Drought Conditions in Maine, 1999-2002: A Historical Perspective

U.S. DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 03-4310

Cover Photograph: St. John River at Ninemile, Maine, September 3, 2002. Photograph courtesy of Greg Stewart.

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By Pamela J. Lombard

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Augusta, Maine
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CONTENTS

LIST OF FIGURES

LIST OF TABLES

CONVERSION FACTORS

Multiply	By	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second per square mile ($(ft^3/s)/mi^2$)	0.01094	cubic meter per second per square kilometer

To convert temperature in degrees Fahrenheit (°F) to degrees Celsius (°C) use the following equation:

°C = 5/9 * (°F - 32)

Drought Conditions in Maine, 1999-2002: A Historical Perspective

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ABSTRACT

Hydrologic drought can be defined as reduced streamflow, declining ground-water levels, and (or) reductions in lake or reservoir levels. Monthly precipitation totals, annual 7-day low-flow surface-water recurrence intervals, and month-end ground-water levels from drought years 1999-2002 show that 1999-2002 was the driest period of hydrologic drought in more than 50 years of record in Maine. Record lows were set in all three data sets at select locations in central Maine in April 1999, and in September 2001 and 2002. Although streamflows recovered to normal levels during 2000, ground-water levels in central Maine indicate that the drought carried over through 2000 into 2001 and 2002 in some locations.

In 2001, annual 7-day low flows with greater than 100-year recurrence intervals were recorded in central Maine and low flows with up to 75-year recurrence intervals were recorded in coastal areas. In 2002, annual 7-day low flows with greater than 100-year recurrence intervals were recorded at 4 of 14 stations analyzed statewide, placing it as the driest single year of hydrologic drought on record. Month-end ground-water levels at one location in central Maine indicate that the recent hydrologic drought years were the most severe in more than 50 years in that region. The period from 1947 to 1950 may have been the only comparable period of drought to the 1999-2002 period, in Maine. The 1960s drought, although extreme in the far northern and far southern regions of the State, was most exceptional for its duration from 1963 to 1969.

INTRODUCTION

Drought is among the most complex and least understood of all natural hazards, affecting more people than any other natural hazard (American Meteorological Society, 1997). Although drought typically is not considered a problem in the humid northeastern United States, it is a normal, recurring feature in all climatic regimes. Drought is a temporary aberration, relative to some long-term (tens of years) average condition, as opposed to aridity, which is a permanent feature of some regional climates (American Meteorological Society, 1997). Many questions still remain concerning the physical mechanisms responsible for the onset, persistence, and spatial extent of regional hydrologic drought in the northeast because of hydrologic variability and the inherent complexity of hydrologic systems (Bradbury and others, 2002).

Dry conditions were present in Maine from 1999 to 2002, with a severe drought in 2001-2002. Most U.S.Geological Survey (USGS) monitoring wells, and many streamflow-gaging stations, set record lows during this period. An estimated 7 percent, or approximately 17,000 private wells in Maine went dry in the 9 months prior to April 2002 (Maine Emergency Management Agency, 2002). Wells in central Maine were the most likely to have low water levels. Thirty-five public water supplies, including eight large community systems, were affected severely (Andrews Tolman, Maine Drinking Water Program, written communication, 2003). Most major surface-water reservoirs released water at levels below their regulatory minimum flows, instream flows for aquatic life were reduced, and critical summer irrigation was limited. Farmers in Maine lost more than 32 million dollars in crops in 2001 and 2002, with some wild blueberry growers recording crop losses of 80 to 100 percent according to a Maine Department of Agriculture water-use survey to which 28 percent of Maine farmers responded (Maine Agricultural Water Management Advisory Committee, 2003).

The effects of past droughts nationwide have been exacerbated by the absence of preparedness plans (American Meteorological Society, 1997). An integral part of any preparedness plan would include meteorologic and hydrologic thresholds based on historical droughts in the region. During 1999-2002, water-resource professionals, farmers, business owners, and others who were concerned with instream flows, storage, or ground-water levels lacked the quantitative historical information necessary to compare the severity of the 1999 to 2002 drought to historical droughts, and to assess the potential of drought to stress water resources. Because droughts will occur in Maine in the future, water-resource professionals will benefit from documentation and analysis of the hydrologic conditions experienced from 1999 to 2002 in Maine. In particular, emergency management workers and public-water suppliers in Maine will benefit from this information by better understanding the complexity of how droughts move through the hydrologic system, and thus, be better able to anticipate drought effects.

Purpose and Scope

The purpose of this report is to document the relative regional and historical severity of the dry hydrologic conditions experienced from 1999 to 2002, and to provide information regarding the occurrence and persistence of droughts in Maine. This report includes a comparison of 1999-2002 daily mean streamflows, month-end ground-water levels, and total monthly precipitation values to historical statistics at select stations. The interaction among precipitation, surface water, and ground water, the annual 7-day surface-water low-flow recurrence intervals for this drought period and for historical droughts, and a comparison of month-end ground-water levels to ground-water statistics for historical droughts also are examined.

Drought Definition

Droughts can be measured or defined on the basis of a wide variety of parameters including precipitation deficits, streamflows, ground-water levels, soil moisture, and economic impacts. The relation among the intensity, duration, and spatial and temporal extent of these parameters defines many different types of events, all of which may be considered droughts. For example, a growing season with no rain in the northern region of the State would be characterized differently than a statewide, multi-year period with below-average precipitation, but both could be considered droughts. Although drought can be defined strictly as a percentage of normal precipitation, it is more often defined as a period of moisture deficit sufficient to have some adverse effect on the social or economic activity of a region (Changnon, 1980; Paulson and others, 1991). The integration of multiple definitions into a combined measure of drought has been problematic in the past for natural resource managers. The many definitions of drought make it difficult to declare the beginning or end of a drought or assess its severity during a drought period.

The American Meteorological Society groups drought into four types including climatologic drought, agricultural drought, hydrologic drought, and socioeconomic drought (American Meteorological Society, 1997). Climatologic drought often is defined by a threshold precipitation deficit or a ratio of actual precipitation to normal precipitation. Agricultural drought links climatologic drought to agricultural effects and is largely the result of a deficit of soil moisture. Hydrologic drought is defined as reduced streamflow, declining ground-water levels, and (or) reductions in lake or storage levels. Socioeconomic drought associates the supply and demand of some economic good with the elements of climatologic, agricultural, and (or) hydrologic drought (American Meteorological Society, 1997). These types of drought usually take place simultaneously; however, hydrologic droughts typically are out of phase with or lag climatologic and agricultural droughts. Meteorologic elements, such as temperature, wind, and relative humidity, can aggravate the severity and the effects of drought (American Meteorological Society, 1997). Although various aspects of all four drought types defined here occurred in Maine from 1999 to 2002, this report primarily documents the characteristics of the hydrologic drought and how the climatologic drought contributed to it.

Previous Studies

There is very little documentation of historical droughts in Maine. In 1991, the USGS defined multi-year historical droughts in each state of the United States, and calculated their recurrence intervals in a National Water Summary on floods and droughts (Paulson and others, 1991). Drought periods identified for the Maine Water Summary are listed in table 1 (Maloney and Bartlett, 1991):

Table 1. Low-flow recurrence intervals for historical droughts in Maine from 1938 to 1988, as identified by Maloney and Bartlett in the National Water Summary, 1991 [Low-flow recurrence interval, the average interval of time within which streamflow will be less than a particular value; >, greater than]

Dates	Area Affected	Low-Flow Recurrence Interval (years)
1938-43	Western areas	15 to >30
1947-50	South-central areas	15 to >30
1955-57	Nearly entire state	15 to >30
1963-69	Statewide	>30
1984-88	Statewide	15 to >30

The recurrence intervals for the droughts in table 1 were calculated on the basis of the cumulative departure from mean monthly streamflows. This method is described in the introduction to State summaries of floods and droughts in the National Water Summary (Jordan and Jennings, 1991). The intensity of the drought was taken into account, but the duration was not; droughts that varied in duration from 1 year to 6 years were ranked on the same scale. This method may be appropriate for identifying multi-year periods of drought, or assigning recurrence intervals to total water deficits in systems that depend on reservoirs such as in the western United States, but it is not appropriate for eastern States except in the most approximate terms. This is because drought in the eastern United States may depend on the timing of precipitation as much as on the total amount of precipitation.

Resource managers in the northeastern United States often use national indices to assess regional conditions despite that these indices may be more appropriate for nationwide water-status monitoring (Skaggs, 1975). Often, the national indices fail to give those affected by the drought or those who make policy a local basis for evaluation and action (Russell, and others, 1970). Even different user groups within a region may experience drought periods in different ways. For example, in the first year of a drought, farmers can face severe shortages while public water suppliers may not experience a deficit. Likewise, in subsequent years of a drought, agriculture may recover because of seasonal rains, but the hydrologic indices such as ground- water levels may take an additional year to recover.

Acknowledgements

The author would like to acknowledge Joseph Nielsen, USGS, for providing technical guidance, Sarah Canon, USGS, for her ground-water data analyses, and USGS Hydrologic technicians in the Maine District for over 100 years of data collection.

DATA COMPILATION

Statewide hydrologic drought conditions in Maine from 1999 to 2002 were examined using data from National Weather Service precipitation stations, USGS streamflow-gaging stations, and USGS ground-water wells at select locations around the State (fig. 1). Stations were chosen on the basis of their length of record and their location. The goal in all cases was to use an even distribution of stations around the State with a sufficient period of record to give historical perspective. Although data are presented through 2003, precipitation data after December 2002 and ground-water and surface-water data after September 2002 are considered preliminary and are subject to change.

Precipitation Gages

Four precipitation stations were used in this study: Caribou Municipal Airport (National Weather Service Station number 171175) in northern Maine, Millinocket (station 175304) and Middle Dam (station 175261) in central Maine, and Portland International Jetport (station 176905) in southern Maine (fig. 1, table 2). Monthly totals are National Weather Service data downloaded off of the Northeast Regional Climate Center's Web site (http://climod.nrcc.cornell.edu). All National Weather Service data prior to January 2003 are final; data from January to May 2003, however, are preliminary and subject to change.

Although the periods of record at these stations range from 55 to 83 years, monthly precipitation data from 1999 to 2002 were plotted against National Weather Service 30-year monthly normals (1971-2000) (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, 2000).

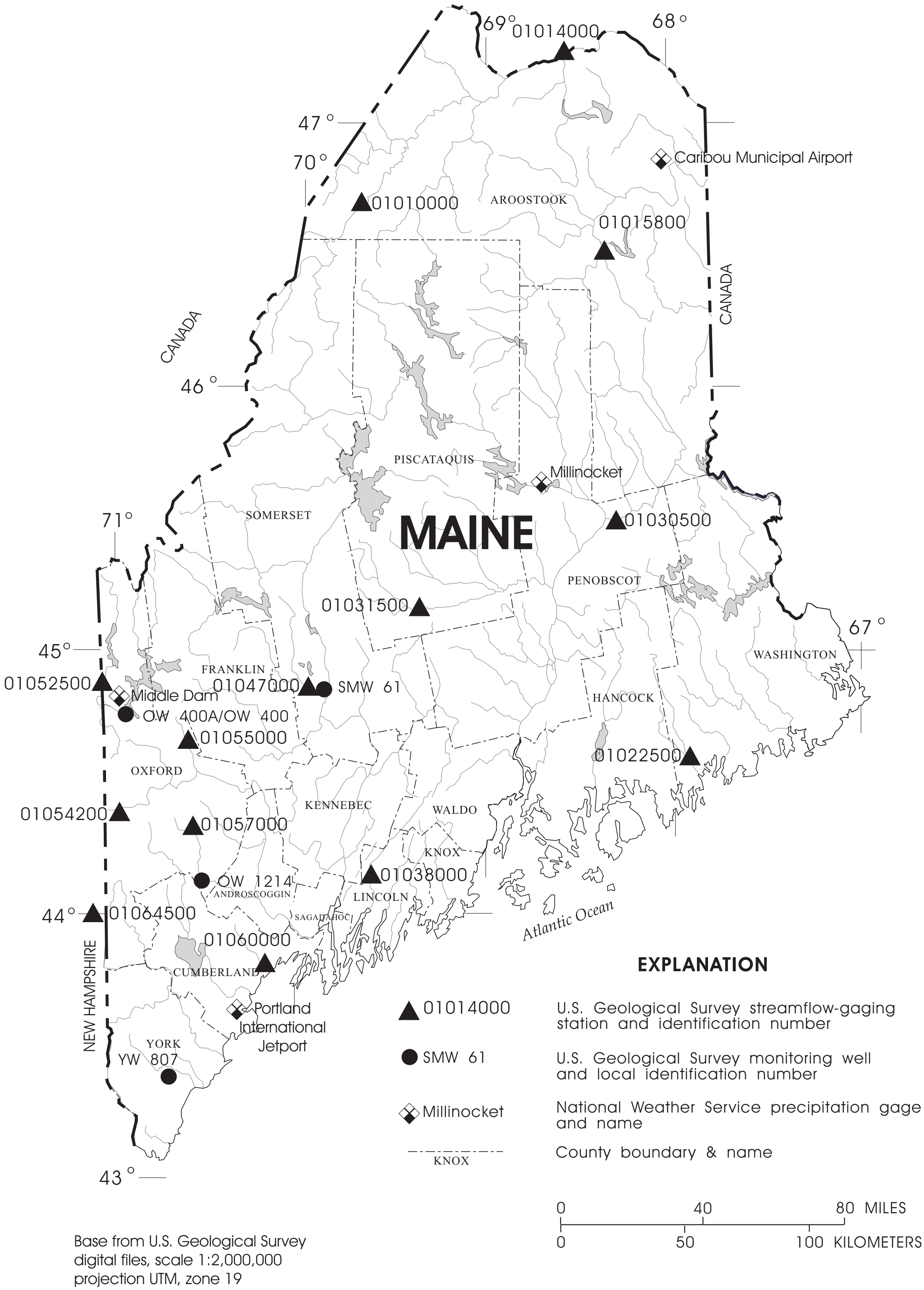

Figure 1. Location of study area and data-collection sites, Maine.

