1936, 1948, 1958, 1963, and 1976. Four more years can be classified as drought years, if we allow one percent for the possible inaccuracy of statewide averages: 1901, 1923, 1939, and 1966. The number of years in the period 1881 to 1978 when the precipitation did not exceed 85 percent or 86 percent of normal are given in Table 7.

Table 7. Number of years when precipitation did not exceed 86 percent of normal for 1889-1978 (30.73 in.)

Percent of Normal	No. of Years	Year	Precipitation (inches)	Precipitation (% of normal)
86	4	1923	26.39	85.9
		1939	26.37	85.8
		1901	26.34	85.7
		1966	26.30	85.6
85	5	1891	26.12	85.0
		1936	25.41	82.7
		1932	25.37	82.6
		1930	25.08	81.6
		1948	24.64	80.2
80	2	1963	22.78	77.4
		1958	23.28	75.8
75	2	1895	22.45	73.1
		1976	21.71	70.6
70	1	1910	21.41	69.7

In addition, there were 8 years when precipitation did not exceed 90 percent (see Table 3).

The years 1930, 1932, and especially 1963 have often been overlooked as statewide drought years in recent publications (Calabresa, 1977; Mitchell, 1977; 1979; Wis. Gov. Task Force, 1977). On the other hand, the year with the big reputation for being very dry, 1939, proved to be marginal in both deficiency (86%) and areal extent (45%). The relative ranking of the 14 worst dry years since 1881 is given in Table 8.

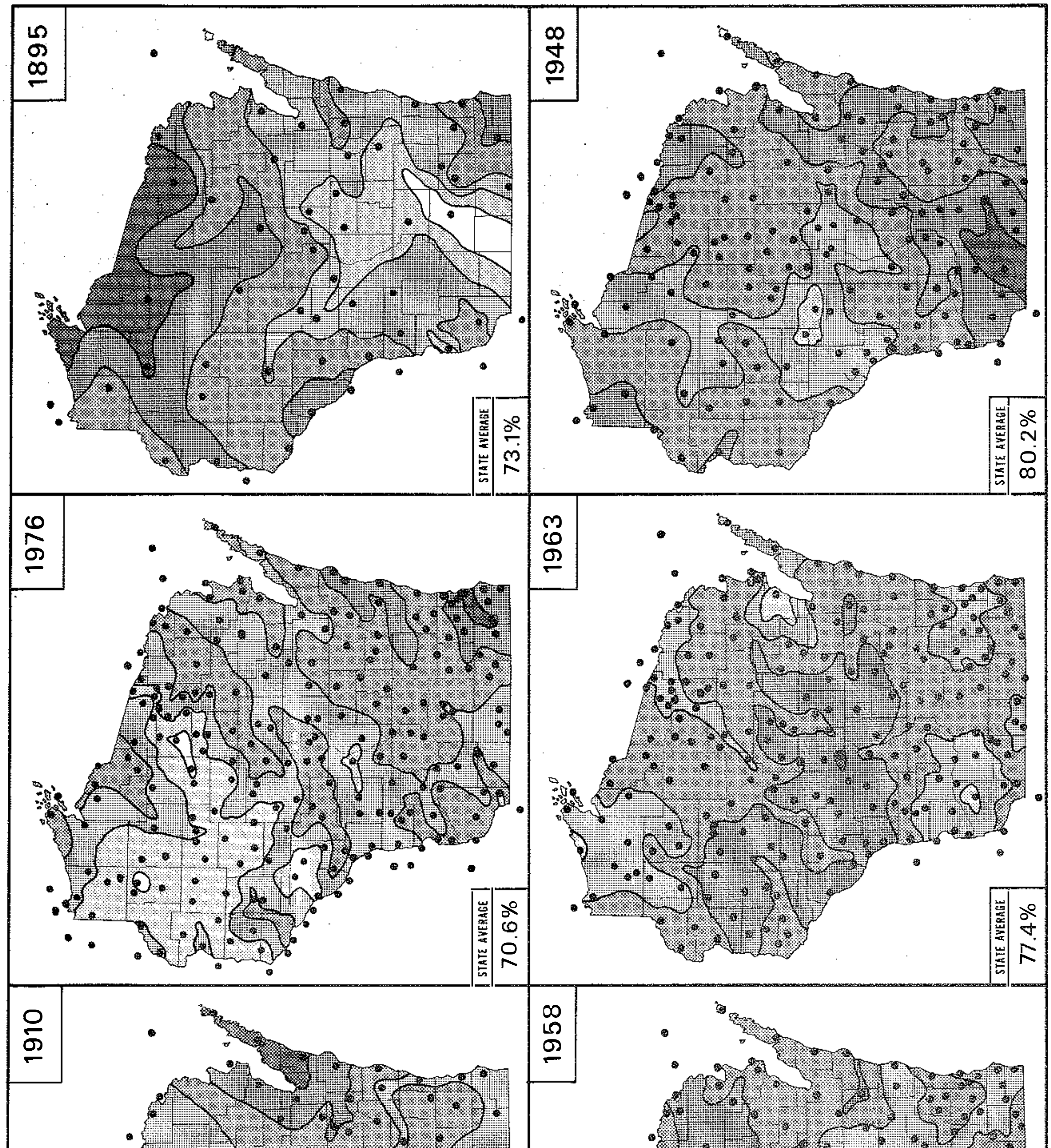
Areal extent of 12 of these 14 years is shown in Figure 9. Although there is no discernible pattern in the areal distribution of drought years over the state, the worst drought conditions, when the deficiency was 40 percent or more, seem to be concentrated in the southwestern half of the state (Figure 10).

Although drought years were defined on the basis of statewide average, this does not mean that drought occurred throughout the whole state. Various parts of the state were affected differently, and some parts may have experienced drought conditions while others had abnormal precipitation. Even in the years when the precipitation did not exceed statewide deficiency of 15 percent, some areas of the state were affected substantially. For example, in 1955 and 1956 approximately 35 percent of the state area was affected by drought. Similar conditions could be expected in the remaining dry years of the 1930's--1933 and 1937; of the 1940's--1944 and 1949; of the 1950's--1957; and of the 1960's--1962, 1964, and 1969, in which the deficiency was at least five percent.

Old records indicate that prior to 1881, there was only one year, 1872, when precipitation did not exceed 85 percent of normal (see Table 10). A good indicator of historical dry periods are the episodes of forest fires, which were recorded in the fall of 1871 and the summers of 1894, 1908, and 1910 (Wis. DEG, 1975). Another widely known source of information on drought periods is tree-ring analysis, which has not as yet been done in Wisconsin.

If we define the drought as a succession of dry years, not just a single year of deficient precipitation, then we can conclude from the cumulative departure curve in Figure 7 that in Wisconsin extended drought periods occurred in 1893-1901, 1917-1937, and 1946-1958. All drought years occurred during the following dry periods: 1889-1901, 1907-1910, 1929-1939, 1943-1958, 1962-1966, and 1974-1976 (Table 9).

Furthermore, the graph of average annual precipitation (Figure 7) shows that in the period 1917-1966 the sequence of dry years was interrupted only three times by more than one year of above-average precipitation: in 1926-28 (three years), 1940-42 (three years), and 1959-61 (three years). In this period of 50 years, 32 years (64%) had precipitation below normal. Such a prolonged period of deficient precipitation necessarily has an effect on ground-water levels. Therefore it is only natural that the all-time minimum levels occurred within this period (1949, 1959, or 1964) and did not follow the drought of 1976, which was a single drought year within the period of above-average precipitation of the last 14 years. In addition, the 1970's belong among the three decades that had above-average precipitation (the other two are the 1880's and 1910's).



1895
STATE AVERAGE
73.1%
1976
STATE AVERAGE
70.6%
1910
STATE AVERAGE
69.7%
1948
STATE AVERAGE
80.2%
1963
STATE AVERAGE
77.4%
1958
STATE AVERAGE
75.8%

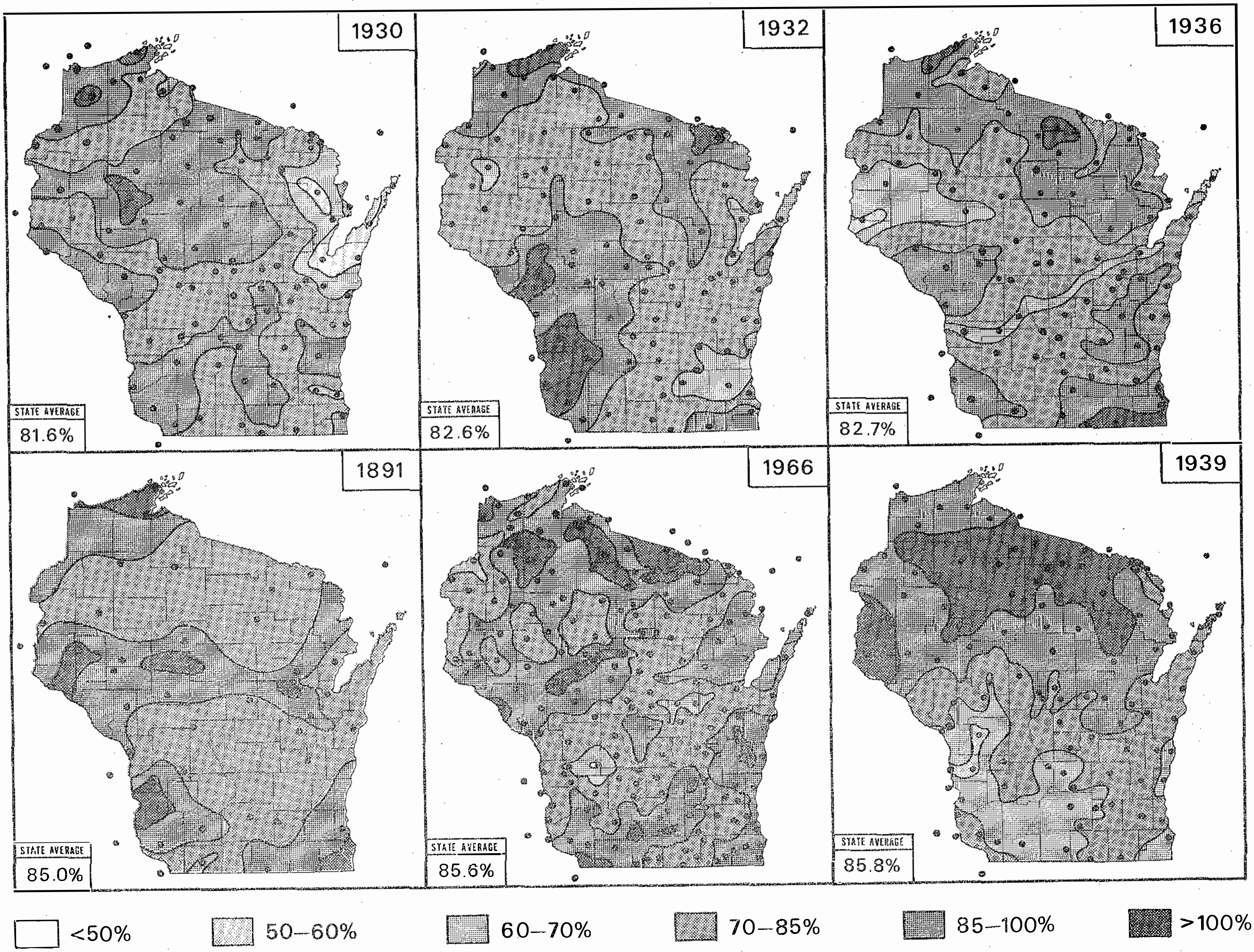


Figure 9. Map showing precipitation deficiency for major drought years in Wisconsin in percent of normal precipitation.

Table 8. Fourteen worst dry years in Wisconsin since 1881

No.	In Chronological Order				In Order of Deficiency			In Order of Area Affected		
	Year	Interval between dry years	Order of precip. deficiency	Order of area affected	Year	Precip. in % of normal	Total Precip. (in.)	Year	Approx. Area (sq. mi.)	In % of Total Land Area
1.	1891	--	10	9	1910	69.7	21.4	1976	51 765	95
2.	1895	4	3	5	1976	70.6	21.7	1910	51 033	94
3.	1901	6	12	14	1895	72.1	22.5	1963	40 555	74
4.	1910	9	1	2	1958	75.8	23.3	1948	39 914	73
5.	1923	13	14	11	1963	77.4	23.8	1895	38 495	70
6.	1930	7	7	10	1948	80.2	24.6	1958	33 112	62
7.	1932	2	8	7	1930	81.6	25.1	1932	33 005	61
8.	1936	4	9	8	1932	82.6	25.4	1936	30 488	56
9.	1939	3	13	12	1936	82.7	25.4	1891	29 894	55
10.	1948	9	6	4	1891	85.0	26.1	1930	29 528	52
11.	1958	10	4	6	1966	85.6	26.3	1923	27 403	50
12.	1963	5	5	3	1901	85.7	26.3	1939	24 266	45
13.	1966	3	11	13	1939	85.8	26.4	1966	22 664	42
14.	1976	10	2	1	1923	85.9	26.4	1901	22 216	41

The year 1872 would qualify as 10th worst year with approximately 85.0 percent.

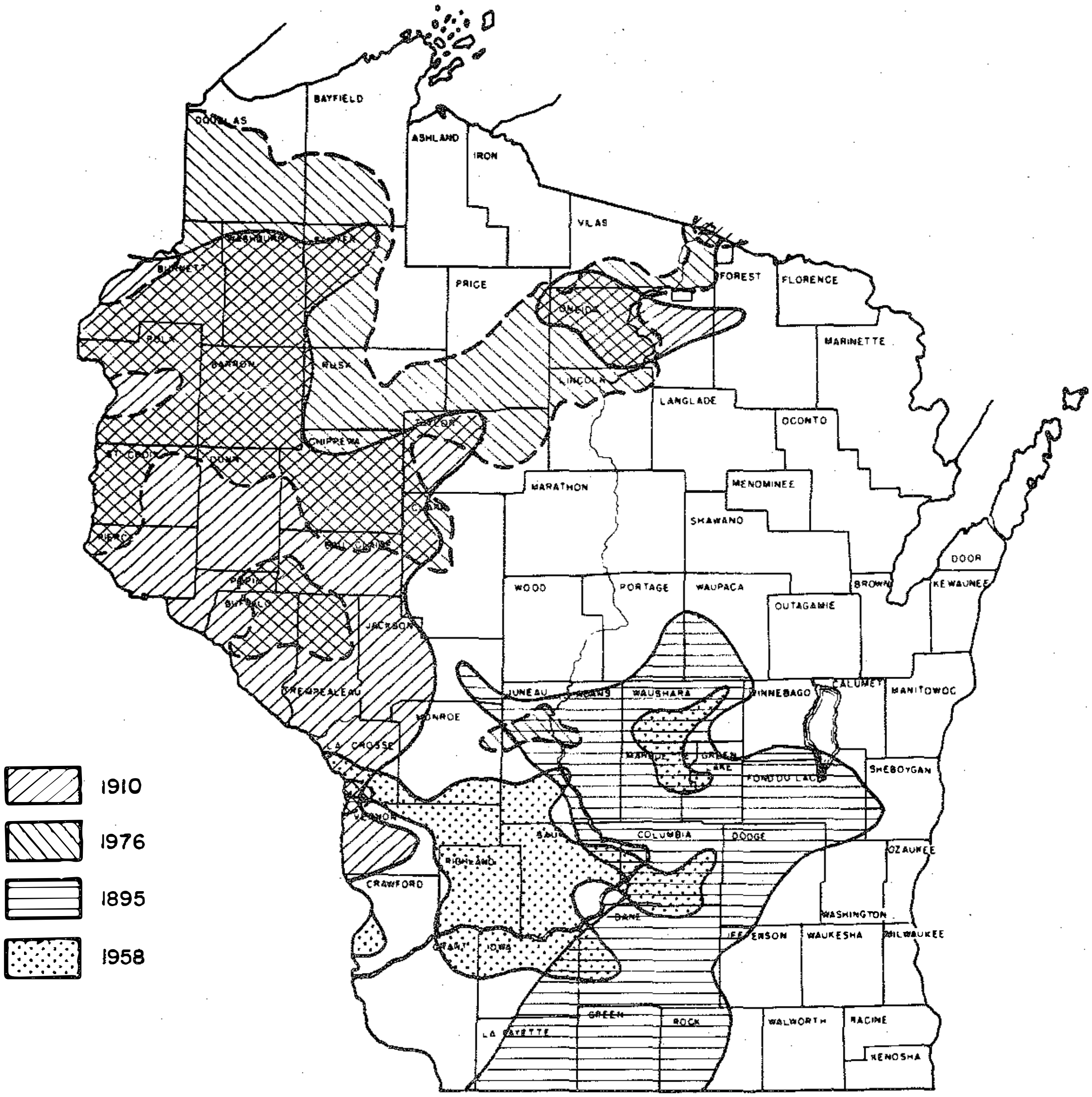


Figure 10. Map showing approximate areal extent of the four driest years in Wisconsin. Areas are selected on the basis of 60 percent or less of normal precipitation.

Table 9. Duration of periods of below-normal precipitation

Period	Number of Years			Drought Years
	Total	Below Normal	% of Total	
1943-1958	16	13	81	1948, 1958
1889-1901	13	9	69	1891, 1895, (1901)
1929-1939	11	10	91	1930, 1932, 1936, (1939)
1917-1925	9	5	56	(1923)
1962-1966	5	4	80	1963, (1966)
1907-1910	4	3	75	1910
1974-1976	3	2	67	1976

Periods were chosen in such a way that the dry years are interrupted only by one year of above-average precipitation.

Long-Term Trends in Precipitation

The intervals between dry years in Table 8 indicate that Wisconsin is hit by drought (deficiency of 15% or more) on the average of once in six to seven years, but there appears to be no pattern or cycle of drought years. If we take the 20 percent or higher deficiency, the number of very dry years is six and the average interval between them is 16 years. Another, and probably much better, indication provides the moving average calculated for successive three-year periods and shown in Figure 7. The interval between dry periods from 1894 to 1975 determined by the three-year moving average varies between five and 15 years and is 11.5 years on the average.

It is important to emphasize the word average, since it means not that the event occurs every 11 years in the chronological sense but that it occurs nine times in 100 years or, on the average, once every 11 years. The disparity between the average occurrence and the range of real occurrences would also preclude use of the word cycle, since this term generally refers to a regular occurrence at time intervals of equal length. Nevertheless the term cycle is loosely used in this report to indicate a period of time during which a recurring succession of events is completed, without regard to the length of intervals.

Table 10. Average annual precipitation prior to 1881

Year	Precipitation		No. of Stations	Stations
	inches	percent of normal		
1866	29.91	97.3	5	Be, Dq, Em, Mc, StP
1867	29.59	96.5	5	ditto
1868	33.10	107.7	5	ditto
1869	36.02	117.2	6	ditto + Mn
1870	29.09	94.6	6	ditto
1871	31.23	101.6	8	ditto + Dl, Mi
1872	26.13	85.0	9	ditto + Gu
1873	32.40	105.4	10	ditto + LC
1874	31.45	102.3	10	ditto
1875	33.13	107.8	10	ditto
1876	39.91	129.9	11	ditto + MG
1877	34.40	111.9	11	ditto
1878	35.34	115.4	11	ditto
1879	33.99	110.6	11	ditto
1880	37.58	122.3	11	ditto

Averages calculated from total annual precipitation at the following stations in Wisconsin: Beloit (Be), Embarrass (Em), LaCrosse (LC), Madison (Mn), Manitowoc (Mc), Milwaukee (Mi); Minnesota: Duluth (Dl), St. Paul (StP); and Iowa: Dubuque (Dq), Guttenburg (Gu), and McGregor (MG).

The data in this table were not included in Table 2 because the small number of stations does not justify their use for statistical analysis. They are included here for illustration of conditions at the beginning of the record.

Figure 7 also indicates similar character in a succession of wet years in the period between 1881 and 1972. The interval between wet periods varies between eight and 15 years and is 11.3 years on the average. The average intervals between dry periods and between wet periods indicate that the period of the next few years might be generally above average, interrupted by a slightly dry year in 1980 and peaking around 1983. The next more severe drought will come after 1985, probably around 1987.