Table 2. National Weather Service precipitation gages used in this study in Maine

National Weather Service Station Number	Name/location	Period of record
171175	Caribou Municipal Airport, Maine	1939-2003
175261	Middle Dam, Lower Richardson Lake, Maine	1948-2003
175304	Millinocket, Maine	1948-2003
176905	Portland International Jetport, Maine	1920-2003

Streamflow-Gaging Stations

Data were compiled from 14 USGS streamflow-gaging stations around the State (fig. 1, table 3). These stations were chosen on the basis of their geographical diversity, period of record, and lack of appreciable regulation. Periods of record range from 37 to 98 years with an average of 68 years. Mean daily flows are published annually in USGS water-resources data reports, the most recent of which is Stewart and others (2003).

Low-flow statistics used in this report are defined in the Annual Data Reports for Maine (Stewart and others, 2003) and are as follows: the annual mean discharge refers to the arithmetic mean of the individual daily mean discharges, the daily mean minimum flow is the lowest daily mean for that day over the period of record, the lowest daily mean flow is the minimum daily mean discharge for any day during the period of record, the instantaneous low flow is the minimum instantaneous discharge occurring during the period of record, and the minimum monthly mean flow is the minimum mean flow for that month over the period of record. The 7-day annual low flow is the mean discharge of the lowest 7 consecutive days during a water year.

Monitoring Wells

USGS monitoring wells used to determine the affect of the drought on ground-water levels were; local number Y807 (USGS number 432310070393301) in York County, local numbers OW 1214 (440823070291501), OW 400 (444637070552301), and OW400A (443647070552302) in Oxford county, and local number SMW 61 (445148069513301) in Somerset County (fig.1, table 4).

Table 3. U.S. Geological Survey streamflow-gaging stations used in this study in Maine

U.S. Geological Survey station number	U.S. Geological Survey Station Name	Period of record	Drainage area (square miles)	Map identification number (fig. 19)
01010000	St. John River at Ninemile Bridge, Maine	1952-2003	1,341	A
01014000	St. John River below Fish River, at Fort Kent, Maine	1928-2003	5,665	B
01015800	Aroostook River near Masardis, Maine	1958-2003	892	C
01022500	Narraguagus River at Cherryfield, Maine	1949-2003	227	D
01030500	Mattawamkeag River near Mattawamkeag, Maine	1936-2003	1,418	E
01031500	Piscataquis River near Dover-Foxcroft, Maine	1904-2003	298	F
01038000	Sheepscot River at North Whitefield, Maine	1940-2003	145	G
01047000	Carrabassett River near North Anson, Maine	1904-2003	353	H
01052500	Diamond River near Wentworth Location, New Hampshire	1942-2003	152	I
01054200	Wild River at Gilead, Maine	1965-2003	69.6	J
01055000	Swift River near Roxbury, Maine	1930-2003	96.9	K
01057000	Little Androscoggin River near South Paris, Maine	1915-2003	73.5	L
01060000	Royal River at Yarmouth, Maine	1951-2003	141	M
01064500	Saco River near Conway, New Hampshire	1905-2003	385	N

Table 4. U.S. Geological Survey ground-water wells used in this study in Maine

Local well number	U.S. Geological Survey well number	Local name, location	Description of Aquifer	Period of record
Y807	432310070393301	South Sanford, York County, Maine	Ice-contact glaciofluvial deposits	1988-2003
OW1214	440823070291501	Oxford, Oxford County, Maine	Stratified sand	1980-2003
SMW61	445148069513301	Madison, Somerset County, Maine	Glaciomarine sand and silt	1985-2003
OW400	444637070552301	Middle Dam, Oxford County, Maine	Glacial till	1944-1992
OW400A	443647070552302	Middle Dam, Oxford County,Maine	Glacial till	1989-2003

Data from these monitoring wells are a combination of continuous- recorder data and month-end water-level readings. Although continuous record is available since 1989 for OW1214 and YW807, 1999 for SMW61, and 2001 for O400A, month-end values were used in all cases to compare conditions from 1999 through 2003 with historical statistics, for which only month-end data are available.

In most cases, month-end ground-water levels represent a single water level recorded some time between the 20th and the end of the month. For cases in which more than one record is available during this period, the record that is closest to the end of the month is used. For continuous record, this is the water level recorded at noon on the last day of the month. Well OW400A was created as a companion well for OW400, and thus the data from these two wells were combined. Well numbers OW400 and OW400A have periods of record from 1944 to 1992 and 1989 to 2003, respectively, giving them a period of overlap from 1989 to 1992 from which a regression equation was derived. Month-end water levels from discontinued well OW 400 were adjusted on the basis of this regression equation so that analyses could be performed on the combined period of record of 57 years (2003 was not used in the analyses). Month-end data from these companion wells represent averages of all records from the 20th until the end of the month. Prior to 2001, this value is an average of from 2 to 3 daily readings, which were taken every fifth day. After 2001, this value is an average of the continuous values from the 20th until the end of the month.

DROUGHT CONDITIONS IN MAINE FROM 1999 TO 2002

The description of drought years 1999 through 2002 includes both the amount and the timing of monthly precipitation, 7-day average streamflows, and month-end ground-water levels during this time period.

Precipitation

Caribou Municipal Airport was within the normal range for monthly precipitation (within 2 in. of the 30-year monthly normals) in 1999 and 2000 (fig. 2). The only appreciable deviation from normal was in September 1999 with 8.8 in. of precipitation (5.5 in. above normal). Accumulated observed rainfall dropped below accumulated normal rainfall in the spring of 2001 and stayed below normal throughout the rest of 2001 and all of 2002 (fig. 3). August 2002, with only 0.55 in. of precipitation was 3.6 in. below normal, leading to one of the driest Septembers on record at various streamflow stations in northern Maine.

Total precipitation of less than 1 in. in April 1999 (2.6 in. below normal), was the lowest April rainfall on record (1948-2002) at Millinocket. In September 1999, however, Millinocket received 7.5 in. of rain (3.8 in. above normal) putting the total precipitation for the year in the normal range. This value indicates that the precipitation deficit and the resulting drought was more a problem of the timing of precipitation than of the total amount of precipitation during 1999 (fig. 4). Accumulated observed rainfall from 1999-2002 departed from accumulated normal rainfalls in January 2001 (fig. 5). Nineteen out of 24 months in 2001 and 2002 received normal or below-normal precipitation with a 2-year total accumulated departure from normal of 19 in. August 2002, with 0.7 in. of rain (3.3 in. below normal), was the lowest August precipitation on record at Millinocket.

Portland had rainfall patterns similar to Millinocket from 1999 to 2002 . Portland received 0.3 in. of precipitation in April 1999 (4.0 in. below normal) (fig. 6). September 1999 had record high amounts of

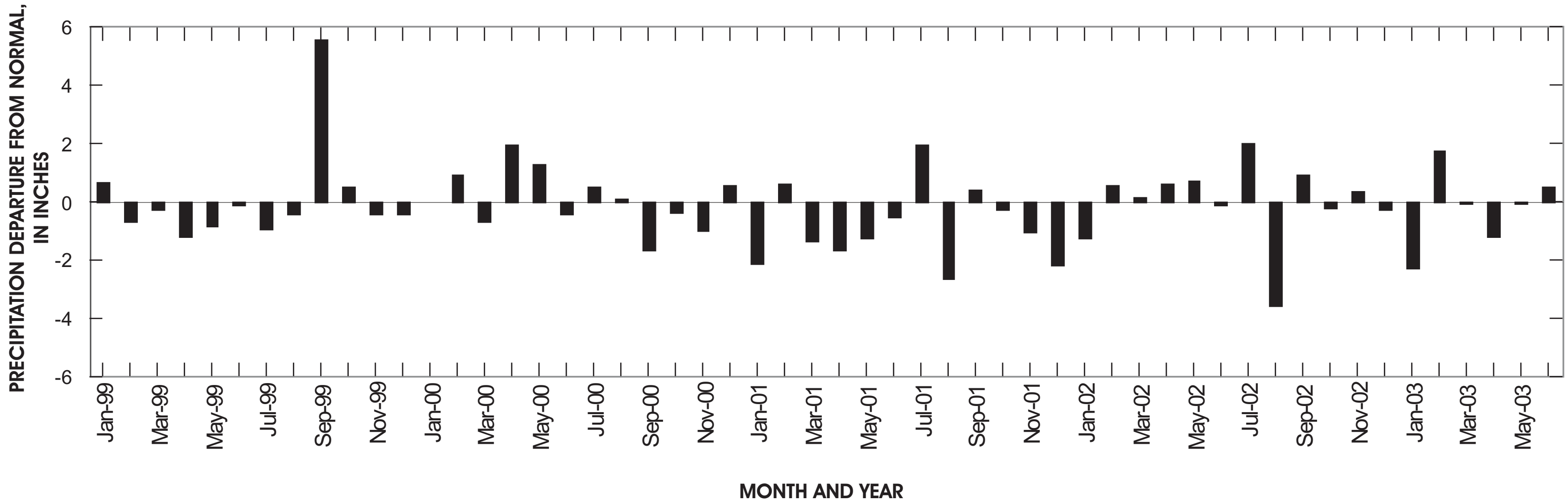

Figure 2. Monthly departure from normal precipitation at Caribou Municipal Airport, Maine, 1999-2003. [National Weather Service Station number 171175; normals are based on National Weather Service observations, 1971-2000]

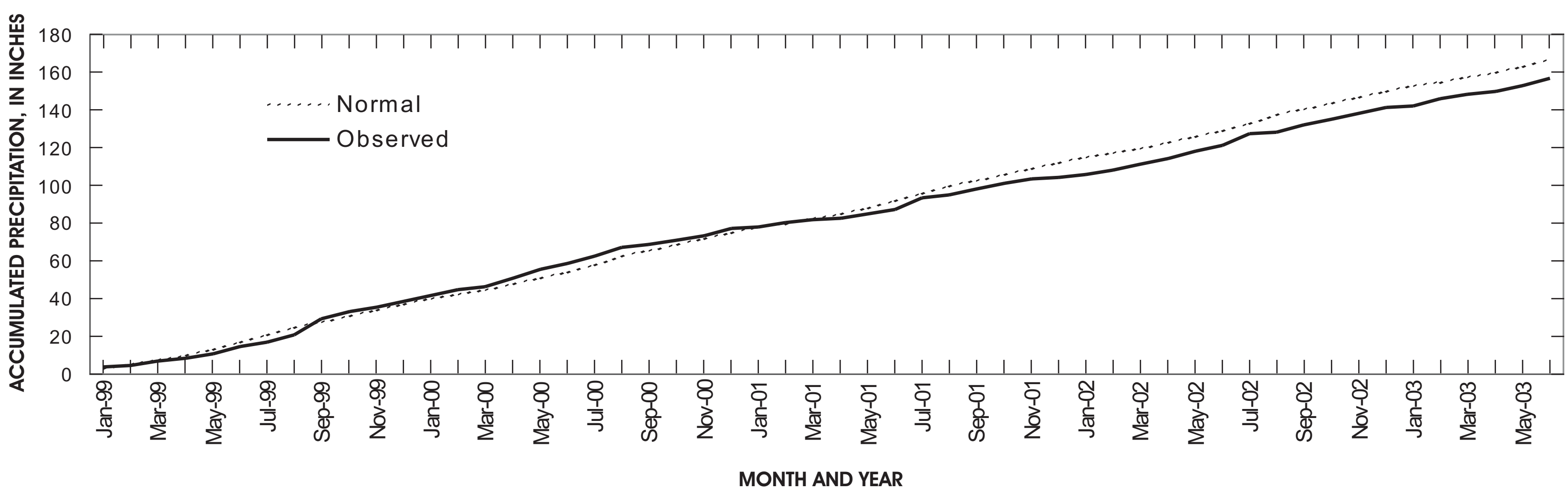

Figure 3. Accumulated departure from normal precipitation at Caribou Municipal Airport, Maine, 1999-2003. [National Weather Service Station number 171175; normals are based on National Weather Service observations, 1971-2000]

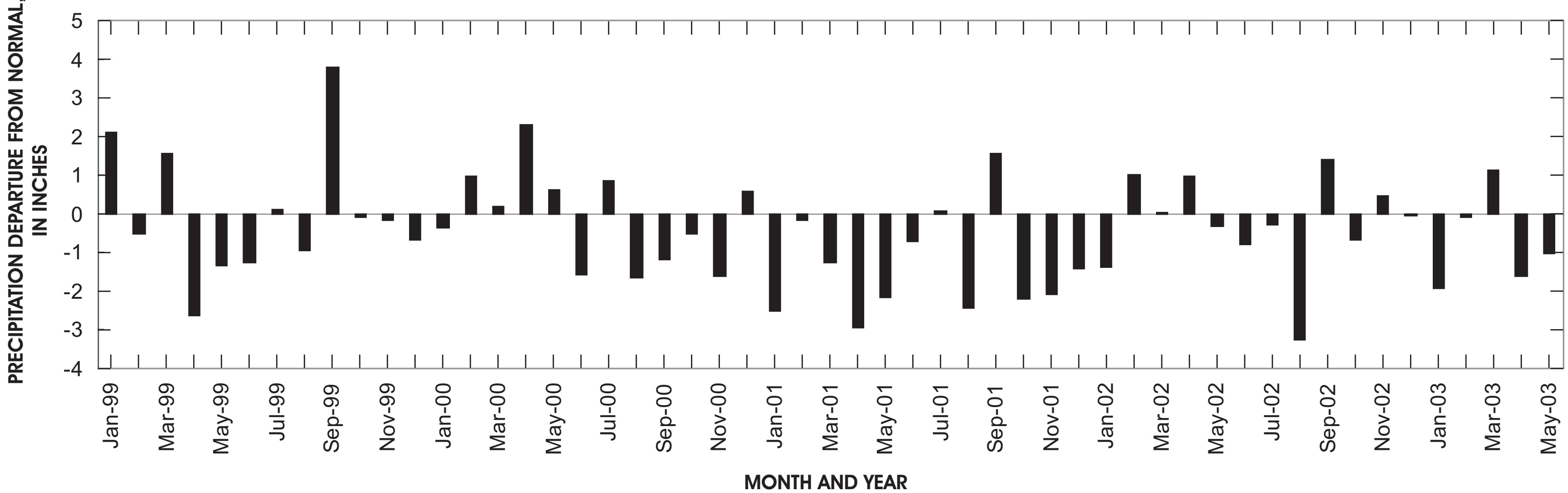

Figure 4. Departure from normal precipitation at Millinocket, Maine, 1999-2003. [National Weather Service Station number 175304; normals are based on National Weather Service observations, 1971-2000]

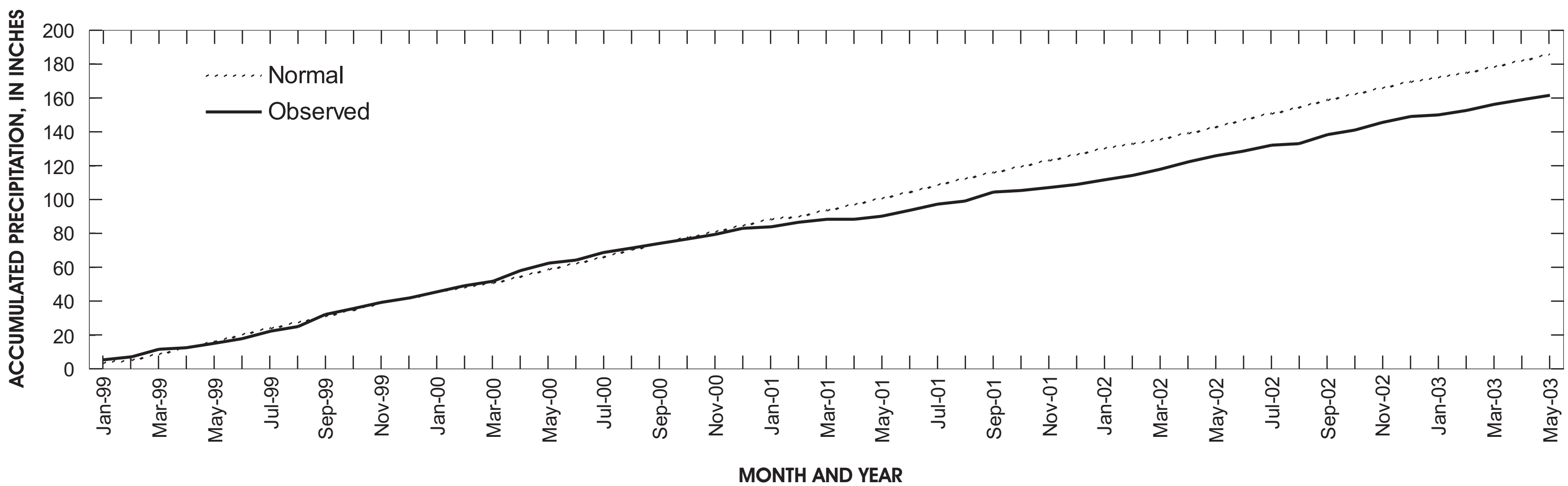

Figure 5. Accumulated departure from normal precipitation at Millinocket, Maine, 1999-2003. [National Weather Service Station number 175304; normals are based on National Weather Service observations, 1971-2000]

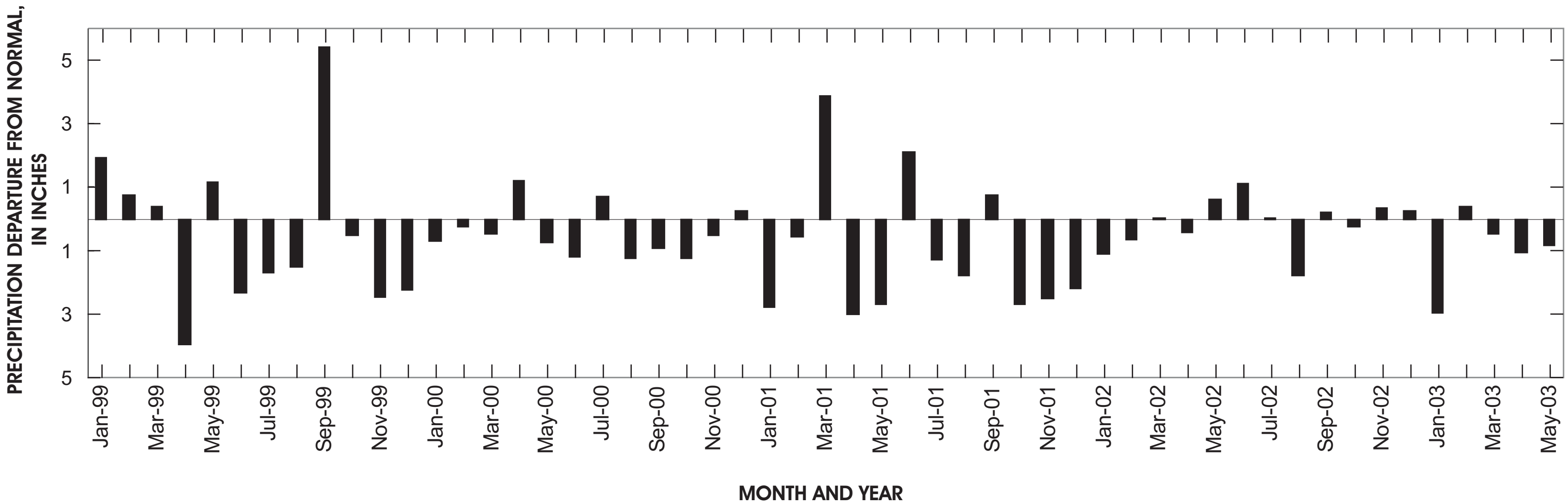

Figure 6. Departure from normal precipitation at Portland International Jetport, Maine, 1999-2003. [National Weather Service Station number 176905; normals are based on National Weather Service observations, 1971-2000]

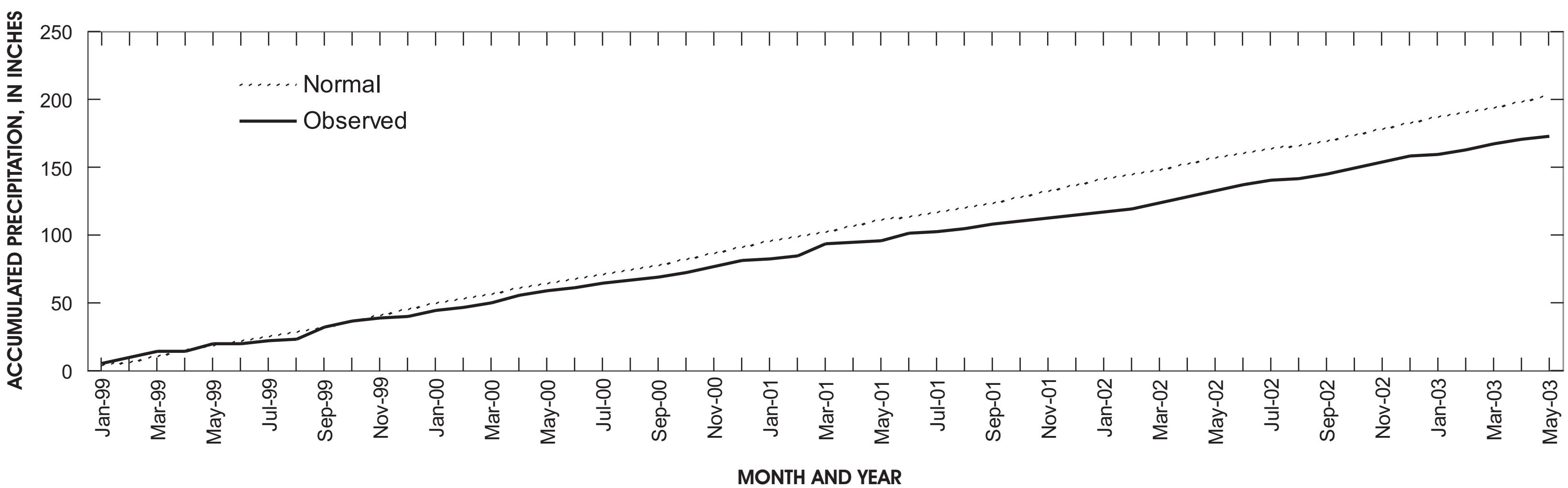

Figure 7. Accumulated departure from normal precipitation at Portland International Jetport, Maine, 1999-2003. [National Weather Service Station number 176905; normals are based on National Weather Service observations, 1971-2000]

precipitation resulting from two hurricanes during that month totaling 8.8 in. (5.4 in. above normal). Sixteen of 24 months received normal or below normal precipitation during 2001 and 2002. Accumulated observed precipitation departed from accumulated normal rainfalls in 2000 and stayed below normal through May 2003 (fig.7).

Surface Water

Seven-day running averages of daily discharge from January 1999 to May 2003 were plotted against 7-day running average minimum-, maximum-, and mean-statistics for the period of record at each station. Streamflow in the central and eastern parts of the State was below normal (below the 25th quartile) during 1999, setting record-minimum flows at some locations in the spring of that year. Streamflows in central and coastal Maine indicated above normal streamflows (above the 75th quartile) in the spring of 2000, but then were at or below normal throughout the remainder of the year. In 2001, record-low conditions were recorded in many central and coastal locations. In 2002, the drought continued to be severe in central Maine. Drought conditions spread north and west but lessened near the coast.

The Piscataquis River near Dover-Foxcroft in central Maine (USGS station 01031500) recorded extremely low streamflow relative to seasonal normals in the spring of 1999, and in 2001 and 2002, setting new daily mean minimum streamflow records during some days in April and May 1999, July through September 2001, and in August and September 2002 (fig. 8). Streamflow came close to the lowest daily mean flow of 5.0 ft^3/s, set in 1905, with a flow of 8.6 ft^3/s both on September 16, 2001, and on September 13, 2002. A record minimum August mean streamflow of 14.6 ft^3/s was set at this station in August 2001.

In coastal Maine, the Narraguagus River at Cherryfield (USGS station 01022500) had a record low, annual mean low flow in 2001 with a flow of 256 ft^3/s. The station also had a record low 7-day low flow of 20 ft^3/s in September 2001. The Narraguagus River at Cherryfield set record low daily mean flows in April, May, August, September 1999; May, June, and August-December 2001; and January 2002. The station recorded monthly mean low flow records in November 2001 and January 2002. Streamflow returned to normal conditions at the end of 2002 (fig. 9).

The hydrologic drought in northern and western Maine was not as extreme in 1999-2001, but became quite severe in 2002. In September 2002, the Wild River at Gilead (USGS station 01054200) set records for the lowest daily mean and the lowest annual 7-day minimum with flows of 6.1 ft^3/s, and 7.1 ft^3/s respectively (fig. 10). The instantaneous low flow was a record low of 6.0 ft^3/s on September 10, 2002. The Swift River near Roxbury (USGS station 01055000) also set records for the lowest daily mean and the lowest annual 7-day minimum with flows of 2.9 ft^3/s, and 3.4 ft^3/s, respectively, in September 2002. The instantaneous low flow of record, 2.7 ft^3/s, also was recorded on September 10, 2002. A monthly mean flow of 9.66 ft^3/s in August 2002 was the lowest recorded August mean flow.

The St. John River in northern Maine was extremely low in all locations in September 2002. On September 10, 2002, record instantaneous low flows and daily mean low flows were set at Ninemile Bridge (USGS station 01010000). The St. John River below Fish River at Fort Kent (station number 01014000), had a record low September mean flow of 893 ft^3/s in 2002 (fig. 11).

Surface-water levels were low in southern Maine during both 2001 and 2002, but were not as extreme as in other parts of the State. The Royal River at Yarmouth (station number 01060000), with 53 years of record had a record low October mean flow of 30.5 ft^3/s in 2001 while the Saco River near Conway, N.H. (USGS station 01064500) with 73 years of record had a record August mean flow of 120 ft^3/s in 2001.