Besides the three-year moving average, five-year and 10-year moving averages were also calculated. The five-year average showed intervals similar to the three-year average; the 10-year average indicated an approximate interval of 28-30 years between both dry and wet years. The succession of dry periods, as determined from the 10-year moving average curve, was 1897, 1932, and 1959, with 1932 having the lowest average. The succession of wet periods was 1881-1904-1942-1969, with the peak at the beginning of the sequence.

Overall trends in precipitation can be best observed on the curve of cumulative departure from mean precipitation in Figure 7. The first generally increasing trend culminated in 1890 when the cumulative departure reached an absolute peak. Since 1890, the generally decreasing trend has been interrupted by intervening increasing periods peaking in 1916 and 1945, and reached an absolute low in 1964. During the last 14 years the trend has been generally increasing. Data prior to 1881 (Table 10), even though based on an insufficient number of stations, confirm the sharply increasing trend starting in 1873 and culminating in 1890, and show another deep low in 1867 (probably deeper than in 1964). The trends indicated by the cumulative-departure curve have approximately the same character as those indicated by the 10-year moving average, but the lows and peaks generally lag behind those of the 10-year average. The curve also shows that we are approximately in the middle of a period of increasing precipitation, which could possibly culminate around the turn of the century.

Cyclicity of Precipitation

The author realizes the desirability of including into the evaluation of long-term trends in precipitation also a discussion of possible causes of drought. Although this is beyond the scope of this paper, numerous publications are available on this subject (see for example Thompson, 1973; U.S. National Research Council, 1977; Warrick, 1975). Droughts are related to changes in the normal atmospheric circulation pattern. There is no general agreement yet among meteorologists as to how these abnormal circulation patterns are generated. The most frequently mentioned cause is changes in the radiation received from the sun.

Variations in sunspot numbers have been known and recorded for centuries, and analyses have shown the existence of many cycles and oscillations in the sunspot records such as basic 11-year cycle, the double cycle of 22 years, the Bruckner cycle of about 33 years, and an 80- to 90-year cycle. Various authors have attempted to establish drought cycles and correlate them with sunspot cycles, but the conclusions have been far from unanimous. Any given series of observations, including random ones, can be resolved into a system of harmonies of different periods and amplitudes which resemble cycles. And with as many cycles as have been found in the sunspot data, it is not difficult to find one that fits. There is an indication that the drought period tends to be at a maximum only during a certain phase of the double (22-year) sunspot cycle. Thompson (1973) determined that drought periods in Nebraska occurred after the peak of the minor cycle and before the peak of the major cycle in every case. This also applies to Wisconsin, with the exception of drought periods in the 1960's which occurred after the peak of the major cycle and before the peak of the minor cycle.

However, the periodicity of precipitation is influenced by the periodicity of many other heliogeophysical factors besides the solar radiation--stratospheric winds, velocity of rotation of the earth, wobble of earth axis, earth and lunar tides, earthquakes, volcanic activity--cycles of all of which overlap and are superimposed on each other, forming a very complex multicyclic pattern. Their different intervals and amplitudes make the task of separating and identifying the cycles of individual factors extremely difficult. Bryson and Starr (1978) attempted to separate the effect of the motion of the axis of rotation of the earth (the so-called Chandler motion) on precipitation at Poona, India. The analysis of the frequency of Chandler motion indicated cycles with intervals of 5.0-5.5 years, 6.0-7.2 years, and 10.2 years.

There is no question that certain cyclic patterns can be found in the precipitation data in Wisconsin which are very close to the length of the sunspot cycle (11 years) and to about three times the length of the sunspot cycle (30 years). However, periods of drought do not appear to follow a regular pattern of recurrence. The length of the various intervals exhibited in this study varies from six to 15 years, or from 24 to 38 years. How many cycles were introduced by the analysis and how many really exist in the data cannot be determined without looking into the subject in much greater detail and with more powerful techniques than the author had at his disposal. Further mathematical treatment of the data may disclose factors that will make it possible to determine whether such cycles exist. Extended knowledge of historical data on precipitation would also be of great value for better understanding fluctuations in ground-water levels and estimating their future trends.

GROUND-WATER LEVELS IN NORTHERN WISCONSIN

Water-Level Fluctuations

One of the main reasons for collecting data on water levels in observation wells is to determine the relationship of precipitation and other natural factors to fluctuations in water level. Ground-water levels are almost constantly fluctuating and decline or rise within a relatively short time in response to changes in periodic recharge and continuous discharge. Fluctuations in water levels indicate both changes in actual quantity of water stored in aquifers and movement of ground water. A continual decline in water levels results when discharge exceeds recharge; water levels usually rise when recharge is greater than discharge. Character of water-level fluctuations depends on the character of the aquifers. Water levels in confined aquifers (piezometric surface) under natural conditions generally fluctuate to a much greater extent than water levels in unconfined (water-table) aquifers. However, the actual amount of water taken from or added to storage (per unit change in water levels) under water-table conditions is generally many times larger than under artesian conditions.

Water-level fluctuations can be classified into several types, on the basis of either time or origin (Table 11). According to the duration of variations in water levels, three types are recognized: (1) short-term fluctuations (lasting from a few minutes to several days); (2) seasonal fluctuations (lasting from a few weeks to several months, depending upon the quantities of water recharged and discharged during the year); and (3) long-term, or secular, fluctuations (extending over periods of several years). According to their origin, water-level fluctuatins may be caused by (1) changes in ground-water storage (S); (2) meteorological phenomena (atmospheric pressure, wind) (M); (3) deformation of aquifers (external loading, earthquakes) (L); and (4) disturbances within the well (leaking pipes, objects falling into wells, gas bubbles) (D). Table 11 summarizes the fluctuations and their causes.

The majority of water-level fluctuations are caused by changes in ground-water storage. They can be of periodic or nonperiodic nature, and caused by natural or man-made factors. Natural changes of storage, such as those caused by recharge from precipitation or rivers, spring flow, and evapotranspiration losses, generally give rise to rather gradual changes in water levels. Near river channels, however, the increase in storage may be rather abrupt in response to flood flow. Artificial changes of storage, caused for example by pumping, are responsible for rapid fluctuation of water levels. However, the changes of storage caused artificially can be also gradual; examples are those caused by changes in land use which result in changes of recharge characteristics and by gradual depletion of aquifers in area of heavy pumping. Nonperiodic fluctuations are usually caused by factors other than changes in storage and are readily discernible. Periodic fluctuations occur at more or less regular intervals, exhibit a normal probability distribution, and can be subjected to statistical analysis.

Wells Selected for Analysis

A good record of changes in ground-water levels in Wisconsin is being obtained from periodic measurements of water levels in some 200 observation wells maintained by the USGS and WGNHS, in cooperation with other agencies. The records of some of these wells extend back 40-45 years. The first complete records are available for the hydrologic year 1935. Systematic measurement of water levels in northern Wisconsin, one of the first areas of the state to make systematic measurements, began in 1937. Presently, there are 53 observation wells in the study area tapping glacial deposits. Of that number, 20 wells have an automatic recorder or weekly measurements going back at least 20 years, which is the minimum time needed for a reliable statistical analysis of long-term trends. The analyzed wells represent 35 percent of all wells available for statistical processing.

The analysis presented in this study is based on data from seven wells (Table 12). These are aligned in a cross-section from Burnett to Marinette County in a west-east direction, and from Lincoln to Portage County in a north-south direction (see Figure 1). Primary reasons for selecting only seven wells were the time limitation of the study and limited funds, which did not allow computer processing and analysis of a larger sample. All computations were done on a hand calculator. Wells were carefully selected for spatial distribution and hydrogeologic characteristics. Basic requirements were a complete record of 20 years (preferably 30 years) of weekly measurements, location in glacial deposits, and control of

Table 11. Classification of causes of fluctuations of ground-water levels

	NATURAL		MAN-INDUCED
	Periodic	Nonperiodic	Mostly Nonperiodic
SHORT-TERM (minutes, hours, days)	Geyser effects (S) Diurnal (daily): Evapotransp. (S) Changes in atmos. pressure (M) Temperature changes (M) Ocean tides (L) Earth tides (L)	Air entrapment during ground-water recharge (S) Floods (S) External load of surface water (L) Earthquakes (L) Bubbling gas (D) Animals falling into a well (D)	Pumping (S) External load: Construction blasting (L) Earth-moving machinery (L) Passing trains (L) Water cascading from pipes (D) Rocks thrown into a well (D)
SEASONAL (weeks, months)	Recharge from precipitation (S) Variations of surface-water stages (S) Bank storage effects (S) Recharge from springs (S) Evapotransp. and phreatophytic losses (M)		Seasonal pumping (irrigation, seasonal industry) (S)
LONG-TERM (SECULAR) (years)	Recharge from precipitation (S) Discharge of springs and streams (S)		Heavy pumping (S) Artificial recharge (S) Drainage (S) Seepage from dams (S) Deep-well injection* (S) Infiltration gallaries (S) Changes in land use (D)

ORIGIN OF CAUSES: S -- Changes in storage; M -- Meteorological phenomena; L -- Deformation of aquifers*; D -- Disturbances within the well

* Applies predominantly to confined aquifers.

water levels by natural factors only (precipitation, evapotranspiration, and natural discharge by springs or streams).

The analyzed wells are uniformly distributed throughout the area. They are on the average 50 miles apart and are located in each of the major drainage basins: St. Croix River--Bt 2 and Sw 7; Chippewa River--Pr 6; Upper Wisconsin River--Ln 25a; Central Wisconsin River--Mr 28; Fox-Wolf River--Pt 276; and Menominee River--Mt 7. The period of record is, with the exception of well Pt 276, at least 35 years. All wells were constructed in glacial outwash or till (Table 12), and all of them are used only for observations.

Of the hydrogeologic characteristics, the depth to water level was the primary criterion. It ranges from 0 to 40 ft below the land surface. The shallowest level is in well Pr 6; levels in wells Pt 276 and Ln 25a are shallow; wells Sw 7, Mr 28, and Mt 7 have intermediate depths; and the deepest level is in well Bt 2 (Figure 11). However, this subdivision was made only for purposes of this analysis; all the water levels in the study area belong to a shallow ground-water system. The character of water-level fluctuations was also considered in selecting the wells. Various types are represented: small fluctuations (less than 5 ft) in wells Sw 7 and Ln 25a; intermediate fluctuations in wells Bt 2, Mt 7, and Pr 6; and large fluctuations in wells Pt 276 and Mr 28 (over 10 ft). Other characteristics, such as relation to streams and depth to bedrock, are included in Table 12.

Statistical Analysis of Data

Water-level measurements for all wells were examined, corrected and supplemented where necessary, and statistically processed. Statistical methods used in the study are described in Appendix A. The averages (monthly and annual) were calculated from weekly or daily measurements and tabulated by hydrologic years (see tables 2 in Appendix B). The average annual levels used in the analysis are simply arithmetic means of monthly averages. The long-term monthly means for the entire period of record were derived from individual hydrologic years. The long-term annual average level was determined as arithmetic mean from individual annual levels. For each well, a hydrograph showing the relation of annual levels to precipitation and stream discharge was plotted (see figures 3 in Appendix B). The analysis also included frequency distributions (both numerical and graphical) and probabilities (tables 4, 5, and 6; and figures 4 in Appendix B). In the evaluation of the individual ground-water levels for abnormality of occurrence and to determine their position relative to average annual level, a five-part classification scale was used (Table 13). In computing the probability values, the Chegodayev formula was used:

$$p = \frac{m - 0.3}{n + 0.4} \cdot 100.$$

The values were computed for the range of 20 to 42 years and are included in Table A-2.

Table 12. Summary of observation wells selected for analysis

Well No.	Well Location				Est. Alt. (msl)	Well Depth (ft)	Avrg. Depth to WT (ft)	Aquifer Tapped	Bedrock		Relation to streams		Length of the records (years)
	County	Town	Range	Sec.					Probable Type	Approx. Depth (ft)	Yes	No	
Bt 2	Burnett	39N	16W	17	981	46	33.90 947	Pleistocene outwash	lava fl.: basalt	150-200		X	42
Ln 25a	Lincoln	34N	6E	36	1435	22	8.62 1,426	Pleistocene outwash	granite	50	X		35
Mr 28	Marathon	27N	9E	31	1229	(27)	20.36 1,209	(Pleistocene till)	Precambr.	<50		X	35
Mt 7	Marinette	37N	20E	34	980	(33)	21.19 959	(Pleistocene outwash)	granite	50	X		40
Pt 276	Portage	23N	10E	18	1090	17	5.74 1,084	(Pleistocene outwash)	Precambr.	100-200		X	21
Pr 6	Price	40N	1W	24	1510	18	2.30 1,508	Pleistocene till	granite	50	X		42
Sw 7	Sawyer	41N	9W	28	1190	25	16.47 1,174	Pleistocene outwash	Cambrian s.s.	100-150	X		42

Estimated or not available data are in parentheses.

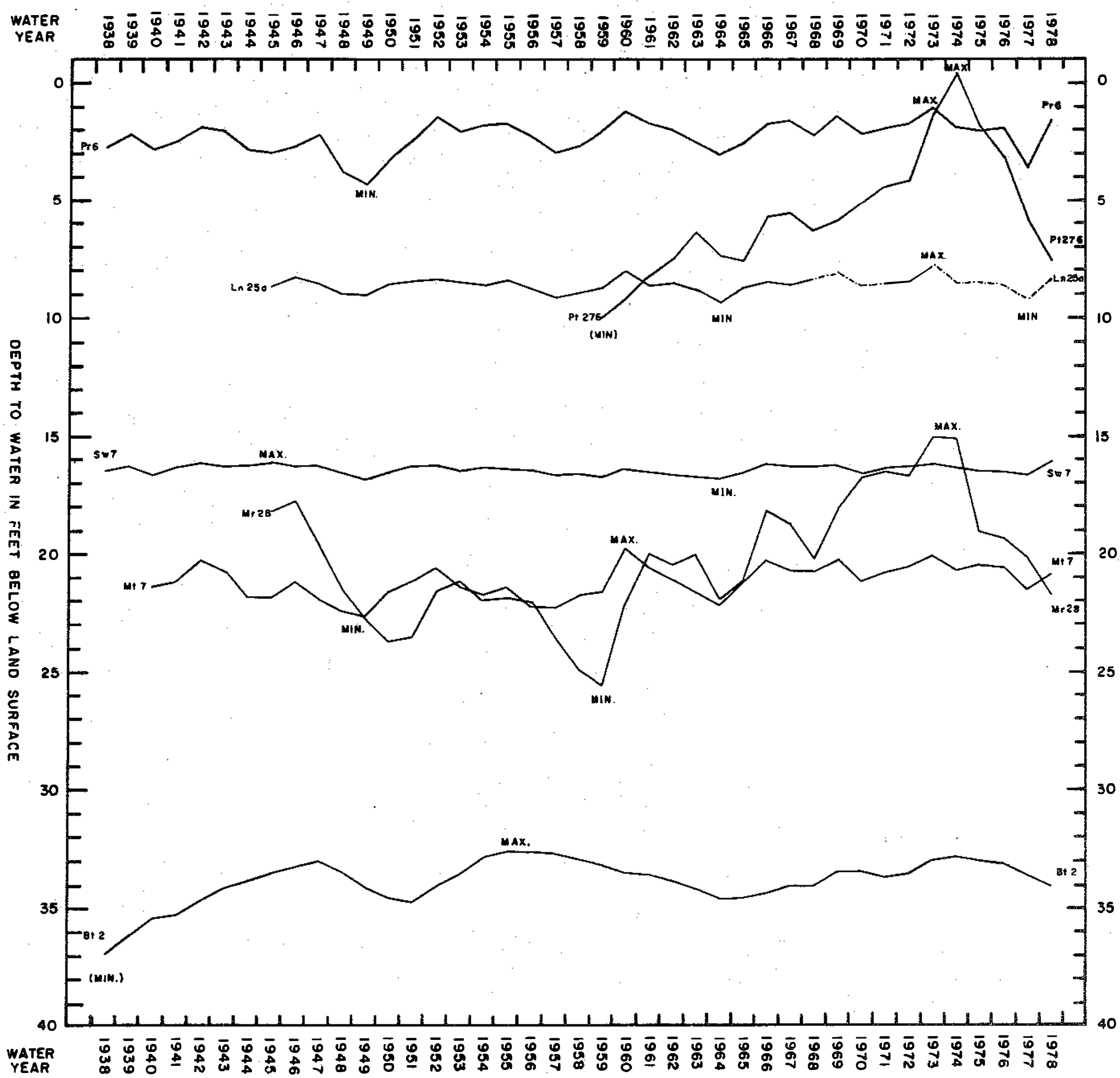


Figure 11. Diagram showing average annual ground-water levels in observation wells selected for analysis.

Table 13. Classification scale of hydrologic years based on probability of exceedance of average annual levels

Probability of Exceedance (%)	Average Annual Level	Symbol
0.00- 10.00	Extremely high	EH
10.01- 40.00	High	H
40.01- 60.00	Average	A
60.01- 90.00	Low	L
90.01-100.00	Extremely low	EL

From the practical point of view, the extremely high and extremely low levels are of greatest significance, especially for the periods where the ground-water level rises over the level exceeded by 10 percent or falls below the value exceeded by 90 percent of days per year. These characteristic levels, $H_{10\%}$ and $H_{90\%}$ (see tables 1 in Appendix B), were determined from the frequency distribution curves for each well (see figures 4 in Appendix B) and the longest duration of periods of extremely low and extremely high levels tabulated (see tables 3 in Appendix B). The difference between these two levels is a much better indicator of the capacity of water level to fluctuate (for which the term fluctuability may be used) than its amplitude (the difference between the maximum and minimum recorded level). By using the values exceeded by 10 percent and 90 percent we eliminate the extreme end values of the set which usually are very rare. The advantage of using the "fluctuability index" instead of the amplitude is clearly shown on well Bt 2, where the maximum fluctuation (amplitude) is 6.72 ft, while the more realistic range of fluctuations (fluctuability) is 2.07 ft (see figures 4 in Appendix B).

However, the fluctuability index is by no means flawless. For the true measure of fluctuability, it would be necessary also to include in the relationship the saturated thickness of an aquifer (m); then the formula for determining the fluctuability would be $f = (H_{10\%} - H_{90\%})/(m) \cdot 100$. However, the saturated thickness is in most cases unknown, and we have to use the simple difference $H_{10\%} - H_{90\%}$ as an indicator of the fluctuability.

Evaluation of Data

The analysis presented in the study was based on data from seven wells aligned in a cross-section from Burnett County to Marinette County in a west-east direction, and from Lincoln County to Portage County in a north-south direction (see Figure 1). The evaluated data have been published separately in the form of an appendix to enable interested readers to use the processed data in other studies of northern Wisconsin. The tables and graphs also provide examples of statistical methods that can be used in any hydrogeologic investigation. The following chapters present only a summary of results and conclusions based on the data.

The basic data and their evaluation are available in Appendix B, Water Data for Selected Wells in Northern Wisconsin (Zaporozec, 1980), which may be obtained on request from the Wisconsin Geological and Natural History Survey. The data are presented numerically in tables and graphically in diagrams. The water levels are always expressed in feet below the land surface datum (lsd). The annual composite average water levels are simply arithmetic means of monthly levels for a hydrologic year starting in October and ending in September. A complete set for each well includes the tables and figures listed below.