Ground Water

Month-end water levels from January 1999 to May 2003 were plotted against ground-water statistics, including the maximum, minimum, median, 25th and 75th quartiles based on the period of record at each station. In most cases, month-end ground-water levels were in the normal range (between the 25th and 75th quartiles) for most of 1999 and 2000 and were not consistently below normal until 2001 and 2002. Centrally located USGS well OW 1214 had normal ground-water levels from the spring of 1999 through the end of 2000, except in September 1999 when it reached record highs. Ground-water levels in this Oxford well started dropping in the fall of 2001 compared to normal fall levels, and attained record month-end lows from November 2001 through

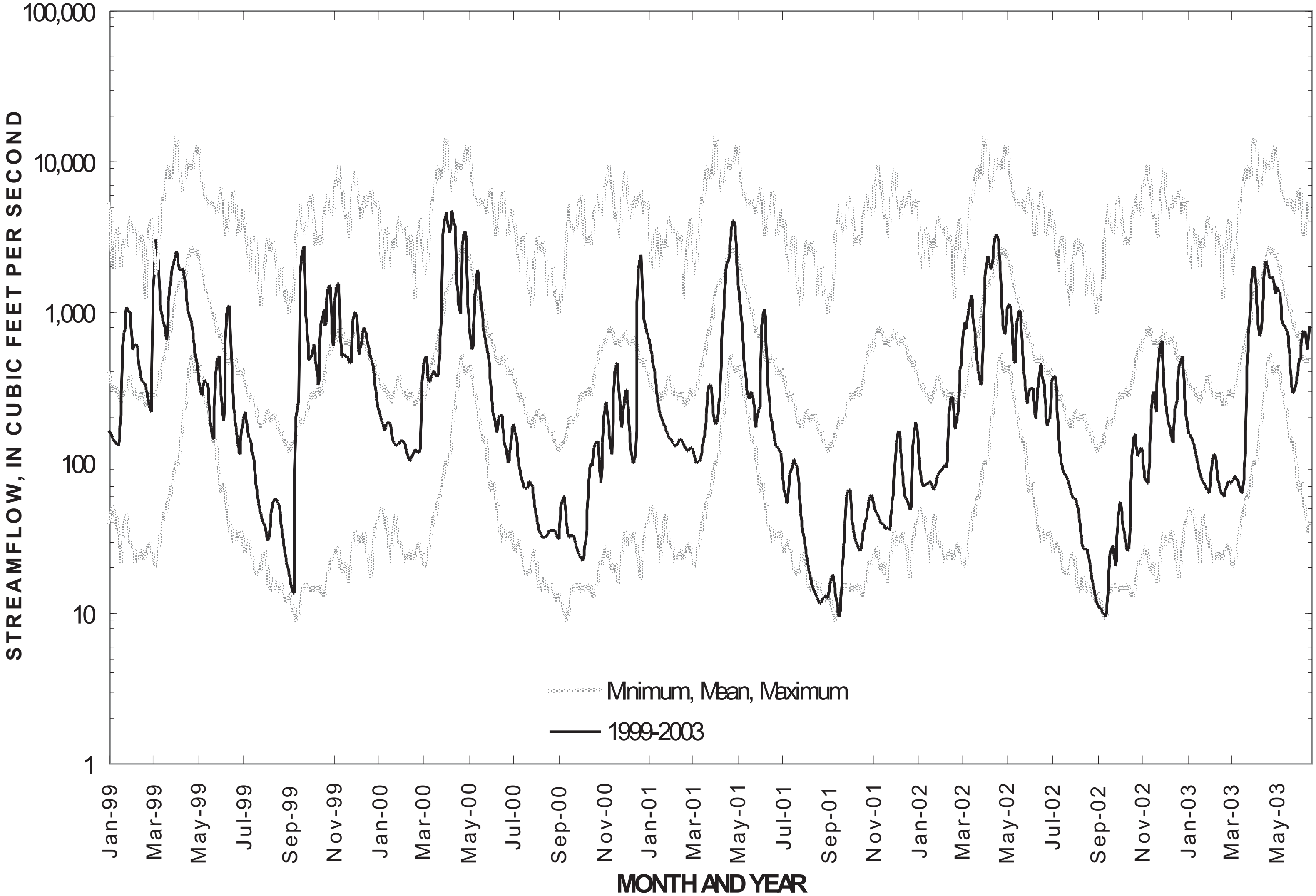

Figure 8. Comparison of 1999-2003 streamflows to historical mean, maximum, and minimum streamflows at U.S. Geological Survey streamflow-gaging station 01031500, Piscataquis River near Dover-Foxcroft, Maine. [streamflows are 7-day running averages of daily minimum, mean and maximum streamflows over the period of record, and 7-day running averages of daily mean flows from 1999-2003; historical period is 1904-98; data from October 1, 2002, through May 31, 2003, are provisional and subject to change]

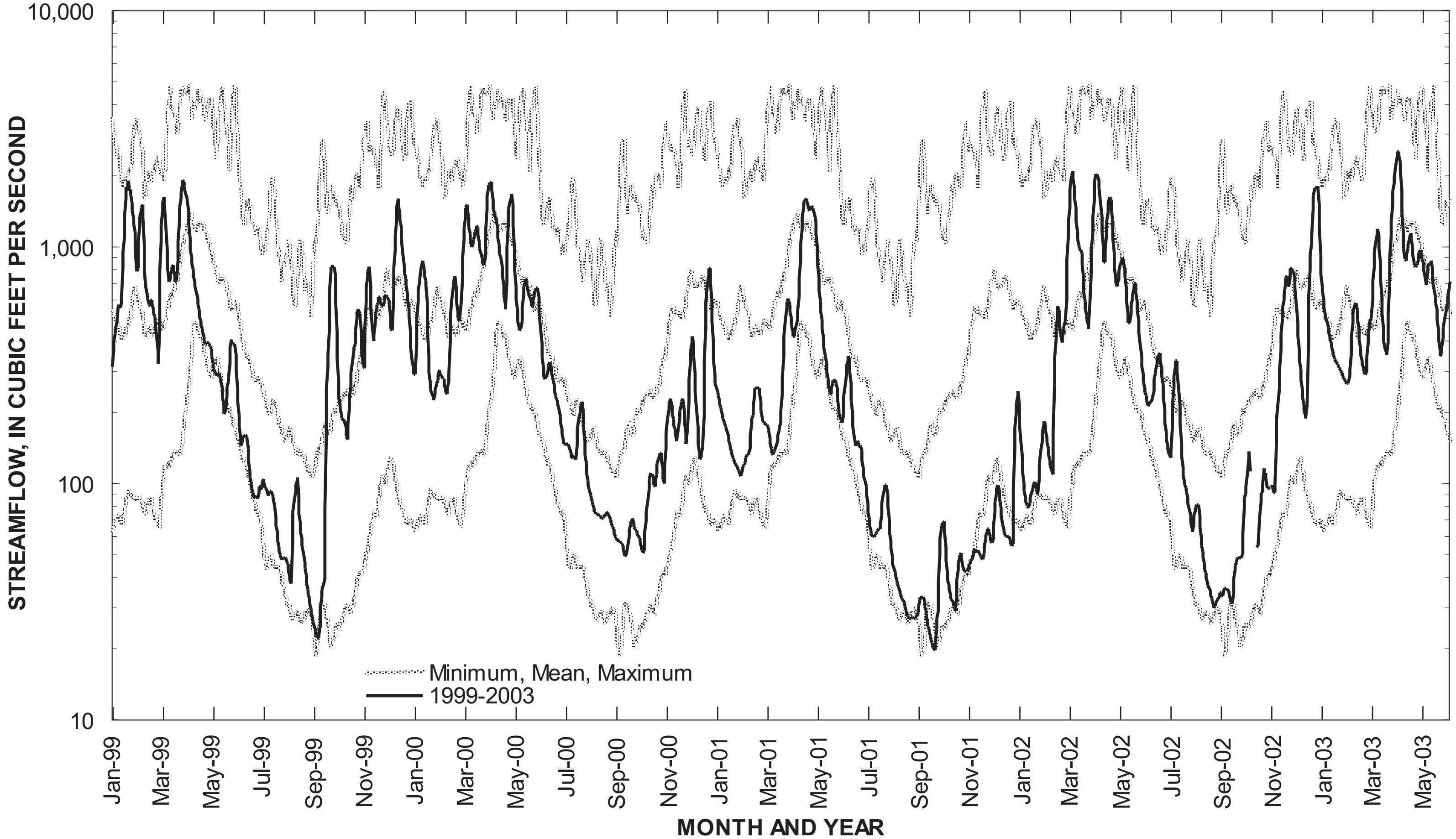

Figure 9. Comparison of 1999-2003 streamflows to historical mean, maximum, and minimum streamflows at U.S. Geological Survey streamflow-gaging station 01022500, Narraguagus River at Cherryfield, Maine. [streamflows are 7-day running averages of daily minimum, mean and maximum streamflows over the period of record, and 7-day running averages of daily mean flows from 1999-2003; historical period is 1949-98; data from October 1, 2002, through May 31, 2003, are provisional and subject to change]

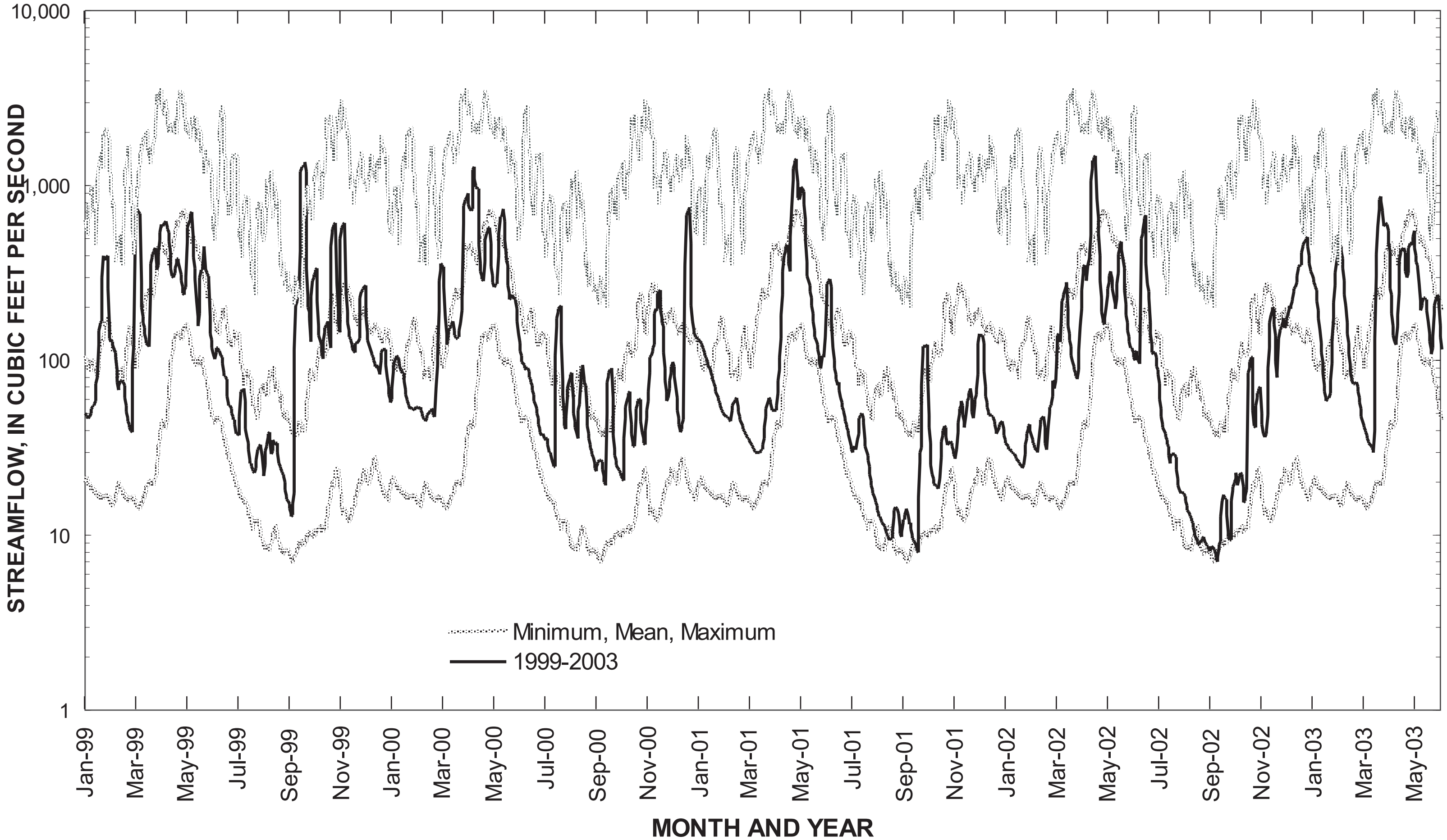

Figure 10. Comparison of 1999-2003 streamflows to historical mean, maximum, and minimum streamflows at U.S. Geological Survey streamflow-gaging station 01054200, Wild River at Gilead, Maine. [streamflows are 7-day running averages of daily minimum, mean and maximum streamflows over the period of record, and 7-day running averages of daily mean flows from 1999-2003; historical period is 1965-98; data from October 1, 2002, through May 31, 2003, are provisional and subject to change]