Tables:

Well Description Sheet

1. Summary of Ground-Water Levels
2. Average Monthly Ground-Water Levels
3. Longest Duration of Extreme Ground-Water Levels
4. Probability of Exceedance of Annual Levels
5. Frequency of Weekly Ground-Water Levels
6. Probability of Exceedance of Weekly Ground-Water Levels
7. Total Precipitation (at the nearest station)
8. Monthly Mean Discharge (when applicable)

Figures:

1. Location Map
2. Hydrograph of Monthly High Water Levels
3. Relation of Annual Ground-Water Levels to Precipitation and Streamflow
4. Frequency Distribution of Weekly Water Levels

Fluctuations of Water Levels in Northern Wisconsin

Ground-water level fluctuations in observation wells reflect the effects of recharge by precipitation and infiltration of spring snowmelt, and subsequent discharge to streams and springs or by evapotranspiration and pumping. Water levels respond to recharge only after a certain period of time. It was not the purpose of the study to correlate precipitation against annual water level. In order to introduce the apparent lag in the evaluation, annual precipitation was calculated for the calendar year, and annual water level for the hydrologic year. Since the hydrologic year (October to September) is designated by the year in which it ends, the graphs (such as Figure 16, or figures 3 in Appendix B) express the effect of preceding-year precipitation on water levels, with the months of October through December overlapping. On the basis of response to precipitation the analyzed wells fall into 2 groups: wells responding to precipitation within a few months--Pr 6, Sw 7, Ln 25a, and Mt 7; and wells responding to the progressive or cumulative effect of precipitation over longer periods of time--Bt 2, Mr 28, and Pt 276 (see figures 3 in Appendix B).

Direct response of the first group to precipitation is also reflected in the comparison of hydrographs of water levels and nearby streams, which are almost identical. On the other hand, the hydrographs of wells of the second group do not show any correlation with the stream hydrographs, with the exception of well Bt 2, where the water levels lag behind stream discharge on the order of one to two years.

Generally, the character of the amplitudes of water-level fluctuations depends on several factors: character of an aquifer, permeability, climate, and geomorphology. First, amplitudes are much greater in unconfined aquifers than in confined aquifers; and they decrease with the increasing depth of water level and the distance from the recharge area. Second, amplitudes are smaller in high-permeable material and greater in low-permeable material. Third, amplitudes are directly related to the amount of available moisture. And fourth, amplutides of fluctuations on ridges and hills exceed those in valleys and depressions.

In general, the maximum fluctuations in the analyzed wells are small as compared to the saturated thickness of the aquifers. It is estimated that they do not occupy more than 15 percent of the saturated thickness; the well Mr 28 is an exception with 30 percent. The amplitudes of annual fluctuations range from .21 to 5.65 ft, the average range being .97-3.93 ft (see tables 1 in Appendix B). The average annual fluctuations are even smaller, averaging 2 ft. The smallest average is 1.1 ft on well Bt 2 and the largest 3.1 ft on well Pr 6. For any practical purpose the variations are negligible. The percentage of occupied saturated thickness varies from 1 to 8. There appears to be no tendency for annual fluctuations to have greater amplitude either in the years with below-average levels or in the years with above-average levels.

Hydrographs of both monthly and annual levels (see figures 2 and 3 in Appendix B) show that the wells can be placed in four groups according to the character of the fluctuations. The first group includes wells Bt 2 and Mr 28, which have almost no seasonal and short-term fluctuations but rather broad long-term variations. Average annual fluctuation is 1 and 2 ft, respectively. Depth to water level is deep to intermediate. The second group includes wells Mt 7 and Pt 276, which have well-defined long-term trends and, in addition, alternating seasonal changes in the spring and winter. Average annual fluctuation is 1.5 and 3 ft, respectively. Depths to water level is intermediate to shallow. The third group includes wells Sw 7 and Ln 25a; these have well-defined fluctuations throughout the year and almost nonexistent long-term trends. Fluctuations are very small, averaging less than 2 ft; and the depth to water level is in the intermediate to shallow range. The fourth group is represented by well Pr 6, which has a very shallow water level, extremely well-defined fluctuations of approximately 3 ft, and gently changing long-term variations. Annual hydrographs are shown in Figure 11. Other wells in northern Wisconsin could be expected to fall into one of these four groups.

Water Levels as Indicators of Hydrogeologic Regime

Analysis of water-level fluctuations can also reveal important characteristics of the hydrogeologic regime around the well, for example the character of recharge and discharge periods. One important indicators is monthly mean water levels (Figure 12), which are generally uniform throughout the region. Minimum water levels occur in February and, less frequently, March, for slowly responding wells. Maximum water levels are attained usually in May; in April for quickly responding wells; or in June and July for slowly responding wells. Water levels rise relatively rapidly in the spring due to recharge from snowmelt and spring rains and then gradually decline throughout the summer when evapotranspiration exceeds precipitation and less water is available for infiltration. A small rise occurring in the fall is caused by fall rains. It is followed by a decline during the winter when precipitation is stored on the land surface as snow.

In individual hydrologic years, however, the behavior of monthly water levels can be slightly different. The extreme annual water levels generally follow the pattern of the monthly means and occur in similar months. The frequency distribution for individual wells (Figure 13) shows that maximum annual water levels usually occur in the spring months of April and May, and less frequently in June, October, and September. The minimum annual levels have been recorded mainly in March, and less frequently in February, September, October. A composite frequency of occurrence of extreme annaul levels on all wells (Figure 14) indicates that the ground-water aquifers are recharged mainly in April to June, and to a lesser degree in the fall months of September and October. The maximum depletion of ground water occurs in March and February when there is no recharge. At that time ground water is being discharged by springs and streams and constitutes a principal portion of streamflows or eventually the entire streamflow. Ground-water discharge or stagnation prevails from November to March, and the rate of recharge and discharge can be considered approximately equal in September and October.

The course of monthly means and the distribution of extreme annual water levels suggest that for further studies of ground water in northern Wisconsin, or in other shallow ground-water systems, a different hydrologic year should be used for presenting data. Hydrogeologic year can be defined as a continuous 12-month period arbitrarily selected for the presentation of data so that all precipitation that has fallen within the period will also recharge the ground water. Since a substantial recharge also apparently occurs in October, it would be more appropriate to use the hydrologic year November-October than October-September.

PATTERNS OF WATER-LEVEL FLUCTUATIONS IN NORTHERN WISCONSIN

Relation to Precipitation

Because precipitation is a major source of ground-water recharge, the rainfall amount has a direct bearing on ground-water storage and ground-water levels, especially in unconfined aquifers. The water table is almost constantly fluctuating as a result of direct recharge from precipitation, evapotranspiration,

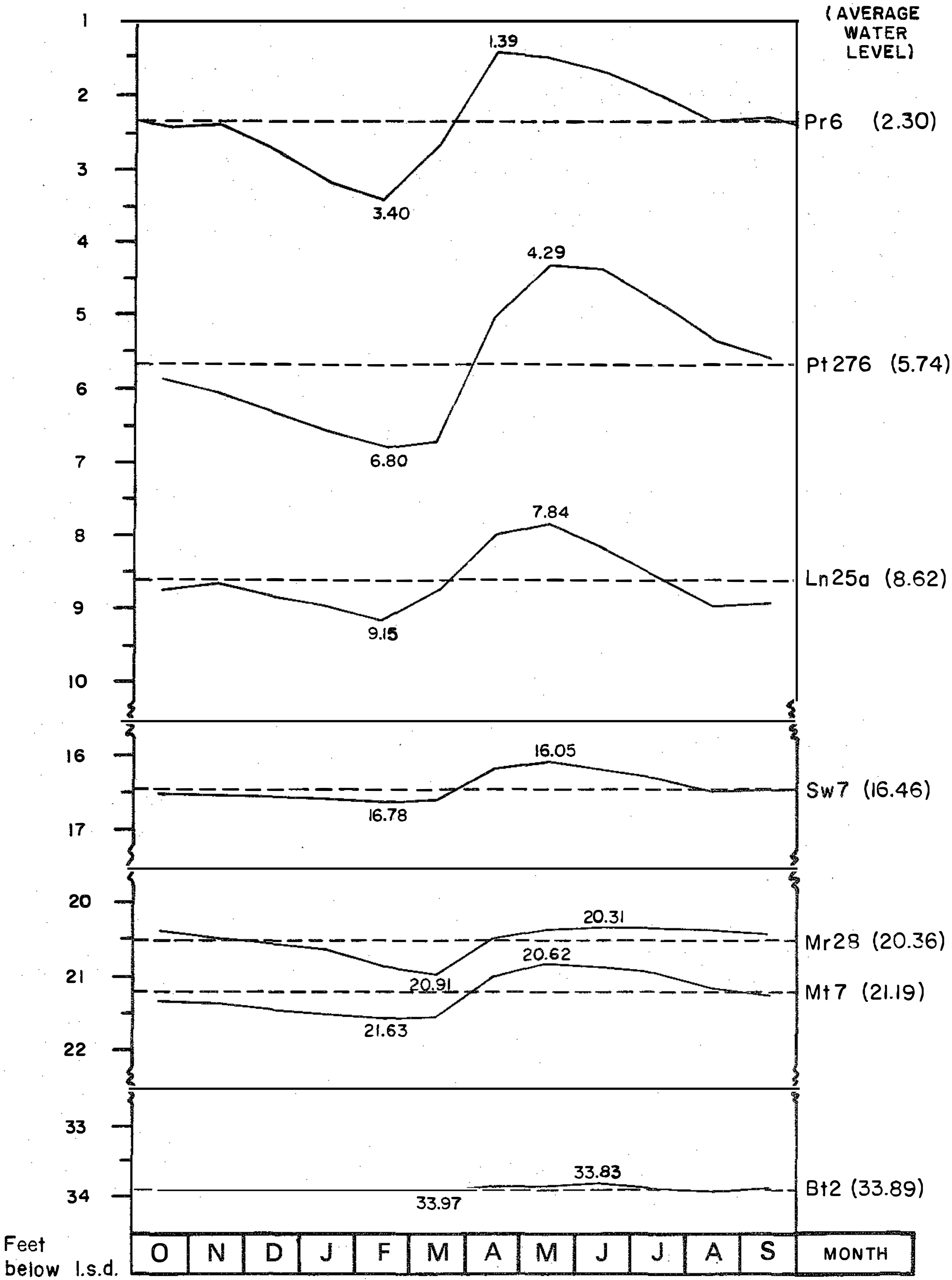


Figure 12. Graph showing monthly mean water levels of analyzed observation wells. Datum is land surface at the well site.

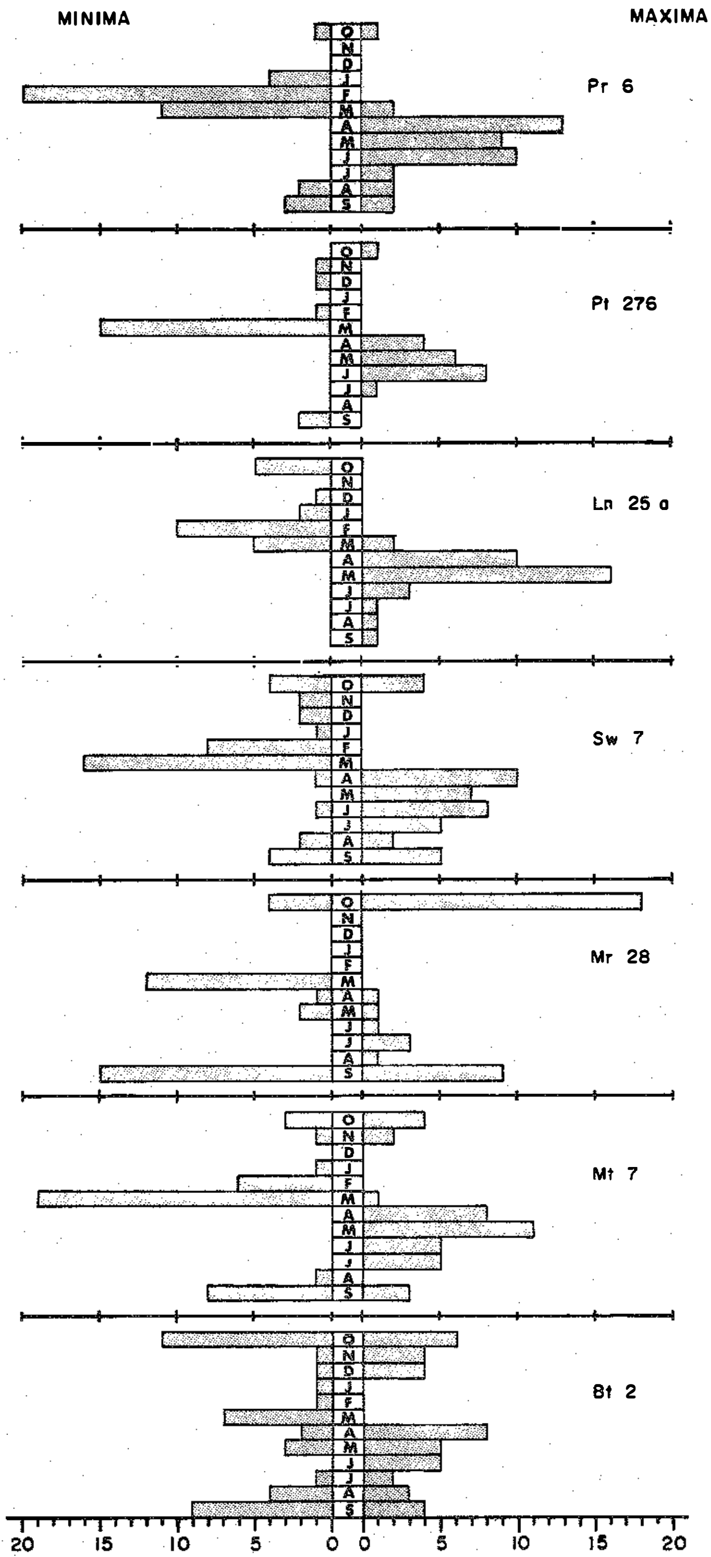


Figure 13. Diagram showing distribution of the annual minimum and maximum water-levels on analyzed observation wells.

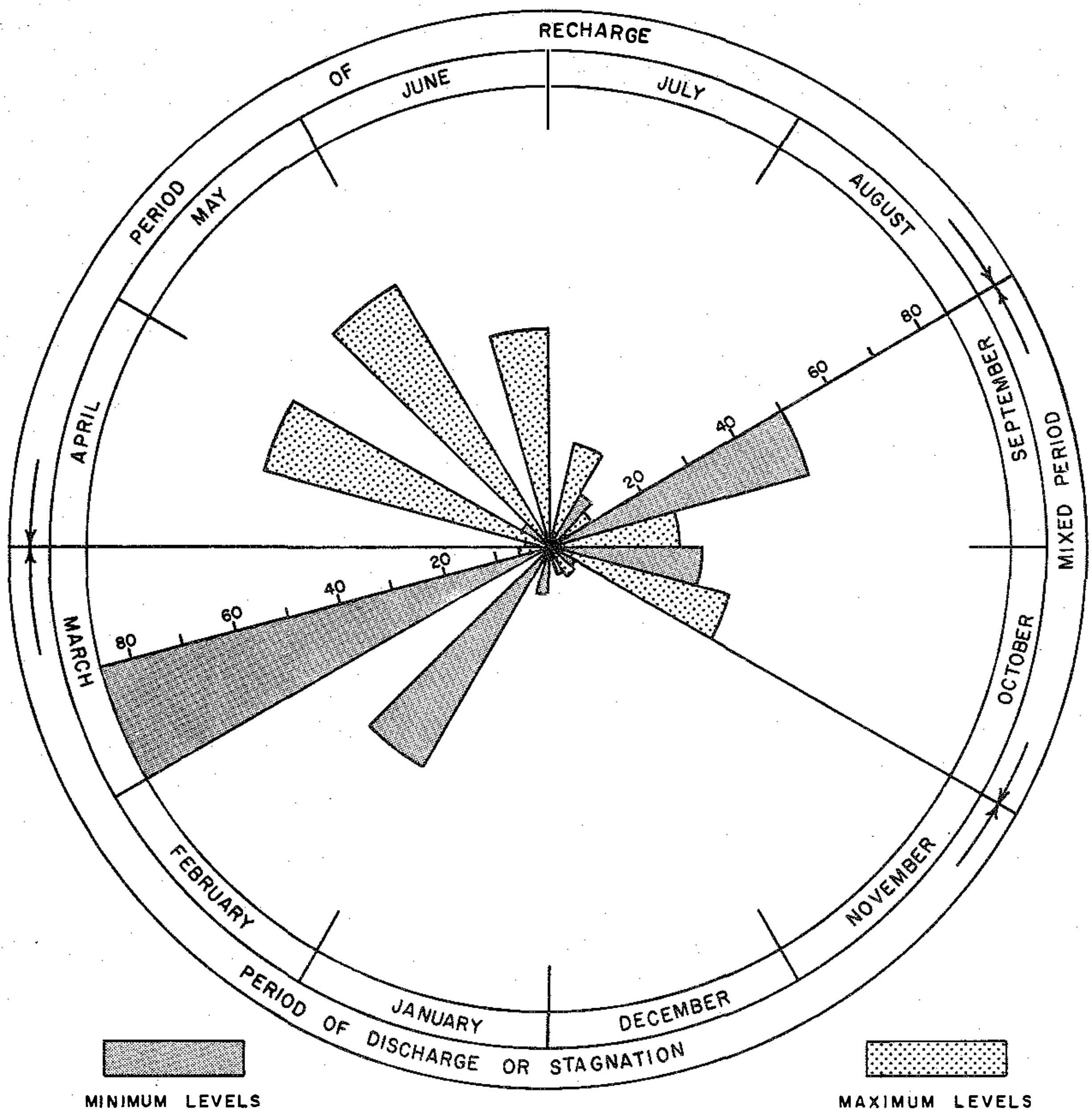


Figure 14. Diagram showing the frequency of occurrence of annual minimum and maximum water levels for all seven observation wells.

withdrawals from wells, discharge to streams and lakes, and other minor factors. Variations in precipitation affect both long-term (secular and seasonal) and short-term fluctuations of water levels. Alternating series of wet and dry years, in which rainfall is above or below the mean, will produce long-period fluctuations of levels. Extended dry periods (droughts) have pronounced adverse effects on water levels because ground-water storage is considerably depleted during these periods and water levels are declining.

A comparison of the annual hydrographs and graphs of annual precipitation (figures 3 in Appendix B) shows a rather close relation between both the trends of the precipitation and the trends of the average annual ground-water levels. As mentioned earlier, ground-water levels in the analyzed wells are a function of precipitation during preceding months or few years, rather than precipitation during earlier years (with the possible exception of the well Bt 2). The similarity between the two graphs--precipitation as the annual averages (wells Pr 6, Sw 7, Ln 25a, and Mt 7) or as the cumulative departure from normal (wells Pt 276, Mr 28, and Bt 2) and water levels--permits not only the analysis of trends from available data but also a reconstruction of water-level fluctuations from the precipitation graphs for earlier periods without water-level records. However, this reconstruction should be used for estimating previous water-level trends rather than for determining their absolute values.

Because of its limited scope, the study did not correlate precipitation with ground-water levels to determine the time lag between the two, which can be from a few days to a few years depending upon the distance of water level from the land surface and character of an aquifer.

Even though the analysis included both high and low levels, and the above-average and below-average years, emphasis has been placed on the below-average levels for two reasons. First, the overall objective of the study was to determine effects of drought on ground-water levels; and second, long-term trends are best reflected in the fluctuations of minimum annual water levels because the discharge of an aquifer occurs much more evenly than the recharge. This is caused by the regulating effect of the water-enclosing medium, which spreads the ground-water discharge over time, while the ground-water recharge is more concentrated.

The alternation of periods of high and low levels is irregular and generally gradual. The analysis showed that high and low levels do not occur unexpectedly, and that a minimum level has never occurred immediately after a maximum level and vice versa. Both the low and high annual levels were recorded, as a rule, after a number of intervening years with moderately low or high levels as compared with the normal. Even the low levels in 1977-78 were preceded by three years of declining water levels.

The relation of periods of deficient precipitation and periods of low water levels is apparent from available records (Figure 15). Besides the worst decade, 1956-65, when water levels in northern Wisconsin (Mr 28, Pt 276, Ln 25a, Sw 7) were at their minimum due to the cumulative deficiency in precipitation in previous years, the effect of drought was also noticeable in 1948-51 (Pr 6, Mt 7), 1970, 1977, and 1940 (Bt 2). For the periods of above-average water levels, 1972-75, with its peak in 1973, predominates. High levels also occurred in the

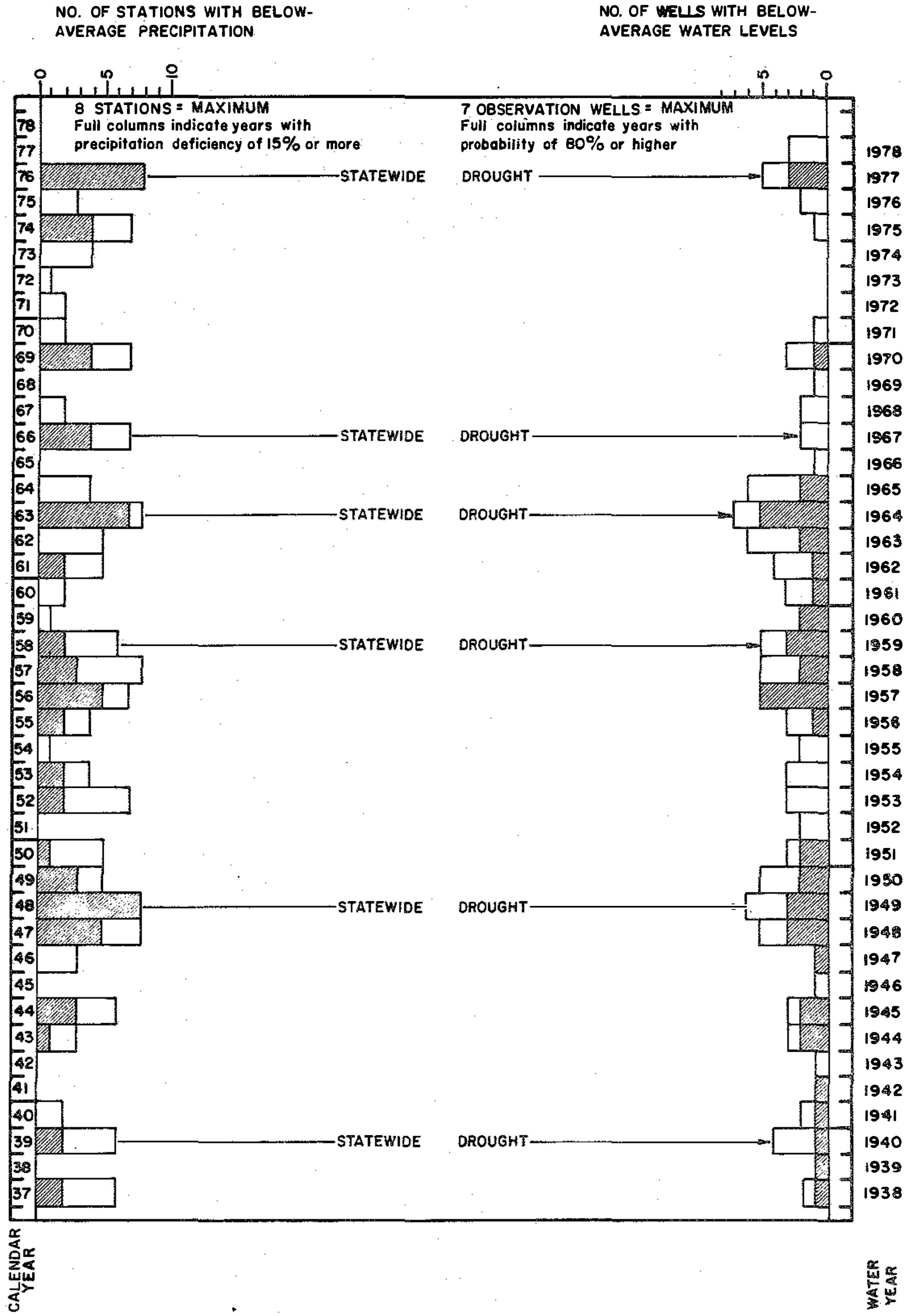


Figure 15. Histogram of number of observation wells and precipitation stations with below-average water levels and below-average precipitation from 1937 to 1978.

years 1969, 1966, 1960, 1955, 1952, 1946, 1942, possibly 1939, and in the recent period 1978-79. The ratio of below- and above-average periods slightly favors high levels (48:52), and corresponds to the ratio of below- and above-average precipitation.

Periods of Low Water Levels

Since the primary objective of this study is to determine the relationship of periods of low water levels to periods of drought, and especially to define the effects of the 1976 drought on water levels as compared to other drought years, the following discussion is limited to the relationship of periods of below-average precipitation and below-average water levels.

Figure 16 summarizes the periods of below-average water levels on all of the analyzed wells. Four major periods are distinguishable: 1948-1951, 1956-1959, 1963-1965, and 1977-1978. The year 1970 can also be classified as generally low and there was probably a low period in 1940-41 or earlier. The very low years are summarized in Table 14 on the basis of occurrence of minimum levels in the analyzed wells. Levels were lowest in the years 1949, 1957, 1964, and 1977.

Table 15 lists all years classified as low (probability of exceedance 60% or more) on individual wells. If we compare the levels resulting from the 1976-77 drought (in 1977 and 1978) to other periods of low levels, the years 1977-78 were on the average exceeded by 80 percent years (that means there were 20 percent lower years). Except for the shallow water levels in alluvial plains (Ln 25a and Pr 6), where the 1977 levels were extremely low and almost reached record minimum, there were many years when the water levels in northern Wisconsin were more severely affected by previous droughts.

The best picture of the effect of individual drought years and their relative importance for ground-water level fluctuations is given by the longest duration of extremely low periods (i.e., those days when the water level was below the level exceeded by 90% of days). $H_{90\%}$ was calculated from the frequency curves of weekly water levels and durations were established for each well, as given in tables 3 in Appendix B. The most serious continuous declines of water levels were generally recorded in the late 1940's, late 1950's, and middle 1960's for periods lasting from one to three years (Table 16). The longest periods of extremely low levels are associated with successions of three to five dry years. The record duration of extremely low levels, which lasted for more than five years (1860 days), was recorded on well Bt 2 in the late 1930's and early 1940's. In comparison, extremely low levels in the much publicized 1976-77 drought did not last more than 305 days maximum (Ln 25a), and normally lasted less than 100 days.

Very important for the management of water supplies in the area is the magnitude of decline of water levels in wells, which in no case exceeded 8 ft. The largest drop in water levels for any successive period was 7.53 ft, recorded in well Pt 276 in 1975-1978. Generally, the larger declines can be observed in wells with gradual, long-term fluctuations (Pt 276 and Mr 28), where the average decline for a three to four-year period is over 4 ft. On the other hand, wells with seasonal fluctuations do not experience declines over 1.5 ft. The same behavior

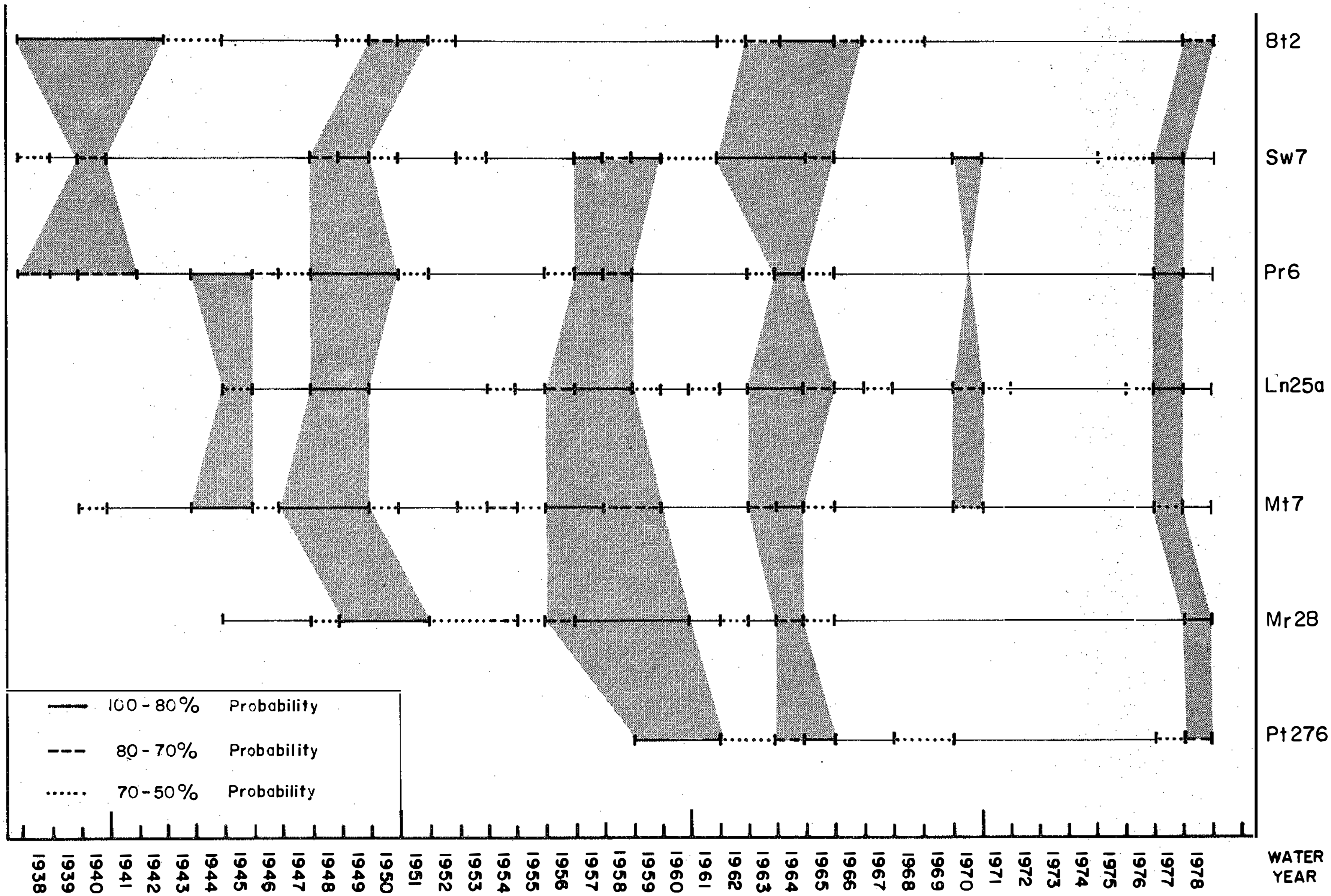


Figure 16. Diagram showing periods of below-average water levels in analyzed wells from 1938 to 1978. Shaded areas accentuate greater than 70 percent probability of below-average water levels.

Table 14. Nine lowest hydrogeologic years in northern Wisconsin

No.	Year	Interval Between Years	Corresponding Period of Drought
1.	1940	-	1939
2.	(1945)	5	1944
3.	1949	4	1948
4.	(1954)	5	
5.	1957	3	1956
6.	1964	7	1963
7.	1968	4	1966
8.	1970	2	1969
9.	1977	7	1976

The statewide drought years are underlined. The low periods prior to 1940 cannot be determined for lack of data. In the table, only the lowest years are included. Low years also occurred in 1948, 1950, 1956, 1959, 1963, and 1965.

is exhibited by the maximum declines over a period of one year. Larger declines were observed in wells Pt 276 and Mr 28: 2.39 ft; and smaller declines in the rest of the wells: .78 ft. On the average, the percentage of the years with declining water levels and rising water levels is approximately equal, with the percentage of rising levels slightly higher.

Long-Term Trends in Water Levels

The study of long-term trends in ground-water levels has been neglected in the literature in recent years. Analyses of local trends published between 1958 and 1963, apparently as a result of the impact of the 1950 drought, are primarily concerned with the southwestern states that rely heavily on ground water--Texas, Oklahoma, New Mexico, and Arizona--and the Long Island area. The only publication summarizing long-term fluctuations in the United States up to 1954 is that of Fishel (1956), who analyzed water-level records in nine states including Wisconsin. On the basis of a relatively short period (20-27, occasionally 50 years), he concluded, "No long-term trends of rise or decline of the water levels are discernible in areas not affected by pumping." Unfortunately this conclusion from a 23-year old publication--disputable at least in the case of Wisconsin where there are distinct trends within the period 1935-54 studied by Fishel--has been cited in recent textbooks (Walton, 1970).

Table 15. Low hydrogeologic years in analyzed wells in order of magnitude of low levels

Well No.	Bt 2	Sw 7	Pr 6	Mt 7	Ln 25a	Mr 28	Pt 276
1.	1951	1964	1949	1949	1964	1959	1959
2.	1965	1959	1948	1948	1977	1958	1960
3.	1942	1949	1977	1957	1957	1950	1961
4.	1964	1963	1950	1956	1949	1957	1965
5.	1950	1977	1964	1964	1948	1951	1964
6.	1966	1970	1957	1947	1958	1949	1978
7.	1963	1962	1945	1945	1963	1960	1962
8.	1978	1957	1958	1958	1970	1956	1963
9.	1968	1958	1946	1954	1965	1954	
10.	1949	1965	1965	1963	1956	1964	
11.	1952	1948	1963	1959	1959	1955	
12.	1967	1950	1951	1977	1976	1978	
13.		1961		1950	1954	1952	
14.		1976		1955	1967	1948	
15.		1975		1953			

The low years before 1945 were omitted on the wells Bt 2 (1938-41), Sw 7 (1940), Pr 6 (1944, 1940-41, 1938) and Mt 7 (1944) so that all the records would have the same period of 35 years (except for Pt 276 where the measurement started in 1959). The years are listed from the lowest up to 60 percent of probability of exceedance. The lines indicate the probability ranges 90%, 80%, 70% and 60%.

Table 16. The longest durations of extremely low ground-water levels in northern Wisconsin (levels exceeded by 90 percent)

No.	Period Lasting (From - To)	Well No.	Number of Days Below H 90%	Total	% of Total	Corresponding Dry Years	The Lowest Annual Levels (from the lowest up) 1	2	3	4	5	6
1.	May 26, 1937 - Sep. 12, 1942	Bt2	1860	1836	96	1934-35, 1936, 1937, 1939	1938	1939	1940	1941		
2.	Jan. 4, 1957 - Jan. 25, 1960	Mr28	1106	1106	100	1955-57, 1958	1959	1958				
3.	Sep. 24, 1946 - Mar. 21, 1950	Mt7	1082	1275	85	1946-47, 1948-49	1949	1948				1947
4.	Dec. 8, 1947 - Feb. 17, 1951	Pr6	809	1167	69	1946-47, 1948-50	1949	1948		1950		
5.	Sep. 20, 1963 - Feb. 9, 1966	Bt2	771	871	89	1962, 1963, 1964						1964
6.	July 2, 1958 - Mar. 29, 1962	Pt276	767	1366	56	1955-57, 1958	1959	1960	1961			
7.	Sep. 20, 1955 - Mar. 25, 1958	Mt7	713	917	78	1955-57			1957	1956		
8.	Sep. 6, 1955 - Mar. 31, 1958	Ln25a	684	907	75	1955-57			1957			1958
9.	Jan. 7, 1963 - Apr. 5, 1965	Sw7	626	820	76	1962, 1963, 1964	1964			1963		
10.	July 20, 1948 - Mar. 24, 1951	Sw7	623	979	64	1946-47, 1948-50			1949			
11.	Nov. 7, 1949 - Apr. 9, 1951	Mr28	518	518	100	1946-47, 1948-50			1950		1951	1949
12.	May 30, 1950 - Sep. 10, 1951	Bt2	486	486	100	1946-47, 1948-50					1951	
13.	June 30, 1963 - Apr. 19, 1964	Ln25a	457	646	71	1962, 1963		1964				
14.	Aug. 27, 1963 - Apr. 10, 1965	Mt7	323	592	55	1962, 1963, 1964					1964	
15.	June 15, 1976 - Apr. 15, 1977	Ln25a	305	305	100	1976	1977					

Statewide drought years are underlined.

It is interesting to note that the only recent publication on water-level fluctuations in the United States is the work of Russian scientists (Kovalevskiy and others, 1973). This analysis involved data from 129 of 20,000 observation wells published in the USGS Water-Supply Papers, 1936-1969. The United States is divided into two zones: one of prevalent positive trends and one of negative trends. Most of the United States is placed in the zone of declining water levels (the western, southwestern, central, and extreme northwestern areas). A rising trend generally prevails in Oregon, the Great Plains states, and the northwestern United States. Wisconsin is classified as an area with generally declining water levels in the period of 1936-1969, which conforms with the results of the study presented here.

The analysis of the water levels in northern Wisconsin indicates several general long-term trends. Generally, levels can be characterized as declining from 1943-47 to 1965, with the maximum and minimum levels varying throughout the region in accordance with local precipitation. Levels are increasing for the last 14 years, with the peak in 1973-74 or 1979. The cumulative departure curve (Figure 17) shows the long-term variations in water levels. With the exception of well Bt 2, which has had an increasing trend since 1944, the water levels on most wells reached minimum in 1964 or earlier (1959) and then began rising with the peak in the late 1970's (Figure 17).

Cyclicity of Water-Level Fluctuations

Examination of hydrographs of the average annual levels (see figures 3 in Appendix B) reveals certain more or less regular cyclic fluctuations that can be used to estimate long-term trends. Note, however, that the following discussion is general, and cannot be applied to specific places without taking local factors into account. While there is regional variation, which is reflected in the different phases of cycles in different areas, general patterns are uniform throughout the region.

Since little research in the United States has been directed toward the establishment of periodicity in the ground-water regime, European studies have been used for purposes of comparison. Those of Kovalevskiy (1973), Kriz (1972), Konoplyantsev (1970), and Zal'tsberg (1970) deserve particular mention. Review of this literature shows the existence of a wide range of cycles of different duration (two to 34 years), depending on the factor or factors the authors used for correlation with ground-water level fluctuations. Among the great variety of cycles, cycles with a period of two, five to six, 10-12, 19, and 30-33 years are encountered most frequently.

Analysis indicates the existence of similar cycles in northern Wisconsin, especially cycles of shorter duration. The small number of identified cycles longer than 10 years is attributable to the small number of wells with long observation records and not to a decrease in the probability of such cycles. The cycles obtained from the hydrographs are summarized in Figure 18. These cycles can be considered short cycles since they are taken between the immediately following highs or lows. The average length of cycles of both the high and low levels in the areas studied is around seven years. The average length of cycles generally increases with the depth of water table from 4.5 to 13.5 years. In

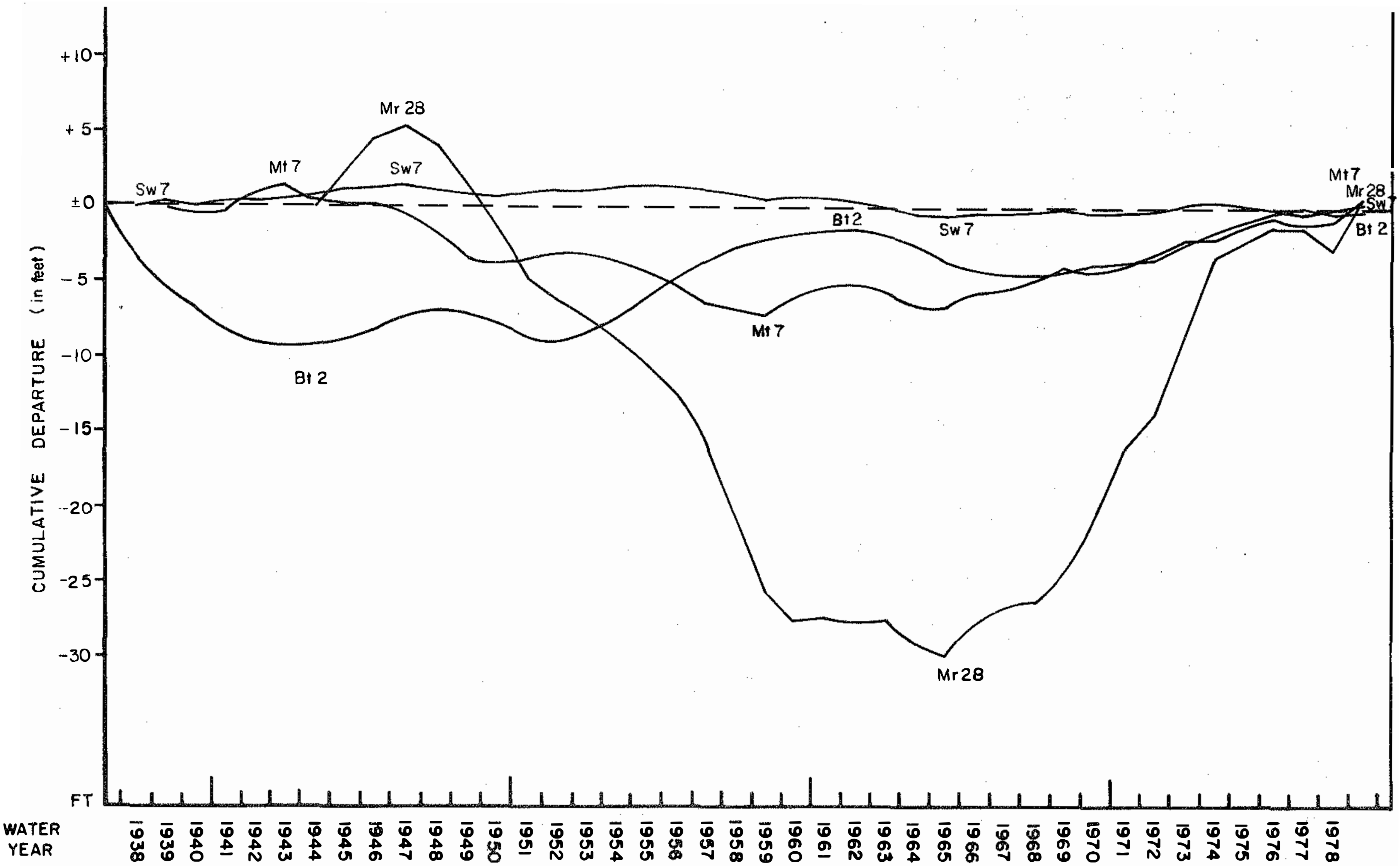


Figure 17. Diagram showing cumulative departures from mean water levels in wells Bt 2, Mr 28, Mt 7, and Sw 7 since 1938.