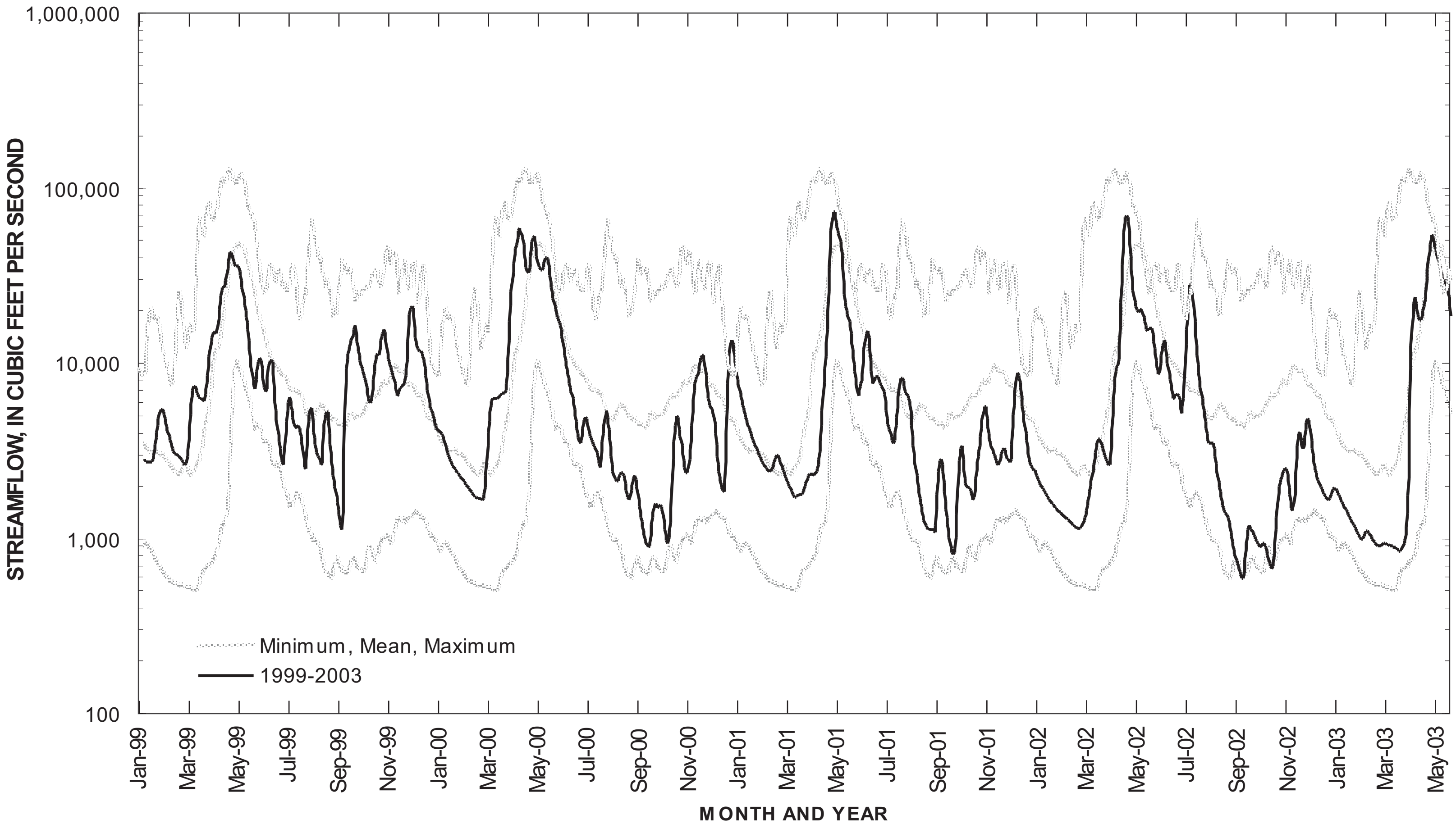

Figure 11. Comparison of 1999-2003 streamflows to historical mean, maximum, and minimum streamflows at U.S. Geological Survey streamflow-gaging station 01014000, St. John River at Fort Kent, Maine. [streamflows are 7-day running averages of daily minimum, mean and maximum streamflows over the period of record, and 7-day running averages of daily mean flows from 1999-2003; historical period is 1928-98; data from October 1, 2002, through May 31, 2003, are provisional and subject to change]

February 2002. Levels stayed below normal through May 2003 (fig. 12).

In central Maine, USGS well number SMW 61 in Madison had record low ground-water levels in May through August 1999, October 2001 through March 2002, and August 2002 through May 2003 (fig. 13). Levels were not in the normal range during 2001 or 2002, and had yet to recover by the end of the study period in May 2003.

USGS well Y807 in York County had normal ground-water levels from the spring of 1999 through the fall of 2000. Month-end ground-water levels were the lowest on record for every month from December 2001 through November 2002 (fig. 14).

Annual Recurrence Intervals of 7-Day Surface-Water Low Flows

Drought usually is defined subjectively or by public perception. In order for water-resource managers to characterize a drought objectively, and place it into historical context, objective parameters must be analyzed. Although droughts can be defined by the intensity and/or duration of a number of different parameters, annual 7-day surface-water low flows were used in this report to establish recurrence intervals for individual drought years. The annual 7-day low flow is useful in assessing an individual year of drought because it describes a sustained period of low flow.

The 7-day x-year low flow is the annual minimum 7-day consecutive average streamflow that is equaled or exceeded on average every x number of years (where x is the recurrence interval) (Maidment, 1993). The 7-day x-year low flow often is used for regulation purposes, and is familiar to water-resource managers. The 7Q10 or “7-day 10-year low flow” is the most commonly reported statistic for low-flow analyses (Helsel and Hirsch, 1992). Although each year is considered independently when calculating 7-day low flows, the data set consisting of the annual 7-day low flows over the period of record is likely to show serial correlation. This serial correlation could become an issue in a long-term statistical analysis, but is acceptable here so long as it is acknowledged when examining the 7-day low flows over time. The draw-back of using annual 7-day low flows to examine drought is that it does not characterize the overall severity of a multi-year drought, but rather characterizes the individual years that make up that drought.

Table 5. Station name, location, number, and 7-day low-flow recurrence intervals for individual years 1999-2002 at select USGS streamflow-gaging stations in Maine [<, less than; >, greater than]

U.S. Geological Survey station number	Station name	7-day low-flow recurrence interval (years)			
		1999	2000	2001	2002
01010000	St. John at Ninemile,Maine	< 10	< 10	20	>100
01014000	St. John River at Fort Kent, Maine	< 10	< 10	10	55
01015800	Aroostook River near Masardis, Maine	< 10	< 10	15	< 10
01022500	Narraguagus River at Cherryfield, Maine	40	< 10	65	10
01030500	Mattawamkeag River near Mattawamkeag, Maine	< 10	< 10	10	15
01031500	Piscataquis River near Dover Foxcroft, Maine	30	< 10	>100	>100
01038000	Sheepscot River at North Whitefield, Maine	< 10	< 10	10	< 10
01047000	Carrabassett River near North Anson, Maine	30	< 10	30	>100
01052500	Diamond River near Wentworth Location, N.H.	< 10	< 10	< 10	40
01054200	Wild River at Gilead, Maine	< 10	< 10	30	75
01055000	Swift River near Roxbury, Maine	60	< 10	45	>100
01057000	Little Androscoggin River near South Paris, Maine	< 10	< 10	60	40
01060000	Royal River at Yarmouth, Maine	<10	< 10	35	35
01064500	Saco River near Conway, N.H.	< 10	< 10	35	30

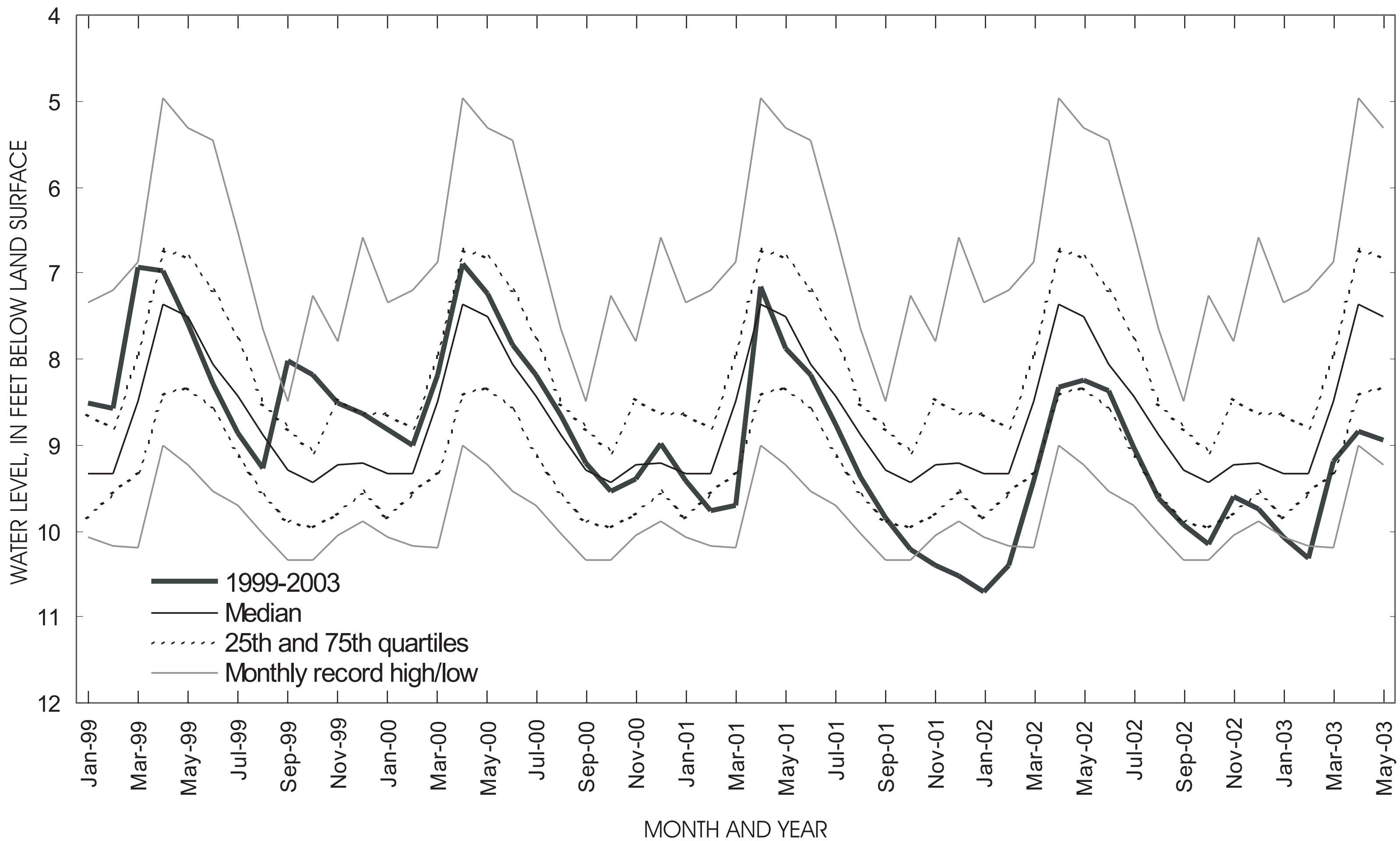

Figure 12. Comparison of 1999-2003 month-end ground-water levels to historical median, maximum, and minimum month-end ground-water levels at U.S.Geological Survey monitoring well OW 1214 (440823070291501), in Oxford, Oxford County, Maine. [historical period of record is 1980-98]

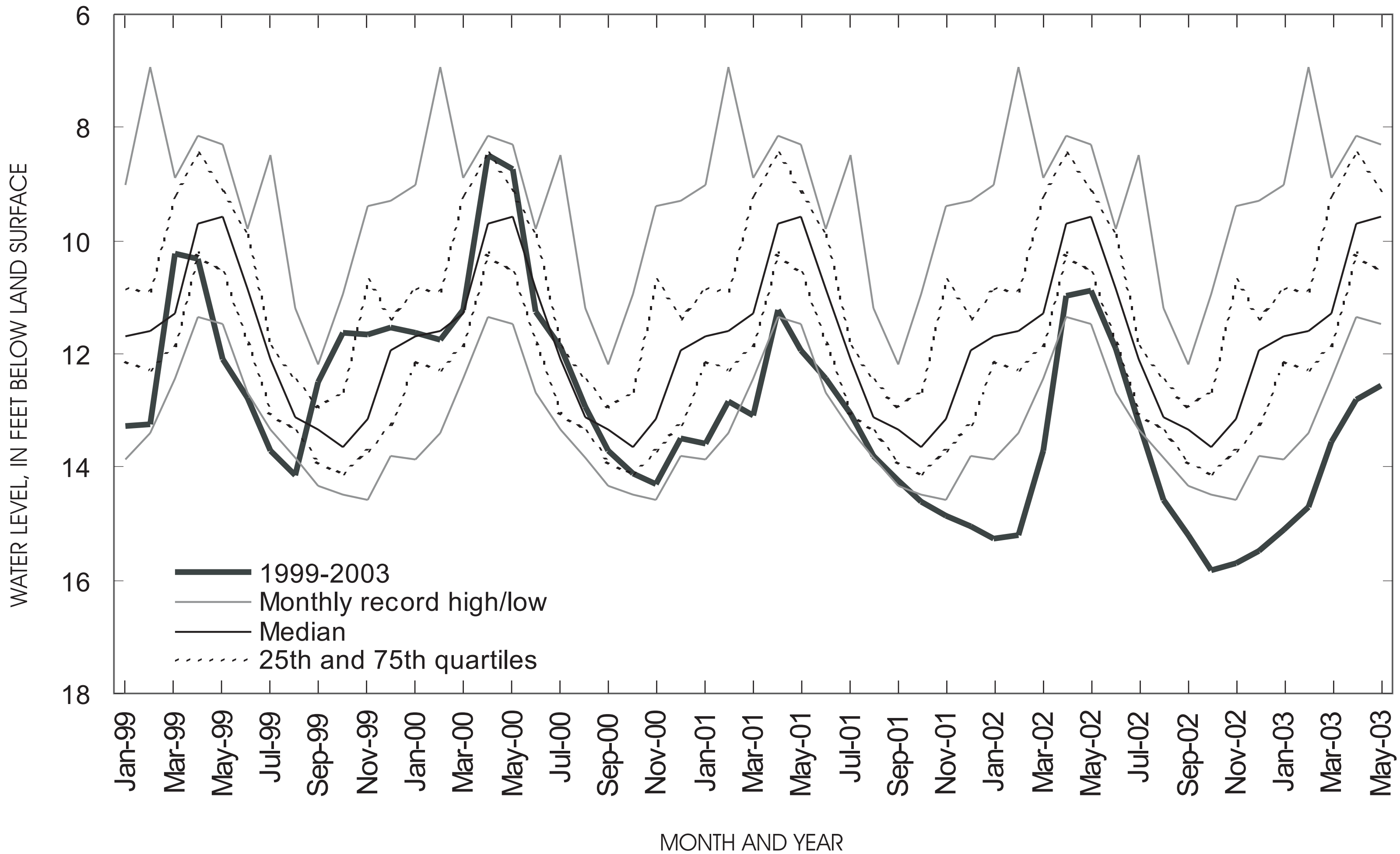

Figure 13. Comparison of 1999-2003 month-end ground-water levels to historical median, maximum, and minimum month-end ground-water levels at U.S.Geological Survey monitoring well SMW 61 (445148069513301), in Madison, Somerset County, Maine. [historical period of record is 1985-98]