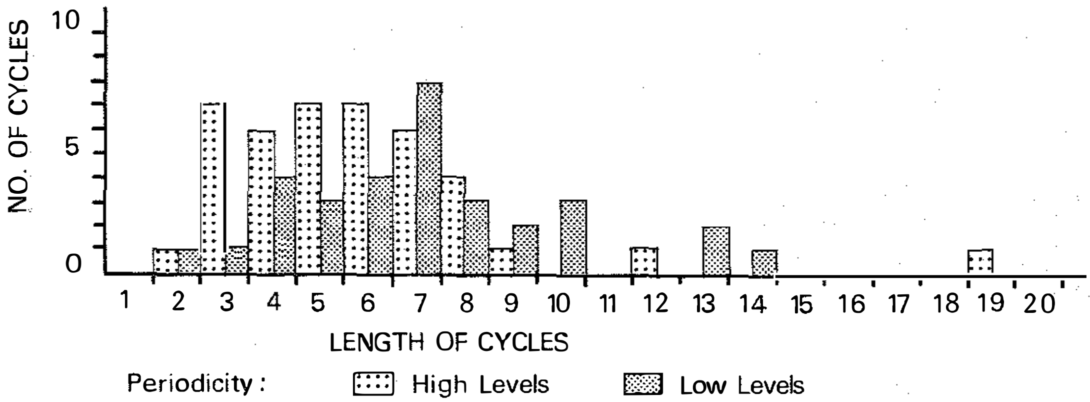


Figure 18. Histogram illustrating length of cycles of high and low ground-water levels.

view of the average length of short cycles, the recent increasing trend in water levels can be expected to continue until 1980, and the next low period may occur around 1984-85.

The longer cycles between more distinct lows or peaks last on the average, 14 years for low levels and 18 years for high levels. Length of record was insufficient to establish cycles of any greater duration. Based on the longer cycles, the next significantly high period, occurring around 1986, will probably be higher than the period 1978-80, and the high levels will probably culminate at the end of the century. The next significantly low levels can probably be expected around 1990, though they may not reach the magnitude of the 1965 lows.

The cycles are apparently multicyclic (or polycyclic) in nature, with several cycles of various intervals and amplitudes superimposed on each other. Cycles do not have a strict periodicity, and their names (seven-year and so on) are arbitrary, since they indicate average duration over a long period. Such quasicycles could not be used to forecast long-term fluctuations, especially those close to extreme levels, without identifying the factors that determine their individual periodic components. Nevertheless, the patterns derived from the average characteristics of the hidden periodicity of the cycles can help to identify the main periods of inversions and estimate the trend in future behavior of ground-water levels. The author did not attempt to correlate identifiable cyclic patterns with any of the factors causing ground-water fluctuations or to explain their causes. More sophisticated techniques than were available are needed to verify their existence. The cycles are presented as they are in the hope that they will arouse interest in the genetic relations of the ground-water regime and perhaps serve as a basis for further studies. However, it seems appropriate to review the causes of cyclic patterns listed in the Russian studies described above.

Causes of Periodicity of Water Levels

Kovalevskiy (1973) describes the most frequent cycles discussed in the Russian literature and the possible heliogeophysical factors that determine them (see section entitled "Cyclicity of Precipitation"). Cycles in the ground-water regime usually have analogs in other natural phenomena, principally in heliogeophysical processes that control the variations in long-term climatic characteristics. It is these characteristics that directly determine the behavior of ground-water levels in given groups of years. The shortest cycles (two to four years) are the most difficult to interpret because of their usually small amplitudes. Kovalevskiy associates the shortest cycle, the two-year cycle, with the cycle of zonal stratospheric winds, which have an average periodicity of 26 months. A three-year periodicity has been identified by many Russian researchers, but the reason for these fluctuations is not yet known. The four-year cycles may be a manifestation of double two-year cycles or may be caused by the rhythmic variations in the velocity of rotation of the earth with a period of 4.1 years.

The five- to six-year cycles, which are encountered much more frequently and the less-frequent seven-year cycles, are expressed in greater amplitudes. They are attributed mainly to the periodicity of solar activity, reflected in a similar periodicity of atmospheric circulation (with an average period of 6.6 years). Some authors associated the six-year cycles in the northern coastal zones of the USSR with the rhythm of motion of the terrestrial pole of rotation (Chandler motion), which produces a change in the velocity of ocean currents and subsequently in the temperature regime of the seas. Eleven-year cycles have been known in the Soviet literature for a long time. They are usually associated with known solar-activity cycles lasting from eight to 14 years (averaging 11.1-11.4 years) or related to geomagnetic disturbance cycles of similar length.

Correlation of the longer cycles with heliogeophysical factors has been less frequent and less successful, apparently as a result of the shortage of long-term observation records. The 19-year fluctuations may have an analog in the corresponding fluctuations of the lunar tide, which have an average period of 18.6 years and may affect the amount of transported atmospheric moisture available for ground-water recharge. The 22- to 24-year cycles have been described as double 11-year cycles. The 30-year cycles have been mentioned in the literature very rarely, with no satisfactory explanation of their causes.

It is apparent from this brief review that much remains to be learned about the genetic relations of ground-water level fluctuations, and that this subject may be an interesting research topic for years to come.

Effect of the 1976 Drought on Ground-Water Levels

Periodically declining water levels, as we have seen, are quite common in northern Wisconsin. The water levels are affected, on the average, about 50 percent of the time, with each seventh year bringing substantially low levels. The drought of 1976 was neither an exception nor an event whose effects could not have been anticipated. Water levels in northern Wisconsin had on several occasions been affected by drought to a greater extent than in 1976; the drought in that year actually occurred in the middle of the period of increasing water levels. The effects of 1976 drought were prominent in places because of a relatively sharper decline in water levels that approached almost record minimum levels on wells Ln 25a and Pr 6. However, the low levels did not last long and in 1978 or 1979 water levels were again above normal. In most cases, the year 1977 (or 1978 in the case of wells with a longer response to precipitation such as Mr 28 and Pt 276) ranked below the minimum years of the 1960's, 1950's, and 1940's (see Table 15).

Inadequate well depth was the primary reason for well failures in 1976-77; in most cases sufficient sources of water supplies can be found to meet local needs. Since more periods of low levels can be expected in the future, there is a definite need for proper planning and design of wells for potential declines. The problems of providing emergency water supplies, as in 1976-77, are unnecessary and can be avoided if wells are designed with depth that will ensure water supplies even in the periods of drought. Mitigating the effects of drought on water levels would not place a great financial burden on citizens or communities, since the amplitude of fluctuations and year-to-year declines is small, and much greater additional depth would not be required.

IMPLICATIONS OF THE ANALYSIS OF WATER LEVELS FOR GROUND-WATER MANAGEMENT

Statistical Analysis as a Tool in Ground-Water Management

The random variability of such hydrologic data as streamflow, water levels, and precipitation has been recognized for centuries. The general field of hydrology was one of the first areas of science and engineering to use statistical concepts in an effort to analyze natural phenomena. Many papers and books have been published that amply demonstrate the value of statistical tools in analyzing and solving hydrologic problems.

In spite of the long history and proven applicability of statistical techniques in hydrology, relatively few comprehensive and basic treatments of statistical methods in hydrology have been published in the United States (Chow, 1964; Haan, 1977; Yevjevich, 1972). In the analysis of hydrologic data, the concepts and methods developed for other scientific fields can be used (Arkin and Colton, 1950; Davis, 1973; Kennedy and Neville, 1976; Lewis, 1963; Panofsky and Brier, 1968; Stanley, 1973). More publications can be found in the literature of central and eastern European countries, which are little known and virtually inaccessible to American scientists (from the latest, available in this country: Alekseyev and Rozhdestvenskiy, 1973; Konoplyantsev, 1967; Zal'tsberg, 1976). In addition, there are publications describing one or more individual methods used in the statistical analysis of hydrologic data

(Chow, 1953; Kumaraswamy, 1971; Riggs, 1968). Of all the published material, the author found Engineering Hydrology, by Nemec (1972), to be most helpful. (The references cited in this section are listed separately at the end of Appendix A.)

In the limited selection of publications on statistical hydrology there is no single one which a practicing hydrologist or engineer can use directly in statistical processing and analysis of ground-water levels. He has, therefore, to rely on papers on individual methods published in various journals--with one exception, all are relatively old publications (Huff, 1943; Jacob, 1943; 1944; Kriz, 1972; Remson and Randolph, 1958; Wenzel, 1936). For this reason the author has included a brief review of basic statistical methods and their application to ground-water levels in Appendix A -- just to show those who are afraid of the term "quantitative approach" that such an approach is a valuable tool and does not have to require any special training or involve complicated calculations. The methods that are included require only a knowledge of calculus rather than extensive knowledge of statistics. However, the reader is assumed to have some familiarity with basic statistical concepts and terminology and with computation procedures.

We can only hope that a comprehensive new book on the application of statistical methods in hydrology (perhaps even in hydrogeology) will be published soon, and will treat the methods on the basis of the principles of modern statistics--which is not limited only to empirical description of statistical events, but also helps and serves in the evaluation of the results.

Analysis of ground-water levels, evaluation of long-term trends, and eventual prediction of water-level fluctuations are valuable not only for better understanding of ground-water systems but also for ground-water management. In 1975, 20 percent of the water withdrawn in the United States for various uses came from ground-water sources (Zaporozec, 1979a). In Wisconsin, the importance of ground water to the total water supply is even greater (Zaporozec, 1979b): almost 50 percent of the water used in Wisconsin in 1970 was supplied by ground-water sources (Zaporozec, 1975).

In view of this dependence upon ground water, the desirability of protecting users against the unfavorable effects of drought is obvious. We cannot prevent declines in ground-water levels but we can anticipate them and be prepared for them. Perhaps all that is needed is to make wells deeper; and analysis of past water-level records can tell us how much deeper. Natural changes in ground-water levels might be anticipated and even predicted if correlation were established between precipitation and water levels and between high and low water levels.

Why then, given a seemingly simple concept, have people not tried to prepare for drought? The explanation seems to be embedded in human nature, in the perception of the source of water supplies, and in human behavior in times of disaster.

Water Supplies and Drought Preparedness

Water-supply planning and design technology are based on the assurance that the source of supply and the distribution system are adequate to meet human needs for one of the most basic resources - water (U.S. National Research Council, 1977). Water is such an integral part of modern society that its availability, in whatever quantities may be desired, is virtually taken for granted by the consumer. However, this assumption does not take into account the possible detrimental effects on water supplies of periods of drought.

Drought is one of the common natural disasters to which people are subjected (White and Haas, 1975). Drought and resulting water shortages often have been experienced through variations in climatic conditions in one or another portion of the country for specific periods of time. In Wisconsin, drought periods are relatively common and occur, on the average, every six to seven years (see part on precipitation patterns), although water shortages do not necessarily follow in every case. The effects of reduction in available water range from inconvenience to serious economic loss (U.S. National Research Council, 1977). The effect of drought is basically economic and develops over a prolonged period. Because people are able to adjust their actions in response to environmental conditions, some shortages can be tolerated and overcome by simple conservation measures. However, as the magnitude or duration of a shortage increases, losses and deteriorating effects also increase and may become comparable to the economic effects of more violent types of disaster.

However, disaster protection from drought differs from protection from the more abruptly occurring and violently destructive disasters. The prediction and warning of drought conditions is not such that it can be considered part of a viable protection program. Existing drought-protection methods do not provide a reliable means for avoiding the unfavorable effects of drought on water supplies. Drought-protection methods fall into three categories: (1) passive measures that are taken well in advance (long-range planning); (2) alleviation programs that shield an area from the effect of drought by early preparation; and (3) emergency measures that provide relief and rehabilitation after drought conditions become severe (U.S. Office of Emergency Preparedness, 1972). Of these, the relief and rehabilitation method is most commonly used.

Experience with water-shortage situations in the past indicates that few utilities or governmental units have concrete plans for dealing with water shortages as they develop (U.S. National Research Council, 1977). In many cases, both the water utilities and the users are so relieved when water shortages end that they try immediately to forget actions taken and losses incurred, rather than to document them and use the experience to prepare for the next occurrence. This accurred also in Wisconsin after the 1976-77 drought. Raw data, survey questionnaires, notes, and other information from the affected areas lie unorganized in files, virtually inaccessible if not untraceable.

Future drought-protection measures should be directed toward mitigating the effects of drought on water wells, especially domestic wells. In many cases, the problems of providing emergency water supplies to well owners and communities and the resulting expense to government could be avoided if the wells were designed with "drought-proof" depth. This simple measure could be included in the drought-alleviation programs of federal, state, or local governments.

Drought-Proof Wells

The concept of a drought-proof well is relatively simple. A well would much more likely supply water in periods of drought if it had a depth well below the lowest anticipated ground-water levels. There are, of course, no drought-proof wells in the true sense. If the saturated thickness of an aquifer is inadequate the aquifer could be completely depleted by a prolonged period of abnormal dryness. But in most cases domestic wells do not utilize the entire saturated thickness of an aquifer.

Several methods have been developed for predicting water levels of lakes or ground water on the basis of prior occurrence. These include correlating high and low levels (Pierce and Vogt, 1953); correlating winter precipitation with the annual change in water levels (Rorabaugh, 1956); and correlating annual minimum levels with preceding annual maximum levels (Orsborn, 1966). None of those methods utilizes the relation of long-term average water level to record minimum level for estimating well depths.

On the premise that water levels throughout northern Wisconsin occur in similar hydrogeologic conditions and therefore exhibit a normal probability distribution, a relationship has been established between record minimum and mean ground-water levels. The data has been arranged in Table 17 in order of magnitude for low levels, from the highest level on well Pr 6 to the lowest level on well Bt 2, to determine by graphical analysis the correlation of the record minimum levels with long-term average levels.

The method of least squares was employed to correlate the two levels. The procedure was to (1) plot the mean water level against the corresponding record minimum level for the well on Cartesian coordinate paper, with mean as the ordinate (Y) and the record low as the abscissa (X); and (2) construct a straight line of best fit through all points by the method of least squares. The equation of the line of best fit is $Yc = a + b\ (X)$. For details on the linear relationship, see Appendix A.

The points for all wells are plotted in Figure 19. Their scatter shows a very high degree of correlation. The degree of relationship of two variables, or the coefficient of correlation, r, can be calculated from equation

$$r = \sqrt{1 - \frac{S_Y{}^2}{s_Y{}^2}},$$

where S is the scatter and s is the standard deviation of Y. The data show positive correlation of 0.986.

The results of the analysis indicate that the relationship between minimum and mean ground-water levels can be used for the development of a method for estimating the optimum depth of wells from the regional average levels. Even though the analysis showed a very good direct correlation, it would be necessary to test the relationship on a larger sample to achieve higher statistical reliability and also to test the applicability of the method to different

Table 17. Correlation statistics of mean and record minimum levels on the analyzed wells (in feet below the land surface)

No. (N)	Observation Well No.	Minimum Level (X)	Mean Level (Y)	Calculated Values (XY)	(X^2)	(Y^2)	Standard Deviation(s) y	y^2	Calculated Value of Y (Yc)	Scatter(S) (Y - Yc)	$(Y - (Yc))^2$
1.	Pr6	5.67	2.30	13.04	31.36	5.29	-13.21	174.50	2.99	- .69	.48
2.	Ln25a	10.38	8.62	89.48	107.74	74.30	- 6.89	47.47	7.56	1.06	1.12
3.	Pt276	11.09	5.74	63.66	122.99	32.95	- 9.77	95.45	8.25	-2.51	6.30
4.	Sw7	17.31	16.46	284.92	299.64	270.93	.95	.90	14.28	2.19	4.80
5.	Mt7	23.26	21.19	492.88	541.03	449.02	5.68	32.26	20.05	1.14	1.30
6.	Mr28	26.09	20.36	531.19	680.69	414.53	4.85	23.52	22.80	-2.44	5.95
7.	Bt2	37.32	33.89	1264.77	1392.78	1148.53	18.39	338.19	33.69	.21	.04
	TOTAL	131.12	108.56	2739.94	3176.23	2395.55	0.00	712.69	109.62	1.04	19.99
	MEAN	18.73	15.51	391.42	453.75	342.22	0.00	101.76	15.66	0.00	2.86

STANDARD DEVIATION

$$s_Y = \sqrt{\frac{\sum y^2}{N}} = \sqrt{101.76} = 10.09$$

SCATTER

$$S_Y = \sqrt{\frac{\sum d^2}{N}} = \sqrt{2.86} = 1.69$$

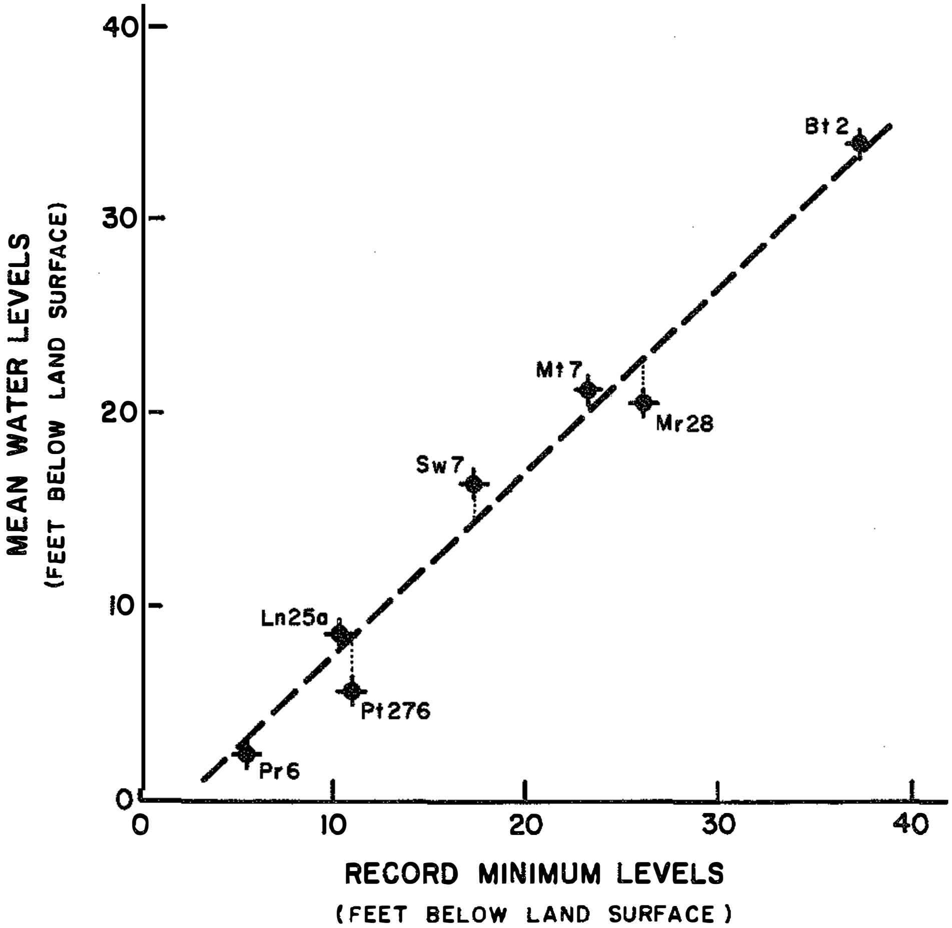


Figure 19. Diagram showing correlation between mean and minimum water levels.

hydrogeologic conditions (deeper water levels, various aquifers, and so forth). If the method proves successful, it will be possible to develop a series of type curves for different hydrogeologic conditions and different regions. These curves could serve in ground-water management planning or disaster-prevention planning as a tool for determining the optimum depth of wells to lessen the effects of droughts.

For purposes of planning, average ground-water levels can be estimated from USGS Hydrologic Investigations Atlases published in cooperation with the WGNHS (USGS, 1968-1975). A map of drought-proof well depths can be compiled, indicating the areas where the required depth is greater than the saturated thickness of an aquifer and where inadequate water supplies are likely to develop in periods of deficient precipitation. This procedure could save substantial amounts of money by eliminating the unnecessary deepening of wells and the need to provide emergency water supplies; it would enable governmental officials to concentrate advance planning for emergency measures in areas most likely to be affected.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The 1976 drought, besides having adverse effects on streamflows, ground-water levels and water supplies, had one beneficial effect: it made officials and legislators realize that ground-water supplies cannot be taken for granted, that we still have to learn a lot about this valuable resource, and that ground water requires more attention than it has been given until now.

During the drought state officials had to set up emergency services to provide water for stock and domestic purposes in areas where wells failed and later on had to help with the replacement and deepening of inadequate wells. The expenditures created concern on the part of state officials involved in providing emergency water supplies, especially the Wisconsin Division of Emergency Government. The Division subsequently requested and sponsored this study to determine the extent and periodicity of historical droughts in Wisconsin and their effect on ground-water levels, and to develop a method or warning system which would prevent the failure of the wells during a drought.

Statistical analysis of precipitation for the state area and water-level measurements taken on seven observation wells in northern Wisconsin have been used to evaluate periods of deficient precipitation and related periods of low water levels and overall trends for the period of record (since 1881 for precipitation and since 1937 for ground-water levels).

The analysis showed that drought periods (when statewide precipitation was 85% or less of the normal) are quite common in Wisconsin and occur on the average once in six to seven years statewide. In the period 1881-1978, 14 years can be considered as dry: 1891, <u>1895</u>, 1901, <u>1910</u>, 1923, 1930, 1932, 1936, 1939, <u>1948</u>, <u>1958</u>, <u>1963</u>, 1966 and <u>1976</u>. The average interval between very dry years (those underlined) is 16 years. The worst year was 1910, with 69.7 percent of normal, and the second worst 1976, with 70.6 percent of normal. During those two years approximately 95 percent of the state area was affected; during the remaining drought years, between 50 percent and 75 percent of the area was affected. However, 1910 and 1976 each represent an isolated occurrence of an abnormally dry year in a period of normal or above normal precipitation, and thus the effects of the drought in those years on ground-water levels were only short-lived. The longest period of deficient precipitation was from 1917 to 1966, when 78 percent of the years were below normal. Overall, the cumulative effect of precipitation shows a decreasing trend from 1890 to 1964, and during the last 14 years an increasing trend.

Since precipitation is a major source of ground water, it is only natural that periods of low ground-water levels closely correlate with drought periods and generally follow the same pattern as precipitation trends. The most serious continuous declines of water levels were generally recorded in late 1940's, late 1950's, and middle 1960's. Besides the worst decade of 1956-1965, when water levels were at their record minimum, the effect of drought was also noticeable in 1948-51, 1970, 1977, and 1940. Earlier records are not available. For the study area in general, there have been nine years in the period 1940-1978 which can be considered generally lowest: 1940, 1945, 1949, 1954, 1957, 1964, 1968, 1970, and 1977.

Inadequate depth of wells was the primary reason for well failures in 1976-77; sufficient sources of water can be found in most cases to meet local needs. The drought of 1976 was neither an exception nor an event whose effects could not have been anticipated. Periodically declining water levels are quite common. Water levels are affected, on the average, about 50 percent of the time, with each seventh year bringing substantially low levels. The average occurrence of extremely low levels corresponds with the average occurrence of droughts. There were several periods when the water levels in northern Wisconsin were affected by drought to a greater extent than in 1976, when the drought occurred in the middle of a period of increasing water levels. Although the effects of 1976 drought were prominent in places due to relatively sharp declines in water levels, the low levels did not last long, and in 1978-79 levels were again above normal.

The analysis of ground-water fluctuations and their maximum and minimum annual levels also revealed important aspects of the shallow ground-water regime in Pleistocene sediments. In general, fluctuations are small and do not seriously deplete the saturated thickness of the aquifer. The average maximum amplitude is 7.4 ft. This value is an average for the entire period of record, however, and thus has no bearing on water supplies, which are directly affected by fluctuations during a year, and from year to year. Annual fluctuations range from .21 to 5.65 ft and average 1.1 to 3.1 ft. The magnitude of decline in ground-water levels is also small. The largest decline recorded for any successive period was 7.93 ft in well Pt 276 in 1975-78. The maximum yearly declines range from .32 to 3.99 ft, which should not seriously affect a properly designed well. Such a small drop could be accomodated in a well of sufficient depth by setting a pump a little deeper.

The evaluation of hydrographs, extreme annual levels, and calculated monthly mean levels indicates that major recharge of ground water in northern and north central Wisconsin occurs in the spring from snowmelt and rains, and that the amount of precipitation received in the March-to-June period is a critical factor in ground-water levels (with the exception of extremely shallow levels in alluvial plains). Normally, precipitation does not contribute significantly to ground-water recharge during the growing season, and water levels gradually decline during the summer from their maximum in May (or April-June, depending upon the response to spring recharge). The replenishment of ground water by fall rains (in September-October) is important in maintaining or raising water levels before they start their winter decline. The minimum is reached in February or March.

The pattern of ground-water recharge also suggests that a change is needed in the designation of a hydrologic (water) year so that the year would include a 12-month period when all precipitation that has fallen will also recharge the ground water. The author recommends the period November-October rather than the October-September period currently used for surface water.

Finally, the results of the analysis indicated that water levels in an area with similar hydrogeologic conditions exhibit a normal probability distribution and that the relationship can be established between record minimum and mean ground-water levels in a form of type curve. Using the developed curve, it would be possible to determine the extremely low level from the average water level in the area and thus to design wells of drought-proof depth.

The study revealed certain aspects of ground-water activities that need improvement. Serious deficiencies exist in the continuous processing and regular publication of data collected on ground water. The wealth of data on ground water is tremendous thanks to the continuous efforts of the Wisconsin Geological Survey and U.S. Geological Survey, who have operated a monitoring network for some 40 years, and of other agencies who collect data for their own purposes. However, the data are scattered in various agency files and are not readily usable or accessible. The data are not statistically processed, and no summaries or basic statistical characteristics are available. Data in a tabulated and summarized form are necessary for any analysis of water resources problems on a larger (regional) scale. It would be more than beneficial to gradually compile, tabulate, summarize, and publish the water-resource data in a uniform format.

Lack of funds for developing an adequate state data base seems to be an eternal problem in Wisconsin. Only a limited amount of raw data is published. In 1977, for example, of 205 wells monitored, measurements on only 67 were published. As a result, the data base is inadequate for quantitative analysis (Stephenson and others, 1978) and the lack of basic processing of data significantly hinders regional evaluation. The author of this study, for example, had to spend about three months on basic processing and summarizing of data. This time could have been more efficiently spent on analysis, or on evaluation of a larger set of data. Even more significant is the need for an adequate data base for problem-solving, management, and policy purposes, and to facilitate prompt response to crisis situations.

Recommendations

Despite its limitations, this study clearly shows the importance of long-term measurement of water levels and indicates how the data could be used. All such records are very valuable, but unless the collection, processing, and retrieval system is improved they will merely fill storage cabinets. More money is needed for basic ground-water programs such as developing a concept of statewide ground-water monitoring based on the review and evaluation of existing data, and subsequent revision and expansion of the existing monitoring network; continuous processing and analysis of incoming data; an efficient storage and retrieval system; and periodical publication of data on ground-water levels, quality, and use. The author believes that studies such as the one presented here, which documents the practical value of the data, would help convince the officials and legislators that data collection is not a waste of resources; that we need more and better quality data; and that the conclusions from evaluation of data could save substantial amounts of money, and would return the money invested in basic data many times.

It is recommended that a computer program be developed for statistical processing and analysis of long-term weekly water-level measurements. In addition, all data currently in agency files should be compiled, statistically processed, and published together with other water-related data (climatological records, and data on streamflows, spring flows, lake levels, water quality, and water use) in volumes of uniform format for the entire state. These would serve as a permanent reference source and could be periodically updated. (The tables in Appendix B indicate a possible format for the tabulations.)

Although the timing and intensity of drought cycles cannot be accurately predicted, historical evidence on the probabilities of recurring drought is apparent from the presented analysis of Wisconsin precipitation. These factors should be considered in planning for the use of emergency measures to protect water supplies from drought. The relationship between record minimum and mean ground-water levels established in this study should be used for developing a method for predicting the extremely low water levels, and consequently, for determining the required depth of a well. However, further research is needed before this method becomes a practical planning tool. A necessary component for determining minimum levels is the estimated regional mean level. In order to refine the existing information on average ground-water levels published in USGS Hydrologic Investigations Atlases, more studies will be needed for better understanding of local ground-water systems (Green, 1979) and for delineation of such systems and their relation and response to precipitation. Then the applicability of the method can be tested for different hydrogeologic conditions and a series of type curves developed. If the method proves successful, drought prevention would have real meaning in disaster preparedness, and dry wells would not cause costly "surprises."

The subject of long-term fluctuations has been largely neglected in recent years, and there is a wide range of topics for research in the area of periodicity of precipitation and ground-water level fluctuations in Wisconsin. Presently, no studies on these topics are available. Verification of precipitation cycles and the predictability of precipitation trends would have great value for better understanding of ground-water fluctuations. The studying of the genetic relations of the ground-water regime would enhance the possibility of predicting water-level trends. Any contingent research studies will require the long-term, large-scale efforts of a scientific team; the cooperation of several funding agencies; and the active support of the State of Wisconsin.

It is hoped that concern about and interest in ground water resulting from the 1976 drought will continue, and not prove to be short-lived and crisis-oriented as it has on similar occasions in the past. Ground water is one of Wisconsin's most valuable natural resources. It supplies 90 percent of communities served by central water-supply systems and over 80 percent of rural users; and its importance is likely to increase in the future. Adoption of a state policy on ground-water development, management, and use, and development of a long-range ground-water planning program is needed to protect the ground water and its availability at any time, in sufficient quantity and in good quality. In order to reach this goal, we have to extend our knowledge of ground water on the basis of reliable and adequate data.

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APPENDIX A: APPLICATION OF STATISTICAL METHODS IN HYDROLOGY[1]

Basic Processing of Data

Data and observations from a ground-water level network, supplied to the hydrogeologist and supplemented by his own field surveys, ordinarily cannot be used directly. Individual values can be regarded as elements of a statistical set; they can be processed by conventional methods of mathematical statistics, modified to the needs of ground-water hydrology, and expressed numerically or graphically. The basic requirement for statistical processing is a sufficiently long period of observation; sufficient measurements are required to obtain a representative sampling of ground-water level fluctuation during a hydrologic year. At least 20 to 25 years of weekly ground-water level observations can be considered sufficient.

Observation series on ground-water levels in Wisconsin have been available for a much shorter time than observations of water stages on rivers or precipitation. The longest observations, as a rule, do not exceed 35 to 40 years. Observation series of more than 40 years are few in number, and not all of them have weekly measurements. If we take into account only the existing observation wells with weekly or more frequent measurements, there are only 28 observation series of 25 or more years available for statistical processing.

Prior to the actual processing, it is necessary to subject the results of observation to a minute check, to correct possible erroneous values and to supplement missing data, and to compute the weekly averages from daily measurements. This task is greatly facilitated if observations were carried out exactly and carefully. However, the observation series are never perfect and it is necessary to correct sporadic inaccurate data or to supplement missing measurements from the records of the nearest observation wells by using graphical correlation methods.

Basic Statistical Parameters

Most of the raw data supplied by observation networks is in the form of time series. Since the data necessarily cover only a certain period of observation, extended as it may be, such data represent only an observed sample of the entire population of the continuous process. While the time or space element of hydrologic phenomena may be the same, each phenomenon is characterized by a certain value which varies in time and space. This characterization is called a variable and its particular value is a variate. Thus, discharge, water level, and rainfall depth are variables. The variable may be continuous or discrete. The variables mentioned above are continuous. Different sizes of rocks contained in a sample are discrete variables.

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[1] Appendix B - Data for selected wells in Northern Wisconsin - is published separately as Miscellaneous Paper MP 80-1.

If the value of one variate is independent of any other, the variable in question is a random variable. In hydrology, practically speaking, most processes are random processes and the respective variables are equally random. The random character of hydrologic variables is most important for justifying the use of statistical methods for their processing.

All the time series (as well as other series) may be characterized by statistical parameters. The study of distribution of values within a given set of data is primarily concerned with two characteristics, the general magnitude of a set of data (averages) and the degree to which the individual items are spread out (dispersion).

Averages -- In describing a given set of data, first consideration is given to the general magnitude of the figures--their average value. In statistical work, several kinds of averages--"measures of central tendency" (or "normals")--are used. The most important are the arithmetic mean, the median, and the mode. The purpose of an average is to indicate the size of the data taken as a whole, as contrasted with that of particular items.

The simplest parameters characterizing a series are means. The most important of the measures of typical magnitude is the arithmetic mean, which is the familiar average of elementary arithmetic. This is found simply by adding the given figures and dividing by the total number of observations. Much faster, though less accurately (probable error 1-2%), the long-term average annual water level (H_a) can be calculated from the following formula (Kriz, 1972):

$$H_a = A + \frac{f \cdot d}{n} \cdot i,$$

where A = arbitrarily selected value; usually the average value of one of the intervals approximately in the middle of the frequency distribution.

f = group frequency of individual intervals.

d = deviation from A in intervals.

i = length of the interval.

n = number of members of the statistical set.

While the mean is the most familiar and the most commonly used of the statistical averages, it is not always the appropriate measure of central tendency. For certain types of data, the second average to be described--the median--may have distinct advantages. The median of a set of data is the value which divides the figures into a lower half and an upper half. There are as many figures smaller in value than the median as there are greater in value. To find the median for ungrouped data, we simply arrange the figures in order of magnitude (in an array) and pick out a value which fulfills this definition. If there are an odd number of items, the middle one is the median. If there are an even number of items, there are two middle cases, and any value between these two has as many cases above as below. In this instance, we take the value half-way between them as the median.

The parameter which would seem most representative of a set of data is that value which occurs most frequently. This is the basis of the third statistical average--the mode. If the data are discrete, so that each class contains cases having a single value, the mode is simply the value of the class having the highest frequency. If the data are continuous, the problem of identifying the mode is more difficult (Lewis, 1963).

There are a number of other partition measures similar to the median all of which divide data in certain proportions: quartiles, deciles, and percentiles. All of them may be regarded as averages; and they overlap. Hence, the fiftieth percentile, the fifth decile, and the second quartile are all identical with the median, since 50/100, 5/10 and 2/4 all equal one-half. Again, the twenty-fifth percentile is the same as the first quartile and the seventy-fifth percentile as the third quartile (Figure A1). The partition measures are more useful, however, in the study of dispersion of data.

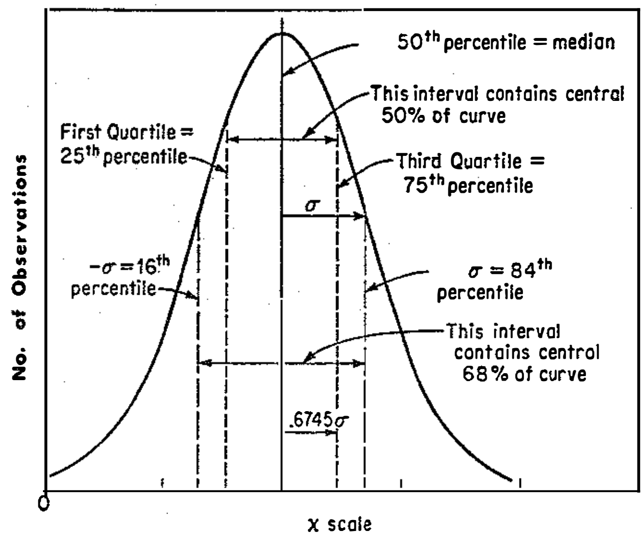


Figure A1. Normal distribution curve showing the median and other partition parameters. The first quartile is a value such that one-quarter of the cases lie below and, of course, three-quarters above. The third quartile is a value such that three-quarters of the cases lie below. The sixth decile is the value such that six-tenths of the cases lie below, and similarly for the other deciles. The sixteenth percentile is a value such that 16 hundredths of the cases lie below. One standard deviation, σ (sigma), brackets 68 percent of the data.

Dispersion -- In addition to the general magnitude of a set of data as measured by the average, the degree to which the individual items are spread out or "dispersed" is an important aspect of the figures. The measures of dispersion can be based either on any pair of values symmetrical about the median (range, 10-90 range, quartile deviation), or on all the items in a given set of data (average deviation, standard deviation).

The simplest measure of dispersion is the range, the difference between the highest (maximum) and the lowest (minimum) values (called in the study the amplitude). Its biggest disadvantage is that it does not represent the characteristic (or prevailing) range of values. The extreme end values of a given set of data normally are very rare, and may change the size of the range substantially.

The pair of dispersion measures most commonly used in hydrology--which removes the disadvantage of the range as statistical parameter--are the tenth and ninetieth percentiles, in statistics the difference between them being called the 10-90 range. For example, the difference between these two values is a much better indicator of the capacity of water level to fluctuate, and the author recommends to use a new term for this difference--the fluctuability, f.

The difference between the first quartile (Q_1) and the third quartile (Q_3) is another measure of dispersion. The more the data are spread out, the wider is the interval within which the middle half of the values lie. In statistical practice, the difference between quartiles is divided in half to get the quartile deviation.

A more satisfactory measure of dispersion of a series is that affected by all the numbers of a set. For that purpose, we calculate the deviations of all the values from the mean of the data. There are two ways of finding the average of these deviations. One is the mean (average) deviation, or the sum of the deviations from the average divided by the number of deviations, where the signs of the individual deviations are ignored and all deviations are considered positive. More useful is the standard deviation, which considers the signs of deviations. The mathematical definition is that it is the root mean square of the deviations from the average ($s_x = \sqrt{(\Sigma x^2)/N}$). By squaring the individual deviations, positive numbers for both positive and negative deviations are obtained. In a normal distribution, approximately two-thirds of all the observation lie in the range of the average $\pm$ 1 standard deviation (Figure A1), and nearly 95 percent lie within range of the mean $\pm$ 2 standard deviations.