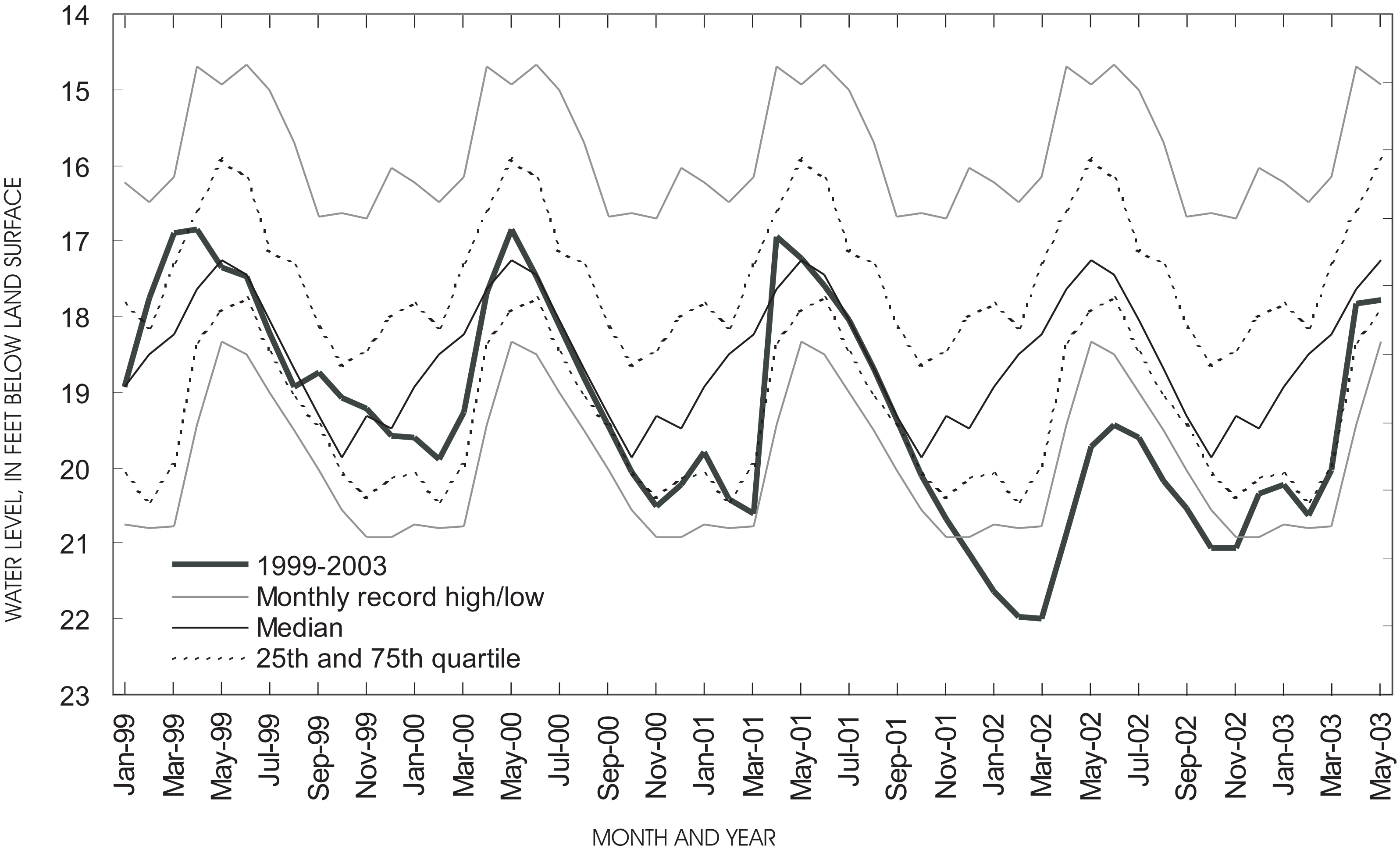

Figure 14. Comparison of 1999-2003 month-end ground-water levels to historical median, maximum, and minimum month-end ground-water levels at U.S.Geological Survey monitoring well Y807 (432310070393301), in Sanford, York County, Maine. [historical period of record is 1988-98]

The frequency of occurrence or recurrence interval is the average length of time between two events of a given magnitude and duration. The recurrence interval describes how likely an event is, but does not describe when it may occur. Recurrence intervals can be calculated for selected time scales and durations. The recurrence interval for the annual 7-day low flow may vary appreciably from the recurrence interval for the 90-day low flow or from the recurrence interval of a multi-year surface-water drought of which it is a part.

It requires a sustained period of below normal precipitation to have an annual 7-day low flow with a large recurrence interval, making it a good indicator of low ground water and surface-water levels, or hydrologic drought. Recurrence intervals calculated in table 5 are based on annual 7-day low flows at USGS streamflow-gaging stations in Maine with 37 to 98 years of record. The historical period used to conduct the low-flow frequency analysis (Maidment, 1993) went through year 2000 in all cases. Recurrence intervals were mapped to determine approximate regional recurrence intervals for individual drought years from 1999 to 2002 (figs. 15-18). These maps show how the drought progressed from 1999 to 2002.

The drought began in central Maine in 1999 with 7-day annual low-flow recurrence intervals from less than 10 to 60 years (fig. 15). The centrally located streamflow-gaging stations recovered in 2000 when recurrence intervals were less than 10 in all locations across the State (fig. 16). The central region of the State, which had the driest conditions in 1999, was the same region that had the most severe drought in 2001 The recurrence intervals of 7-day annual low flows at centrally located streamflow-gaging stations increased to greater than 100 years in 2001 (fig. 17). Southern and coastal regions of the State had recurrence intervals as high as 60 years in 2001 whereas the northern region had recurrence intervals from 10 to 20 years in 2001. The hydrologic drought spread west and north in 2002 so that much of the State had up to 100-year recurrence intervals at some time during this 4-year period. Coastal regions began to recover in 2002 (fig. 18). The central region progressed from recurrence intervals of from 10 to 60 in 1999 to from 60 to greater than 100 in 2001, and northern and southern regions progressed from less than 10 to from 10 to 60 over this same time period.

COMPARISON OF 1999-2002 DROUGHT TO HISTORICAL DROUGHTS IN MAINE

Multi-year drought periods usually are identified in drought analyses. An objective analysis of these multi-year periods is difficult because the range of intensities and durations are difficult to rank on the same scale. As with the analysis of drought conditions from 1999 to 2002, the recurrence interval of the 7-day surface-water low flow is used to define the severity of individual years during historical drought periods. These recurrence intervals then are placed in the context of the multi-year drought periods.

Drought periods identified for Maine in the National Water Summary on floods and droughts were used for this report (table 1) (Maloney, T.J., and W.P. Bartlett Jr., 1991). Additionally, drought years 1952-53 and 1978 were added because they had 7-day low-flow annual recurrence intervals of up to 90 years and 40 years, respectively. The period of 1955-57, identified in the National Water Summary, was expanded here to 1955-1959 because 1959 had a recurrence interval of 85 years in the southern part of the State. Droughts in 1995 and 1999-2002, which occurred after the publication of the National Water Summary were added here as some of the worst drought years on record on the basis of the 7-day annual low flows. The drought from 1938 to 1943 was identified in the National Water Summary, but is not included here because most of the stations do not have sufficient period of record to include it.

A total of eight historical drought periods were determined in this analysis, including 29 out of a potential 57 years from 1947 to 2002. There are two reasons that over half the period from 1947 to 2002 is included in this analysis. Three of these periods, or a total of 12 years, were regional droughts, and thus, no one part of the State had drought during all of these periods. Secondly, hydrologic drought includes both surface-water drought and ground-water drought, and ground-water drought tends to lag surface-water drought by up to a year. This lag means that each drought period can include individual years in the middle and up to one year at the end during which surface water is at or above normal, but ground water still is recovering. Individual years 1958, 1967, 1986 and 2000 in the middle of drought periods, and 1950, 1969 and 1988 at the end of drought periods do not have 7-day low surface-water recurrence intervals greater than 20 years at any stations in the State. These years are included as

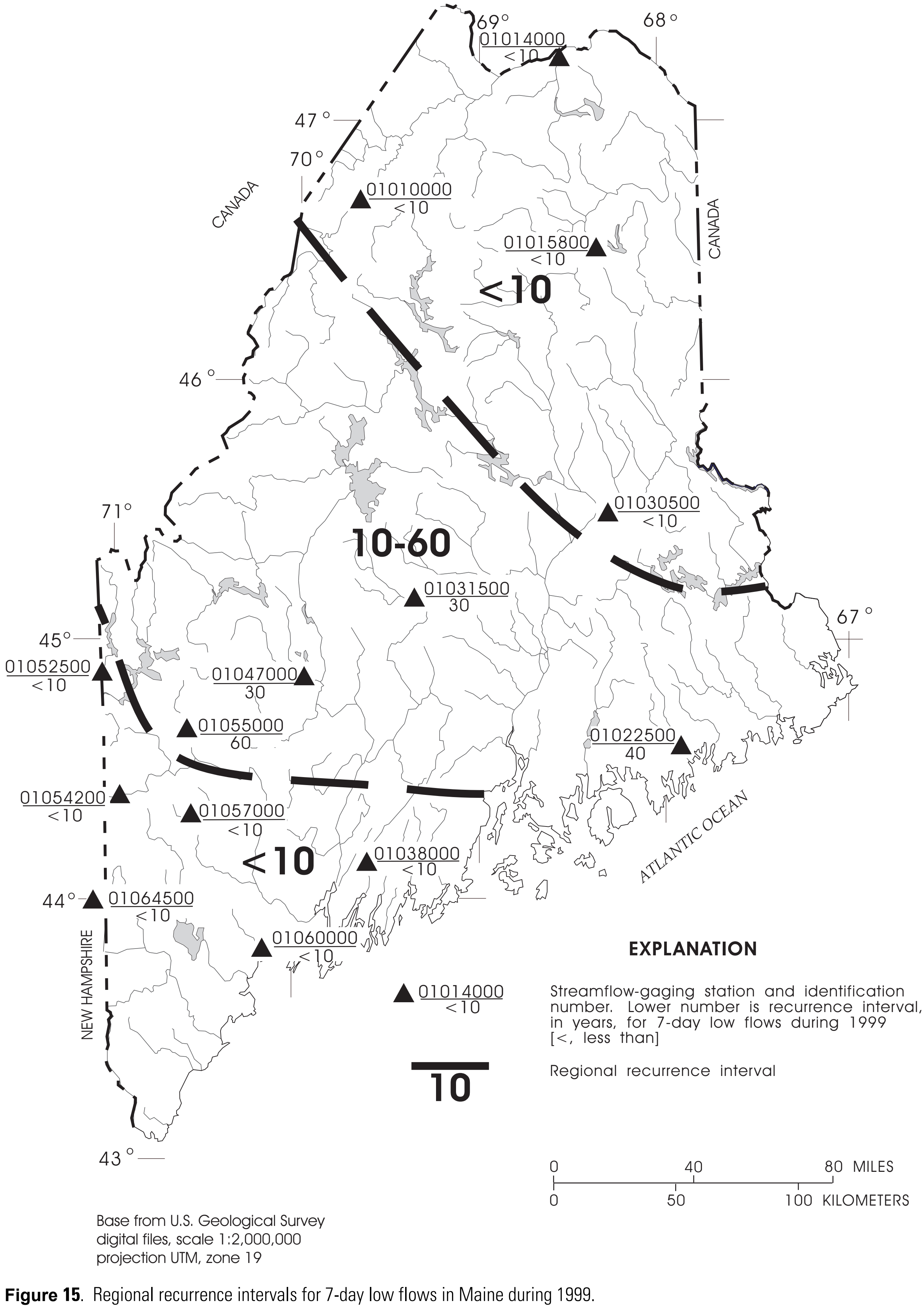

Figure 15. Regional recurrence intervals for 7-day low flows in Maine during 1999.