Standard deviation also can be derived graphically from a plot of the cumulative frequency distribution on a probability paper (Huff, 1943). Two lines are drawn at 15.9 percent and 84.1 percent so that they intersect the frequency curve (Figure A2). The standard deviation is taken as one-half the difference between the water levels corresponding to 15.9 percent and 84.1 percent. Also, the mean can be derived graphically from the intersection of the frequency curve with the ordinate of 50 percent. The values derived graphically are approximately equal to the corresponding values derived from the more accurate but longer computation method, provided the cumulative frequency distribution plots as a straight line.

It is often desirable to compare the dispersion of two sets of data which are expressed respectively in different units of measurement, and to find the relative dispersion. The most commonly used measure of relative dispersion is the coefficient of variation, V. This is found by dividing the standard deviation (σ) by the mean ($\bar{X}$) and expressing it in percent: $V = (\sigma/\bar{X}) \cdot (100)$.

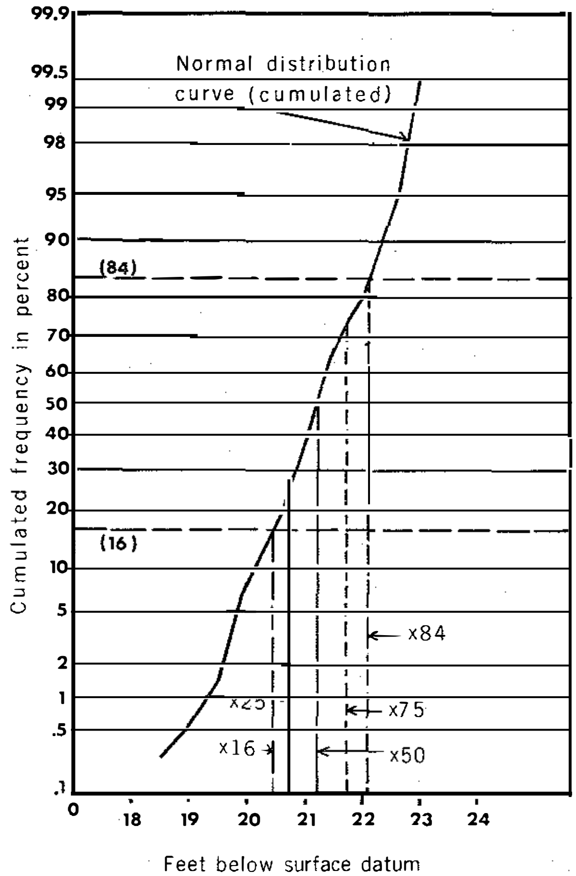


Figure A2. Interpolation of standard deviation (x_{16} and x_{84}) and the mean (x_{50}) from a cumulative frequency curve plotted on probability paper.

Frequency Distribution

The frequency distribution is used to organize data so that their characteristics may be easily and quickly summarized. It can be presented numerically or graphically. A tabular presentation of absolute or relative class frequencies is useful for preparing data and for preliminary calculations of average values discussed above (Table A1). Since it is difficult to grasp the total data picture from tabulations, a useful step in data analysis is to show a frequency distribution by means of a frequency histogram or frequency polygon. This is done by grouping the data into classes of an equal interval and then plotting a bar graph with the number of absolute frequency of observations in a class versus the midpoint of the class interval (Figure A3a). The area of each bar is proportional to frequency.

The selection of the class interval and the location of the first midpoint (class mark) can appreciably affect the appearance of a frequency histogram. The appropriate widths of a class interval depend upon the range and behavior of the

Table A1. Frequency of weekly ground-water levels

Class Interval (in ft below lsd)	Frequency (n)		Cumulative Frequency (Duration)	
	Absolute (n)	Relative n/N	Absolute (Σn)	Relative ($\frac{\Sigma n}{N}$)
18.01-18.50	6	.3	6	.3
18.51-19.00	6	.3	12	.6
19.01-19.50	21	1.03	33	1.63
19.51-20.00	135	6.63	168	8.26
20.01-20.50	268	13.16	436	21.42
20.51-21.00	402	19.74	838	41.16
21.01-21.50	456	22.40	1294	63.56
21.51-22.00	373	18.32	1667	81.88
22.01-22.50	283	13.90	1950	95.78
22.51-23.00	76	3.73	2026	99.51
23.01-23.50	10	.49	2036	100.00
	N = 2036	100.00%		

Data from this table used for plotting Figures A3 and A5.

data and the number of observations. The criteria for the selection of the class interval are not rigid. One suggestion is that there be five to 20 classes. Too many classes result in erratic patterns of alternating high and low frequencies. Too few classes eliminate detail and obscure the basic pattern of the data.

A distribution may also be represented by the midpoints of the classes or a frequency polygon (Figure A3b). This type of graphical presentation has the disadvantage that areas are no longer proportional to frequencies. The greater the number of class intervals, the smoother the frequency polygon. If there are a very large number of classes of very small intervals, the frequency polygon will approach a smooth curve or a frequency curve. However, the term frequency curve is reserved for cumulative (probability) distributions.

Various types of frequency curves are available for the statistical analysis of data (Figure 4). The simplest one is the symmetrical normal distribution. The concentration of values (or peak) is in the middle of the scale and the sides of the curve rise and fall in a symmetrical slope. The mean, median, and mode are the same value. However, data used in hydrology are not normally distributed. Rather many frequency distributions are nonsymmetrical, or skewed. For such distributions, the mean, median, and mode have different values. The position of the mean with respect to the median on the curve depends on the degree and direction of skewness, and the direction in which the frequency distribution is cumulated. Skewness may be shown graphically as right or left; and it may be described mathematically as positive or negative. If a right (positively) skewed distribution, if cumulated from the high end, the mean is to the right of the median; if cumulated from the low end, the mean is to the left of the

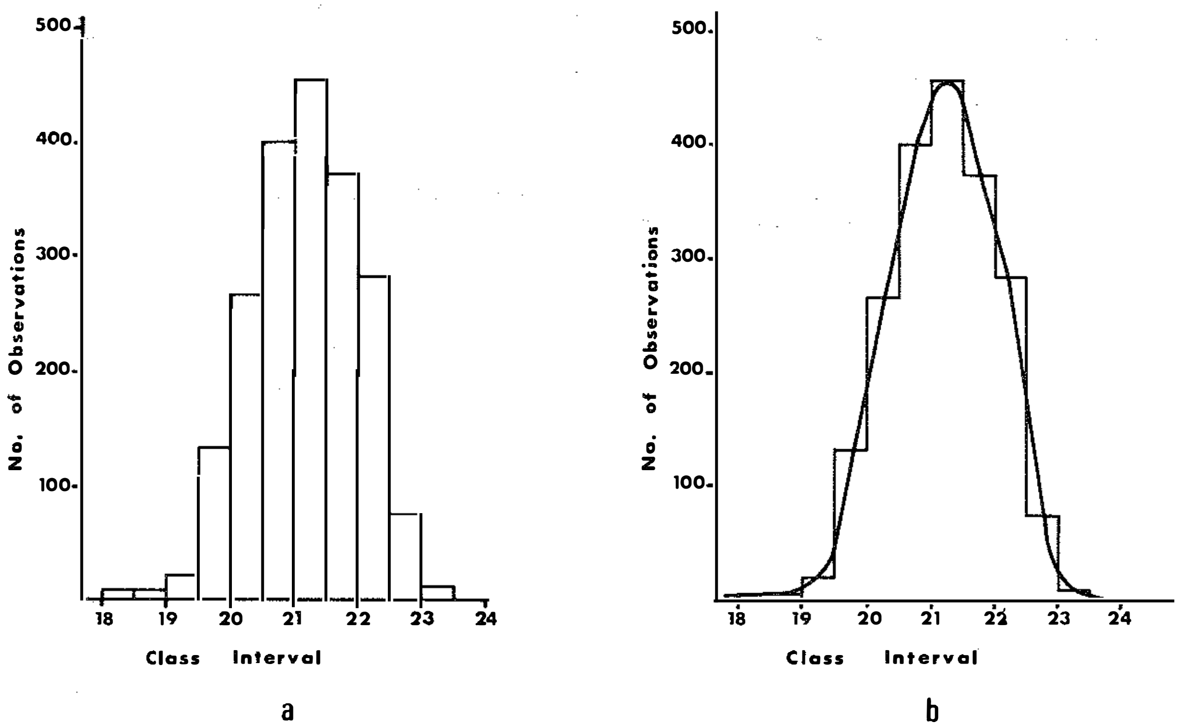
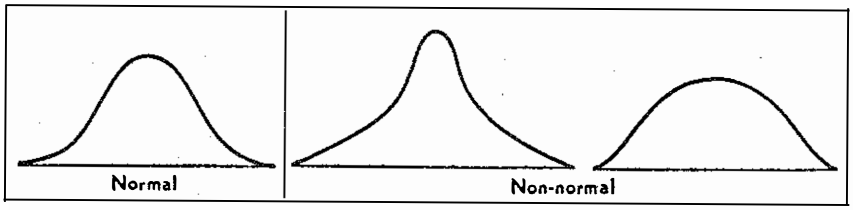
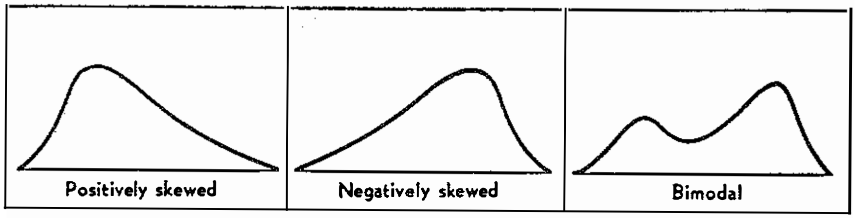


Figure A3. Frequency histogram (a), showing transition to a frequency polygon (b).

TYPES OF FREQUENCY DISTRIBUTION CURVES:

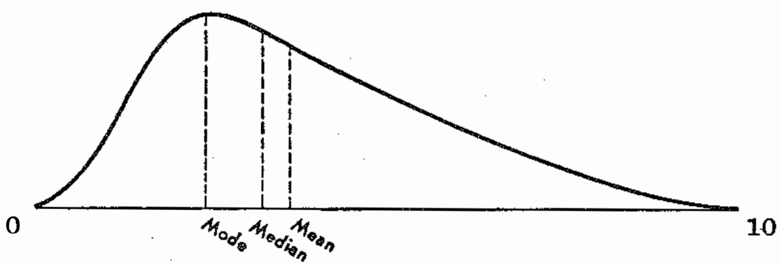


A. Symmetrical Distribution

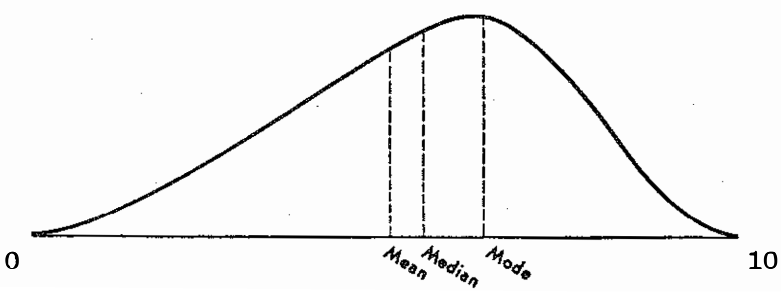


B. Nonsymmetrical Distribution

POSITIONS OF AVERAGES IN NON-SYMMETRICAL CURVES:



C. Positively (Right) Skewed Distribution



D. Negatively (Left) Skewed Distribution

Figure A4. Types of frequency distribution curves (from Lewis, 1963).

median. These relations are reversed for a left (negatively) skewed distribution. In all cases, the mode is always on the opposite side of the median from the mean. Relative positions of the mean, median, and mode on nonsymmetrical frequency curves are shown in Figure A4.

Probability Distribution

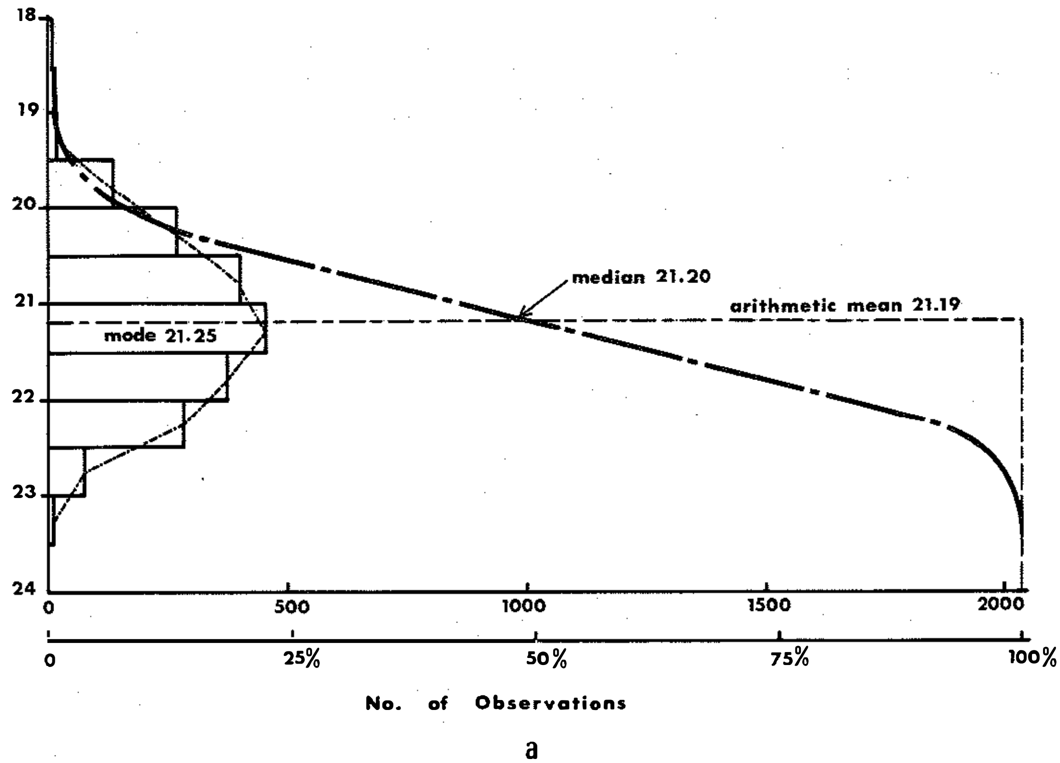
Another common method of presenting data is in the form of a cumulative frequency distribution. Cumulative distributions relate magnitude of a variable to frequency of occurrence, or to probability of exceedance or non-exceedance. They are formed by summing relative frequencies and plotting the accumulated sum against the corresponding data value from one end of the curve (Figure A5a). If the ordinates are summed from the smaller (larger) data values to the larger (smaller) values, the resulting cumulative frequency refers to the frequency of observations less (more) than the corresponding data value. Points on the cumulative curve should be plotted on the right (left) boundary of the class interval. When the probability curve is cumulated from the right end, the probabilities of exceeding the various magnitudes are obtained. If cumulated from the left, probabilities of not exceeding those magnitudes are obtained. The chart for a cumulative distribution is called an "ogive", or a duration curve (or probability curve). The broken line of an ogive can be smoothed by inspection to draw the line of best fit. Cumulative distributions also can be plotted on normal probability plotting paper to obtain a straight line (Figure A5b).

For time series, frequency curves also relate magnitude of a variable to recurrence interval or return period. The return period is defined as the average elapsed time between occurrences of an event with a certain magnitude or greater. For example, a 25-year peak discharge is a discharge that is equaled or exceeded on the average once every 25 years over a long period of time. It does not mean that an exceedance occurs every 25 years, but that the average time between exceedance is 25 years. An exceedance is an event with a magnitude equal to or greater than a certain value.

Sometimes the actual time between exceedances is called the recurrence interval. With this definition for recurrence interval, the average recurrence interval for a certain event is equal to the return period of that event.

The return period can be related to a probability of an exceedance. If an exceedance occurs on the average once every 25 years, then the probability or chance that the event occurs in any given year is 1/25 = .04, or 4 percent. Probability, p, and return period, T, are thus reciprocal values: $T = (1)/(p)$.

The plotting of data on a probability paper requires the knowledge of plotting positions. Each individual in the statistical set is assigned a probability, or recurrence interval. Assignment of probabilities is by means of a plotting-position formula. Numerous methods have been proposed for the determination of plotting positions. Most of them are empirical (Chow, 1964).



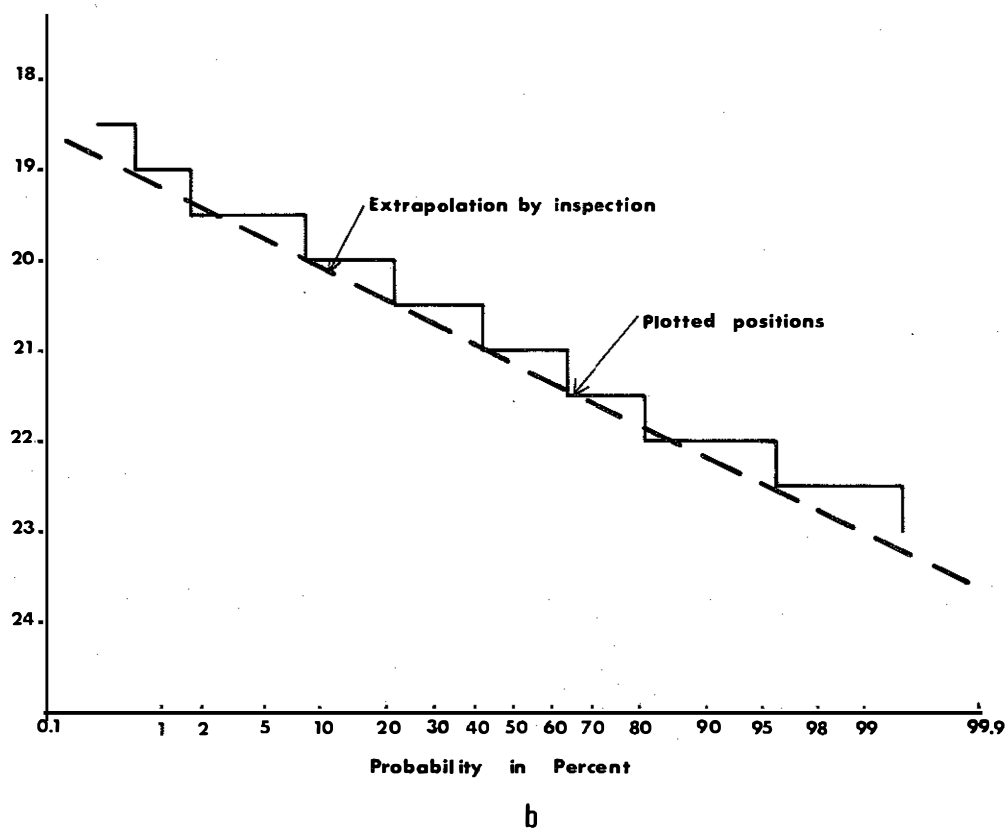


Figure A5. Frequency distribution of ground-water levels. (a) Frequency distribution graph and duration curve; (b) Duration curve on probability paper.

The simplest, and the least accurate, is a formula using the basic probability formula $p = (m)/(n)$, where m is a serial number of an event (or frequency of an event) and n the total number of occurrences. Probability is expressed as a fraction or a percentage. This computation of probability is applicable to closed series only. However, time series in hydrology are seldom closed, since it is impossible to ascertain all values of occurrences in the past. A lower than the lowest and higher than the highest recorded annual precipitation may have occurred in the unrecorded past and certainly may occur in the future. Therefore, for open series it is necessary to modify the basic probability equation.