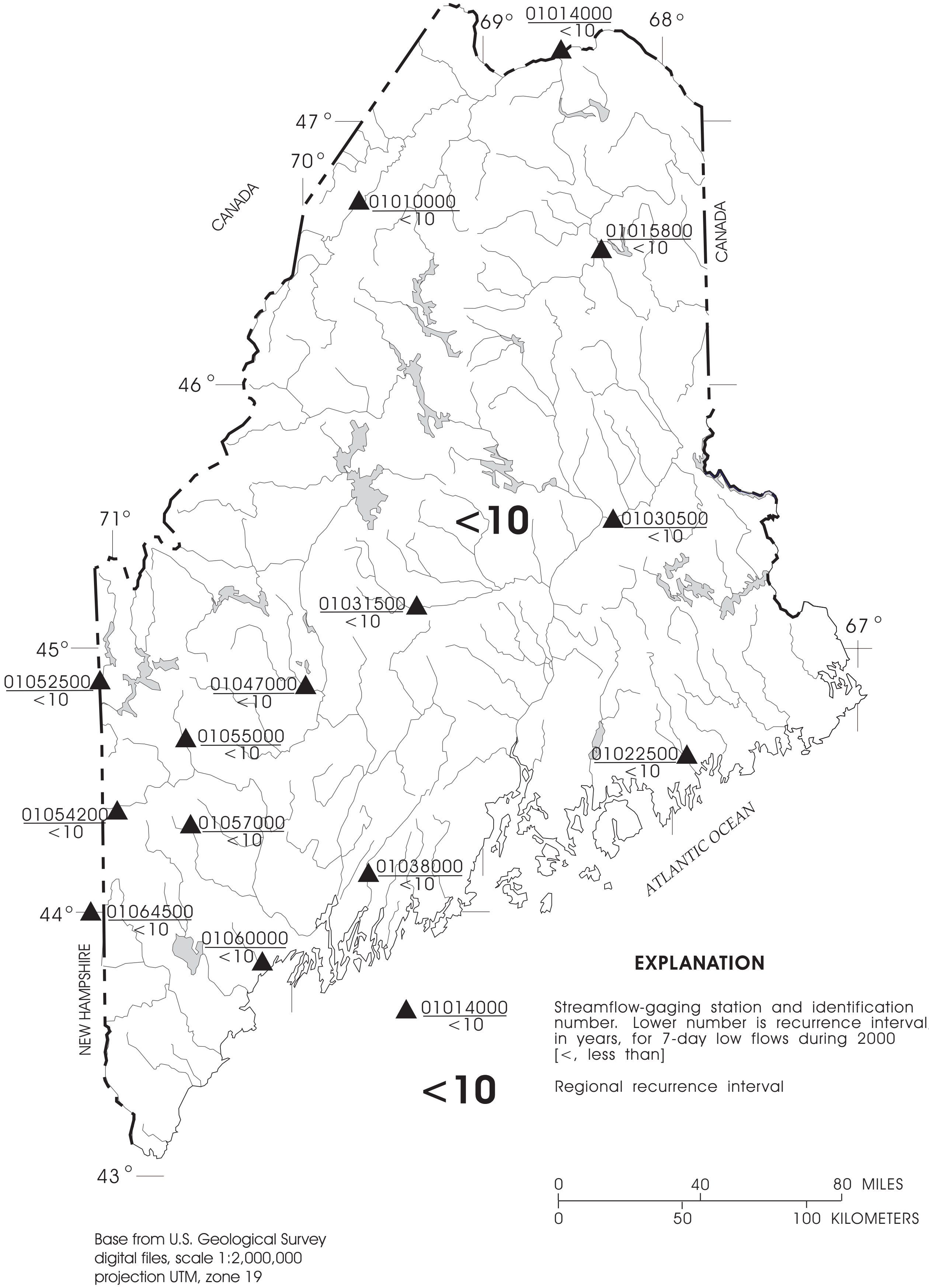

Figure 16. Regional recurrence intervals for 7-day low flows in Maine during 2000.

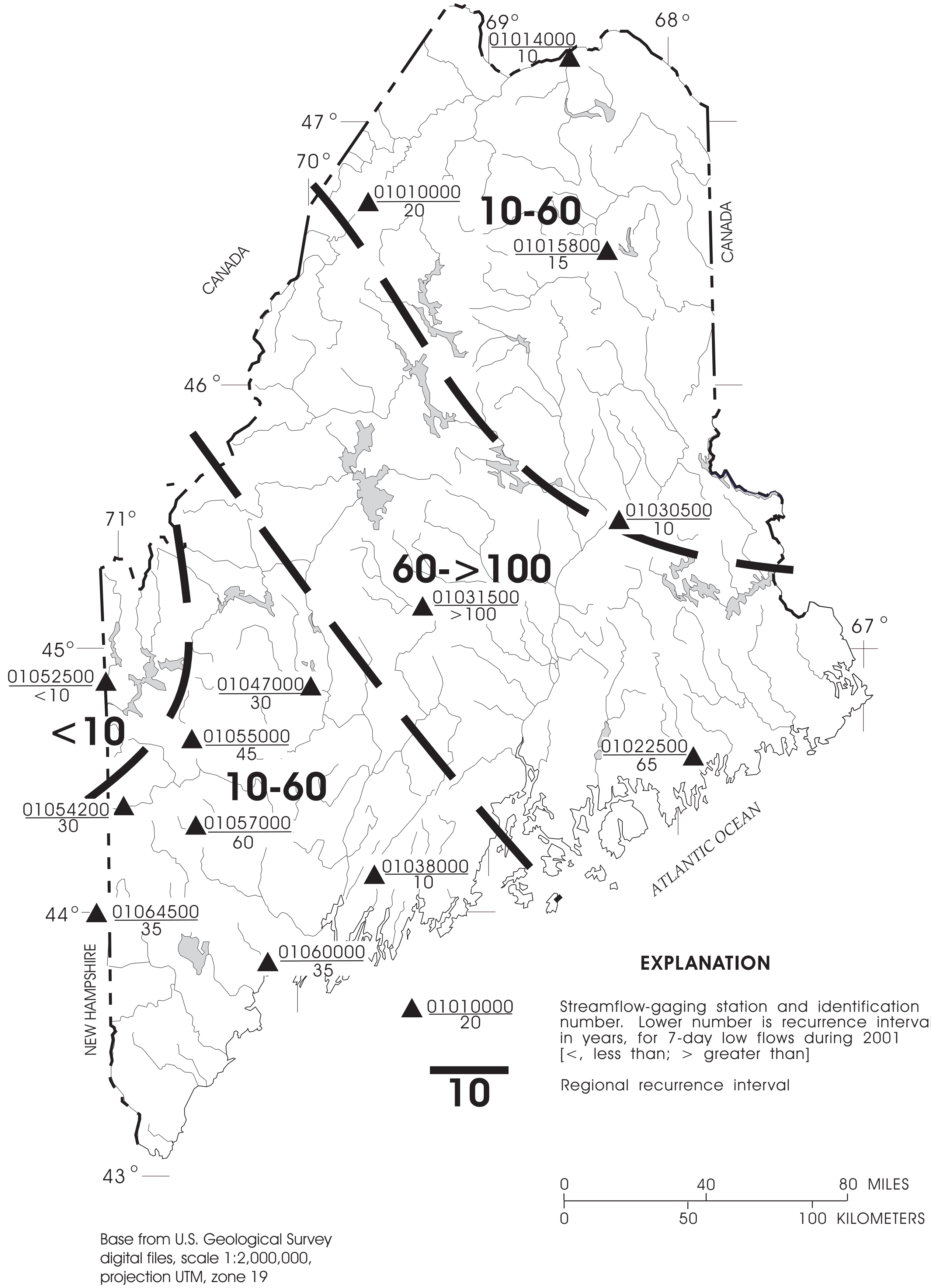

Figure 17. Regional recurrence intervals for 7-day low flows in Maine during 2001.

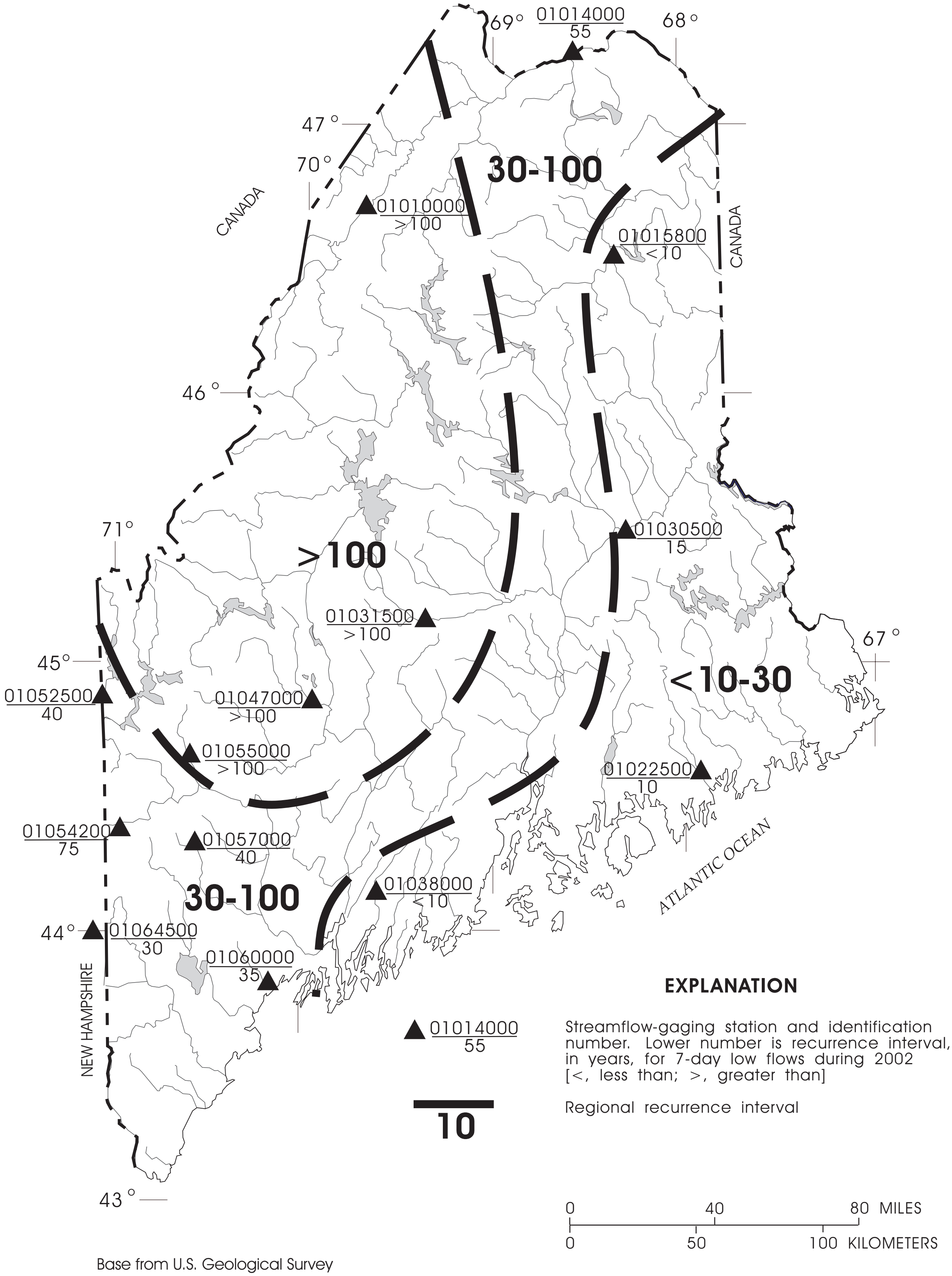

Figure 18. Regional recurrence intervals for 7-day low flows in Maine during 2002.

a part of the multi-year drought period because the ground water still was rising back up to normal levels during these years.

Annual Recurrence Intervals of 7-Day Surface-Water Low Flows

All identified historical drought periods either were severe in one region of the State or moderately severe statewide (table 6, fig. 19). The recurrence intervals of the lowest annual 7-day low flows during the drought period are shown in figure 19 (for example, if one region of the State had a 100-year drought in one year and another region had a 100- year drought the next year, a 100-year drought is mapped for both regions for that 2-year period). Stations in figure 19 that do not have a recurrence interval associated with them also did not have sufficient years of record to be included in that particular drought period. Both the average and the range of recurrence intervals for the 7-day low flows were calculated for the multi-year drought periods identified below (table 6). The range of recurrence intervals is the range of 7-day low recurrence intervals across all stations analyzed statewide for each drought period. The average recurrence interval is the average of the recurrence intervals of the lowest 7-day lows during the drought period at each station. To calculate the average recurrence intervals, values of 10 and 100 were used for stations listed with recurrence intervals of "less than 10" and "greater than 100", respectively.

The periods of statewide hydrologic drought that were most severe were 1947-50 and 1999-2002. These periods had greater than 100-year recurrence intervals at at least three stations across the State, and 50- to 100-year recurrence intervals in additional parts of the State (fig. 19). The period from 1999 to 2002 seemed to be slightly more severe statewide than the period from 1947 to 1950, however the period from 1947 to 1950 omits three stations that did not have records during this period. Additional years of severe statewide drought included 1963 to 1969, and 1995. The period from 1963 to 1969 included recurrence intervals of 70 years, and greater than 100 years in the north and south, respectively, and 40 years in the coastal region, but was most remarkable for its duration. No other drought period spanned 7 years. In contrast, the single year drought in 1995 had some of the lowest 7-day surface-water low flows on record for a single year; only 2002 was more severe in terms of hydrologic drought (figs. 18 and 19).

There was only mild statewide hydrologic drought during many of the drought periods identified; however severe hydrologic drought often occurred regionally. The period 1952-1953 was driest in the western and northern regions of the State, 1955-59 was most severe in the south, and 1984-88 was most severe centrally. 1978 had mild drought statewide with recurrence intervals only as high as 35 years.

Table 6. Approximate recurrence intervals for historical droughts in Maine, 1947-2002 [Recurrence interval, the average interval of time within which streamflow will be less than a particular value; <, less than; >, greater than]

Drought period	Individual years of surface-water drought*	Region Affected	Average Recurrence Interval (years)	Range of Recurrence Intervals (years)
1947-50	1947, 1948, 1949	Statewide	45	<10 to >100
1952-53	1952, 1953	West & north	25	<10 to 90
1955-59	1957, 1959	South	20	<10 to 85
1963-69	1965, 1966, 1968	Statewide	25	<10 to >100
1978	1978	Statewide	15	<10 to 35
1984-88	1985, 1987	Central	20	<10 to 65
1995	1995	Statewide	40	<10 to >100
1999-2002	1999, 2001, 2002	Statewide	60	<10 to >100

* Includes any year with a 7-day surface-water low flow with a recurrence interval of at least 20 years at two stations or a recurrence interval greater than 40 years at any one station.

Ground-Water Levels at Middle Dam, Lower Richardson Lake, Maine

Monitoring wells in Maine generally only have from 15 to 25 years of record, making it difficult to establish long-term trends. The companion wells at Middle Dam, Lower Richardson Lake, well numbers OW 400A and OW 400 with a combined period of record of 57 years, make it possible to place the most recent drought years into historical context. Month-end ground-water levels at Middle Dam were graphed against historical maximums, minimums, medians and 75th and 25th quartiles for the periods of drought identified above (figs. 20-27).