Theoretical works in frequency analysis (Chow, 1964; Nemec, 1972) have proposed changing the equation given above so as to serve the purpose of analyzing relatively short time series, representing a relatively limited sample of the whole population. In the United States, the Weibull formula $p = (m)/(n + 1)$ has been recommended for standard use. In this study, the author used the Chegodayev formula $p = (m - 0.3)/(n + 0.4) \cdot 100$, an empirical formula commonly used in the USSR for flood peak computations, and widely used in Czechoslovakia for the determination of the empiric probability of exceedance of ground-water levels or precipitation. The values of probability computed by this method are included in Table A2. All methods of determining plotting positions give practically the same results in the middle of a distribution but produce different positions near the "tails" of the distribution.

After the hydrologic data are plotted on a probability paper, a curve may be fitted to the plotted points. The curve is a straight line if linearization of the distribution is attempted. Curve fitting may be done either mathematically or graphically. The mathematical fitting does not necessarily require data plotting on a probability paper. In general, a mathematical curve fitting can be achieved by three methods: the method of moments (Gumbel extreme-value distribution; Pearson Type III distribution), the method of least squares (regression line), and the method of likelihood (Kimball method) (Chow, 1964). The first method gives a theoretically exact fitting, but the accuracy can be substantially affected by any errors involved in the data at the tails of the distribution where the moment arms are long and the errors are thus magnified. The curve fit obtained by the second method may not represent the exact theoretical distribution, but it gives a better overall fit than the method of moments. The third method provides the best estimate of the parameters, but it is usually very complicated for practical application. In graphical fitting, a straight line is simply drawn to fit the plotted data by visual inspection (eye-fit). This method is the simplest but involves human error. All curve-fitting in this study was done graphically, with the exception of Figure 19.

The frequency distribution graphs and cumulative frequency curves (duration curves) have many uses in hydrology.

The frequency distribution graph indicates several characteristics of the series. The value of the variate having the highest frequency, or the maximum abscissa of the frequency distribution curve, is the mode. The value of the variate having a 50 percent cumulative frequency, in other words, half of the variates being below it and the other half above, is the median of the series. Finally, the arithmetic mean may also be ascertained from both the frequency distribution graph and duration curve. In the first case, the abscissa passing through the center of gravity of the graph indicates on the axis of the ordinates the value of the arithmetic mean. In the second case, it is indicated by the abscissa which halves the area of the duration curve (Figure A6).

Table A2. Probability values for the time series of 20 to 42 years. Plotting positions by the Chegodayev formula:

$$p = \frac{m - 0.3}{n + 0.4} \cdot 100$$

m \ n	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
1	3.43	3.27	3.13	2.99	2.87	2.76	2.65	2.56	2.46	2.38	2.30	2.23	2.16	2.10	2.03	1.98	1.92	1.87	1.82	1.78	1.73	1.69	1.65
2	8.33	7.94	7.59	7.26	6.97	6.70	6.44	6.20	5.98	5.78	5.58	5.41	5.25	5.09	4.94	4.80	4.67	4.55	4.43	4.31	4.21	4.11	4.01
3	13.20	12.60	12.00	11.50	11.10	10.60	10.20	9.85	9.50	9.18	8.88	8.60	8.33	8.08	7.85	7.52	7.41	7.22	7.03	6.85	6.68	6.52	6.37
4	18.10	17.30	16.50	15.80	15.20	14.60	14.00	13.50	13.00	12.60	12.20	11.80	11.40	11.10	10.80	10.45	10.16	9.89	9.64	9.39	9.16	8.94	8.73
5	23.00	22.00	21.00	20.10	19.30	18.50	17.80	17.20	16.50	16.00	15.50	15.00	14.50	14.10	13.70	13.28	12.91	12.57	12.24	11.93	11.63	11.35	11.08
6	28.00	26.60	25.40	24.40	23.40	22.40	21.60	20.80	20.10	19.40	18.80	18.20	17.60	17.10	16.60	16.10	15.66	15.24	14.84	14.47	14.11	13.77	13.44
7	32.80	31.30	29.90	28.60	27.50	26.40	25.40	24.40	23.60	22.80	22.10	21.30	20.70	20.00	19.50	18.93	18.41	17.91	17.45	17.00	16.58	16.18	15.80
8	37.80	36.00	34.40	32.90	31.60	30.30	29.20	28.10	27.10	26.20	25.30	24.50	23.80	23.00	22.40	21.75	21.15	20.59	20.05	19.54	19.06	18.60	18.16
9	42.60	40.60	38.80	37.20	35.70	34.30	33.00	31.80	30.60	29.60	28.60	27.70	26.90	26.10	25.30	24.58	23.90	23.26	22.66	22.08	21.53	21.01	20.52
10	47.50	54.30	43.30	41.50	39.80	38.20	36.70	35.40	34.10	33.00	31.90	30.90	30.00	29.10	28.20	27.40	26.65	25.94	25.26	24.62	24.01	23.43	22.88
11	52.50	50.00	47.80	45.70	43.90	42.10	40.50	39.10	37.70	36.40	35.20	34.10	33.00	32.00	31.10	30.23	29.40	28.61	27.86	27.16	26.48	25.84	25.24
12	57.30	54.70	52.20	50.00	48.00	46.10	44.30	42.70	41.20	39.80	38.50	37.30	36.10	35.00	34.00	33.05	32.14	31.28	30.47	29.70	28.96	28.26	27.59
13	62.20	59.40	56.70	54.20	52.00	50.00	48.10	46.40	44.70	43.20	41.80	40.40	39.20	38.00	36.90	35.88	34.89	33.96	33.07	32.23	31.43	30.68	29.95
14	67.20	64.00	61.20	58.50	56.10	53.90	51.90	50.00	48.20	46.60	45.10	43.60	42.30	41.00	39.80	38.70	37.64	36.63	35.68	34.77	33.91	33.09	32.08
15	72.00	68.70	65.60	62.80	60.20	57.90	55.70	53.60	51.80	60.00	48.40	46.80	45.40	44.00	42.70	41.53	40.38	39.30	38.28	37.31	36.39	35.51	34.67
16	77.00	73.40	70.10	67.10	64.30	61.80	59.50	57.30	55.30	53.40	51.60	50.00	48.50	47.00	45.60	44.35	43.13	41.98	40.89	39.85	38.86	37.92	37.03
17	81.90	78.00	74.60	71.40	68.40	65.70	63.20	60.90	58.80	56.80	54.90	53.20	51.50	50.00	48.50	47.18	45.88	44.65	43.49	42.39	41.34	40.34	39.39
18	86.80	82.70	79.00	75.60	72.50	69.70	67.00	64.60	62.30	60.20	58.20	56.40	54.60	53.00	51.50	50.00	48.63	47.33	46.09	44.92	43.81	42.75	41.75
19	91.67	87.40	83.50	79.90	76.60	73.60	70.80	68.20	65.90	63.60	61.50	59.60	57.70	56.00	54.40	52.82	51.37	50.00	48.70	47.46	46.29	45.17	44.10
20	96.57	92.06	88.00	84.20	80.70	77.60	74.60	71.90	69.40	67.00	64.80	62.70	60.80	59.00	57.30	55.65	54.12	52.67	51.30	50.00	48.76	47.58	46.46
21		96.73	92.41	88.50	84.80	81.50	78.40	75.60	72.90	70.40	68.10	65.90	63.90	62.00	60.20	58.47	56.87	55.35	53.91	52.54	51.24	50.00	48.82
22			96.87	92.73	88.90	85.40	82.20	79.20	76.40	73.80	71.40	69.10	67.00	65.00	63.10	61.30	59.62	58.20	56.51	55.08	53.71	52.41	51.18
23				97.01	93.03	89.40	86.00	82.80	79.90	77.20	74.70	72.30	70.00	68.00	66.00	64.12	62.36	60.70	59.11	57.61	56.19	54.83	53.54
24					97.13	93.31	89.80	86.50	83.50	80.60	77.90	75.50	73.10	70.90	68.90	66.95	65.11	63.37	61.72	60.15	58.66	57.24	55.90
25						97.24	93.56	90.10	87.00	84.00	81.20	78.70	76.20	73.90	71.80	69.77	67.86	66.04	64.32	62.69	61.14	59.66	58.25
26							97.35	93.80	90.50	87.40	84.50	81.90	79.30	77.00	74.70	72.60	70.60	68.72	66.93	65.23	63.61	62.08	60.61
27								97.44	94.01	90.80	87.80	85.00	82.40	80.00	77.60	75.42	73.35	71.39	69.53	67.77	66.09	64.49	62.97
28									97.54	94.22	91.10	88.20	85.50	82.90	80.50	78.25	76.10	74.06	72.14	70.30	68.56	66.91	65.33
29										97.62	94.41	91.40	88.60	85.90	83.40	81.07	78.85	76.74	74.74	72.84	71.04	69.32	67.69
30											97.70	94.59	91.70	88.90	86.30	83.90	81.59	79.41	77.34	75.38	73.51	71.74	70.05
31												97.77	94.75	92.00	89.20	86.72	84.34	82.09	79.95	77.92	75.99	74.50	72.40
32													97.84	94.91	92.20	89.55	87.09	84.76	82.55	80.46	78.46	76.57	74.76
33														97.90	95.06	92.37	89.84	87.43	85.16	82.99	80.94	78.98	77.12
34															97.97	95.20	92.58	90.11	87.76	85.53	83.41	81.40	79.48
35																98.02	95.33	92.78	90.36	88.09	85.89	83.82	81.84
36																	98.07	95.45	92.97	90.61	88.37	86.23	84.20
37																		98.13	95.57	93.15	90.84	88.65	86.56
38																			98.18	95.69	93.32	91.06	88.91
39																				98.22	95.79	93.48	91.27
40																					98.27	95.89	93.63
41																						98.31	95.95
42																							98.35

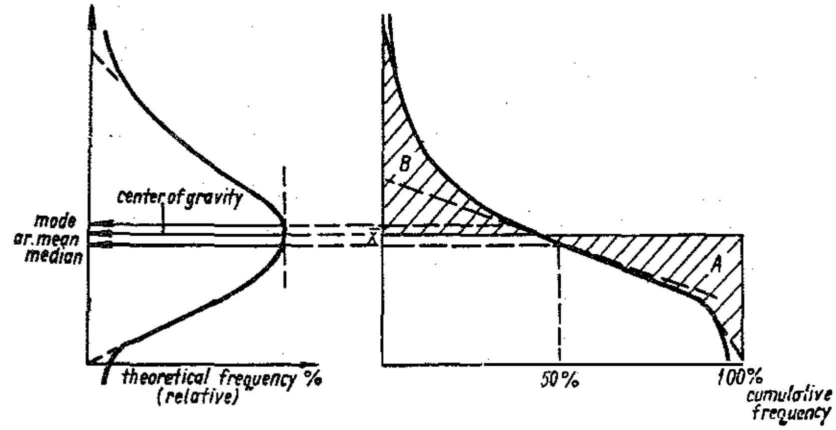


Figure A6. Graphical derivation of the mean, median, and mode from frequency distribution and probability curves (after Nemec, 1972).

Cumulative frequency curves have typical shapes and if constructed on the same scale and placed on a single chart, comparison is possible by simple visual inspection.

The cumulative frequency curves are also very useful for interpolating the cumulative frequencies for points between the class limits actually plotted. Probability, in the concept of frequency distributions, is defined as relative frequency. Therefore, we can read off from the frequency curve the characteristic water levels exceeded on the average for the time of "n" days, or n% of days per year, and arrange them in tables such as tables 6 in Appendix B. These characteristic values can be used for classification purposes, such as the wetness of individual years (see Table 5) and fluctuations of water levels (see Table 13). Most commonly, the values read at 10, 40, 60, and 90 percent are used for the classification.

Simple Linear Relationship

The preparation of simple linear relations between two variables is well known. The basic device for displaying the relation of two quantitative series is the scatter diagram, or plot of given data. The data are plotted on a Cartesian coordinate paper with one variable on the vertical coordinate, the ordinate (Y), and the other on the horizontal coordinate, the abscissa (X). To characterize the relationship of the X and Y values, a straight line is drawn through the body of the data. This gives us the line of average relationship, or the line of regression. The regression line is not necessarily the same line as one would draw through the plotted points by eye. The regression line can be constructed for both variables, Y and X, using a general regression equation: $Y = f(X)$, or $X = f(Y)$.

One method for constructing the line of regression is the method of least squares. The straight line regression is represented by equation $Y_c = a + b X$, where Y_c stands for the calculated value of Y, and a and b are the numerical constants which identify the so-called normal equations. To determine the regression line, we solve the normal equations for a and b,

$$\sum Y = N a + b \sum X$$

$$\sum XY = a \sum X + b \sum X^2;$$

put the calculated values in the least-square regression equation; and plot the calculated value of Y against X (the given variable) in the scatter diagram. The deviations of the actual data from the points on the regression line are represented by vertical lines connecting these two points. An example of this method is given in the section entitled Drought-Proof Wells. We might, of course, proceed in an opposite fashion, switch variables, and compute an X value by equation $X_c = a' + b'Y$. In this case, the deviations from the regression line would be represented by horizontal rather than vertical lines. If there is a relationship and the regression line goes from lower left to upper right, the relationship is positive. If the relation is of the inverse kind, then it is taken as negative.

We may measure the degree to which the data points depart from the line of regression by squaring the individual deviations, adding and dividing by the number of items, and taking the square root. The resulting measure is called the scatter. Designating it by S_Y (since the deviations, d, are measured here in terms of the vertical scale), we have

$$S_Y = \sqrt{\frac{\sum d^2}{N}} .$$

This measure is very similar to the familiar standard deviation, the only difference being that the deviations are measured from the appropriate points on the regression line instead of the mean.

In the case of a perfect relationship, all the data points lie exactly on the regression line, and the regression value corresponding to any value of X is not only a typical value of Y, but the only possible value. Under these circumstances, the scatter around the line is zero. In contrast, if there is no relation between the two variables, the line of regression is horizontal, giving the same values of Y for low as well as high values of X. In this case, the scatter has the identical value as the standard deviation of Y.

In any given set of data the size of the scatter lies somewhere between zero (for perfect relation) and equality with the standard deviation of Y (for no relation). In view of this, we may construct an abstract measure of the degree of relationship based on the ratio of the scatter (S_Y) to the standard deviation (s_Y). The measure is called the coefficient of correlation, r, and defined as

$$r = \sqrt{1 - \frac{S_Y{}^2}{s_Y{}^2}} .$$

The correlation coefficient expresses the degree of association of one phenomenon with the other and is the mathematical expression of the density of the concentration of points around the regression line.

For perfect correlation, the coefficient of correlation is $\sqrt{1 - 0}$, or $\sqrt{1}$, or 1. For no relation, the coefficient of correlation is $\sqrt{1 - 1}$, or zero. For degrees of relationship between these two extremes, the coefficient of correlation is equal to the square root of the number under the radical sign, i.e., a number between zero and unity. Because the coefficient of correlation can be either positive or negative, it varies between +1 and -1. In hydrology, the following relations between phenomena may be determined on the basis of the values of the coefficient of correlation (Nemec, 1972):

$r = 1$	direct functional dependence
$0.6 < r < 1$	good direct correlation
$0 < r < 0.6$	insufficient direct correlation
$r = 0$	no correlation
$-0.6 < r < 0$	insufficient reciprocal correlation
$-1 < r < -0.6$	good reciprocal correlation
$< r = -1$	reciprocal linear functional dependence

A direct, or directly proportional, dependence means that the increase of one of the phenomena results in the increase of the other (positive coefficient). A reciprocal, or reciprocally proportional, dependence means that the increase of one of the phenomena results in the decrease of the other (negative coefficient).

Time-Series Analysis

When the hydrologic data are treated as a statistical set, they can be arranged in a sequence in accordance with the time of occurrence. This is logical because the hydrologic data reflect the histories of the hydrologic phenomena. The sequence of values collected over time on a particular variable is mathematically known as a time sequence, or time series. The purposes of the statistical analysis of time series are to understand the basic properties of the time series (variability, and characteristics of periodic and irregular fluctuations), and to predict the behavior of the time series in the future. There are four main types of change in magnitude shown over a given period, referred to as the major time-series components:

1. secular (long-term) trend,
2. seasonal variation (intrayearly pattern),
3. cyclic trend, and
4. irregular oscillations.

The secular trend is identified by direct measurement from the data, while the other three components are found by a process of elimination. There are many methods for studying and separating the individual components of a time series. The author has limited discussion here to those used in this study.

To measure secular trend, a straight line or curve may be drawn through the body of the data. One method of showing the general trend of water levels is the moving average. The sum of successive levels for a selected period of time (two, three, five, 10 years, and so on) is first calculated and the average level is then obtained by dividing the sum by the number of dates (years) considered (two, three, five, 10). After the average water level for a selected period at the beginning of the record has been computed, the next successive water level is added to the sum and the first water level is subtracted. Then a new average level is calculated from the new moving sum. We continue calculating until averages are obtained for a selected interval for the entire record. The line representing the moving average is much smoother than the actual data, since the averaging process evens out marked irregularities (see Figure 7).

A very simple mechanical device is useful in this work. We cut a piece of paper just large enough to cover one fewer items than the number of items involved in the moving average. Having found the first sum, we cover all but the first year involved. This leaves above the paper the number to be subtracted, and below the paper the number to be added, in getting the next moving-sum figure. In actual problems, this device saves considerable labor (Lewis, 1963), if a computer is not available.

The procedure just described applies to moving averages based upon any odd number of years. If a moving average is based on an even number of years, the calculations have to be centered by adding an additional step. For example, for the four-year moving average, we find the four-year sums, but we do not average them; instead we add adjacent pairs of four-year sums and divide this sum by eight (2 x 4 years) to find the four-year moving average.

The seasonal component represents a characteristic movement of the series throughout the months of a single year. For many series, the movement recurs in more or less identical form year after year. Then the seasonal may be represented by a set of 12 numbers, one for each month, showing the typical intrayearly fluctuation. The general procedure for finding the seasonal is to eliminate the nonseasonal components from a series and reach the desired pattern as a sort of residual product. There are several specific methods of finding the seasonal, most of them involving extensive calculations (ratios to trend; ratios to moving average; means; and link relatives). Relatively simple, and commonly used in the analysis of the annual variations of water levels, is the method of means. An average (arithmetic mean) of all the actual data is calculated for each month and plotted against time to find the characteristic nature of water-level fluctuations throughout the year (see Figure 12). Water levels tend to be high in the spring months and low in the heart of winter. If the means are calculated for a short series, they may be tilted in the direction of secular trend and subsequently adjusted to eliminate this tilt.

The remaining components of time series, cyclic and irregular, are usually presented in combination since in most cases it is difficult to separate them. In many series, however, the cyclic pattern stands up in spite of the irregularities, which may have the form of short-term, saw-tooth fluctuations around the general path of the curve. In this case, the running of a moving average through the data will smooth out the irregularities and leave the cyclic contour. But if the irregular variations are more substantial, and particularly if they appear to obscure the long-term trend, the moving average is ineffective. The methods for studying the cyclic component of time series and separating it from the regular one are many and varied, and none of them completely satisfactory. The reader is referred to the abundant literature on time-series analysis, for example Haan (1977); Kisiel (1969); Lewis (1963); and Panofsky and Brier (1968).

One more method is very useful in the statistical analysis of time series: the cumulative departure from the normal or mean, or from moving average (Jacob, 1943), which is especially useful for studying the relations between precipitation and water levels (or streamflows). The departures or deviations from the normal, mean, or moving average are calculated for each year (or other selected period of time) and cumulated for the entire period or record. The departures are both positive and negative, and their sum must equal zero. By plotting the cumulative departures, a departure curve is obtained showing the excess or deficiency of a given parameter over the mean (normal or moving average) for a fixed period.

If the departures are not cumulated but plotted for the selected period of time, they show the departure from average water-level curve and the relative position of the water level at any time. By using this method, the effects of seasonal cycles are eliminated, and the departure curve can be used for studying the major trends of the water level, which otherwise might be obscured, or for correlating the ground-water levels with cumulative departures from average precipitation (Wenzel, 1936). The water-level departure curve differs from the actual hydrograph in that it indicates the relative position of the water level at any time, the zero line giving the long-term averages. The distance above or below the line gives the distance of the water level above or below its average position and is often a better indication of recharge from precipitation than the actual hydrograph.

APPENDIX REFERENCES

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