Month-end ground-water levels at Middle Dam in western Maine fell slightly below normal in April 1947 and September 1949 to January 1950, but otherwise were close to the median during the 1947-50 drought (fig. 20). Similarly, ground-water levels were predominately in the normal range during the 1952-53 period, dipping down below normal only in the last few months of 1952 and 1953 (fig. 21). Except for brief periods during the spring of 1955, 1957 and 1959, month-end ground-water levels stayed close to or above the median during 1955-59 (fig. 22). This result provided further evidence that the 1955-59 drought did not heavily affect the central region of the State, as demonstrated by surface-water analyses. Ground-water levels were below normal during parts of every year from 1963 to 1969, and reached record low levels in October of 1966 and November of 1968. This period also can be noted for its few ground-water-level rises above the 75th percentile at any time during this 7-year period (fig. 23). Although the 1978 drought was mild statewide in terms of surface water, ground-water levels came close to record lows by the fall of the year (fig. 24).

Ground-water levels at the Middle Dam well were close to normal from 1984 to 1988, falling below normal in the fall of 1984, the spring and summer of 1986, and the spring of 1987 to the spring of 1988 (fig. 25). During 1995, water levels fell to record lows from June to September (fig.26). Analysis of this well from 1999 to the start of 2003 showed record low month-end values in June and August 1999; October 2000; September and October 2001; December 2001 to February 2002; September and October 2002, and January and February 2003 (fig. 27). This result indicates that, at least in central Maine, ground-water levels were appreciably lower from 1999 to 2003 than they were during other drought periods in the last 50 years.

INTERACTION AMONG PRECIPITATION, SURFACE WATER, AND GROUND WATER DURING DROUGHT

The interaction among precipitation, surface water, and ground water helps to characterize hydrologic drought. The relation among precipitation, surface runoff, soil moisture, stream flow and ground water during times of drought are illustrated in figure 28 (Changnon, 1987). The deficits in streamflow and ground water both lag and attenuate the precipitation deficit. Ground water is the last indicator of drought and does not show a response to brief periods of recovery in the precipitation (fig. 28).

Record lows were set in both the precipitation and the surface water data sets at select locations in central Maine in April 1999 (figs. 6,8, and 9), showing that surface water responded fairly quickly (weeks) to precipitation deficits. Although water levels in one well at Madison in central Maine also set record lows in the spring of 1999 (fig. 13), there were a couple of months of lag time as compared to the precipitation and surface-water records. Furthermore, once ground-water levels started to drop in the fall of 2001 at all locations, they stayed below normal through 2002 (figs. 12-14). Surface-water recovered briefly to normal levels at periods during 2002 at all stations (figs. 8-11).

To understand the interactions among precipitation, surface water and ground water in more than a general way, it is helpful to compare hydrologic parameters at one location. There are few locations in Maine with a precipitation-gaging station, a streamflow-gaging station, and a monitoring well in close proximity to one another and each with a historical period of record of over twenty years. Middle Dam, near lower Richardson Lake in Oxford County Maine is one of these locations. The USGS streamflow-gaging station, number 01052500, in Wentworth Location, N.H., is approximately 10 mi away from the NWS precipitation gage, 175261, and USGS wells, O400 and O400A at Middle Dam. Additionally, Middle Dam is in a region that had severe drought during both 2001 and 2002.

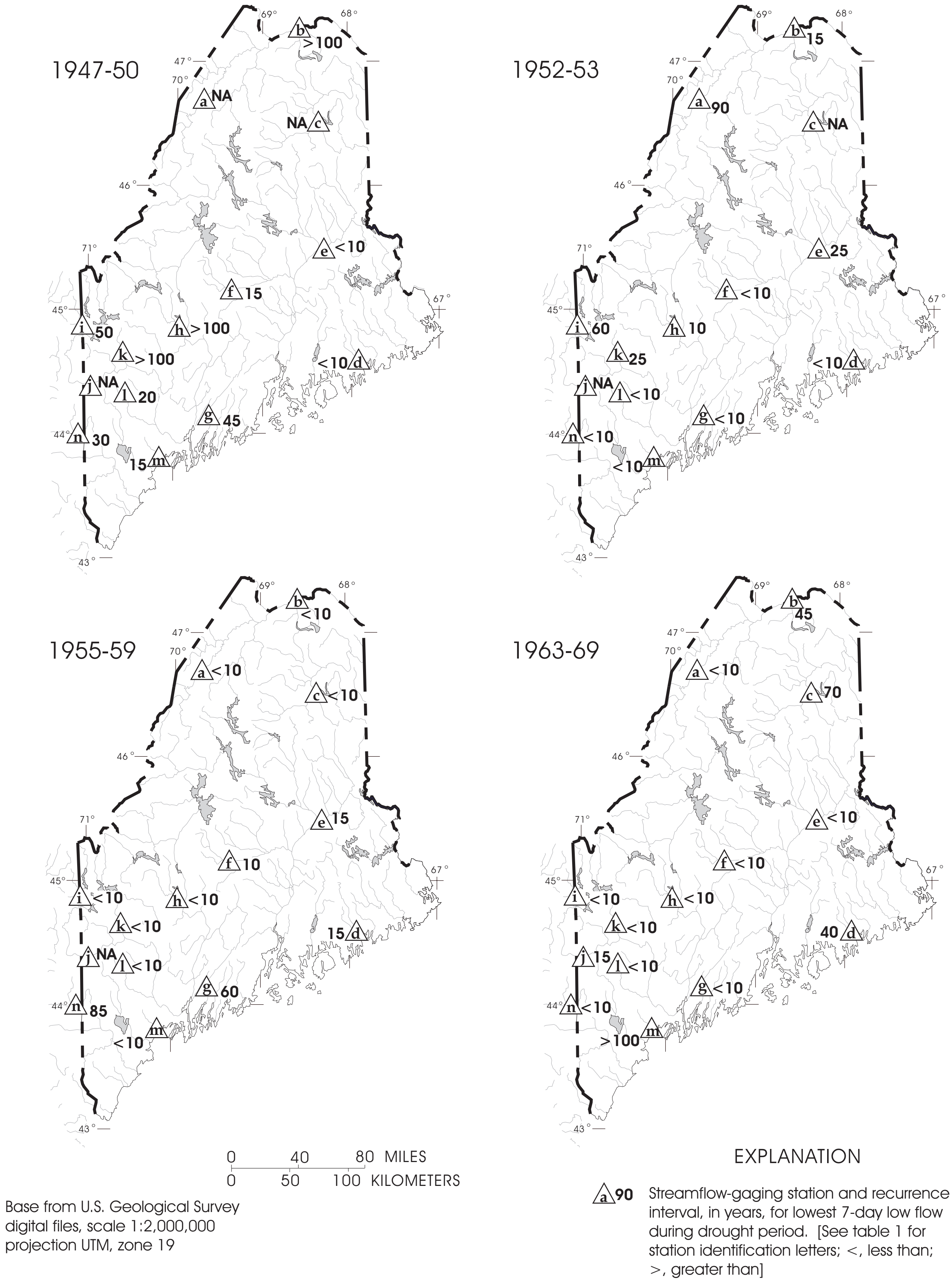

Figure 19. 7-day low flow recurrence intervals for seven historical drought periods and 1999-2002 drought in Maine. [NA, no data available]

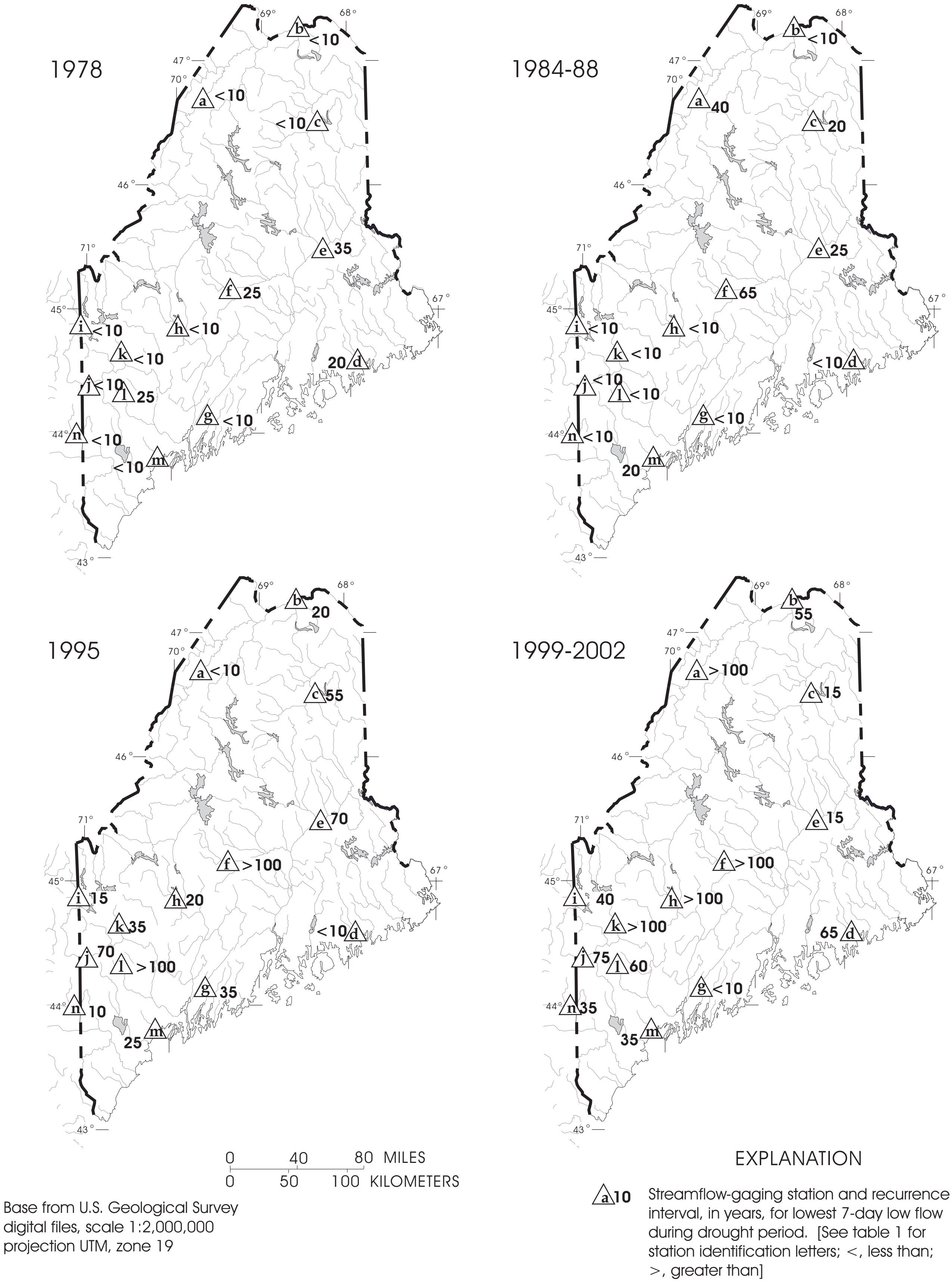

Figure 19 (cont). 7-day low flow recurrence intervals for seven historical drought periods and 1999-2002 drought in Maine. [NA, no data available]

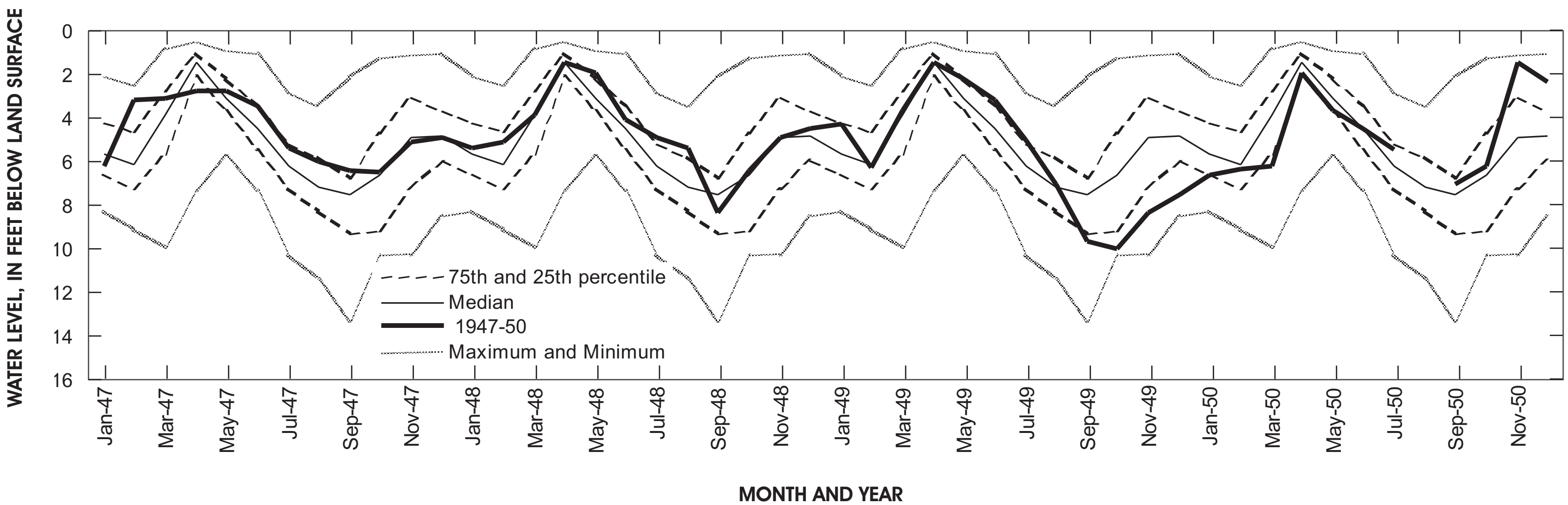

Figure 20. Comparison of 1947-50 month-end ground-water levels to historical median, maximum, and minimum month-end ground-water levels at U.S. Geological Survey companion wells OW 400 and OW 400A in Maine (444637070552301 and 443647070552302). [historical period of record is 1944-98]

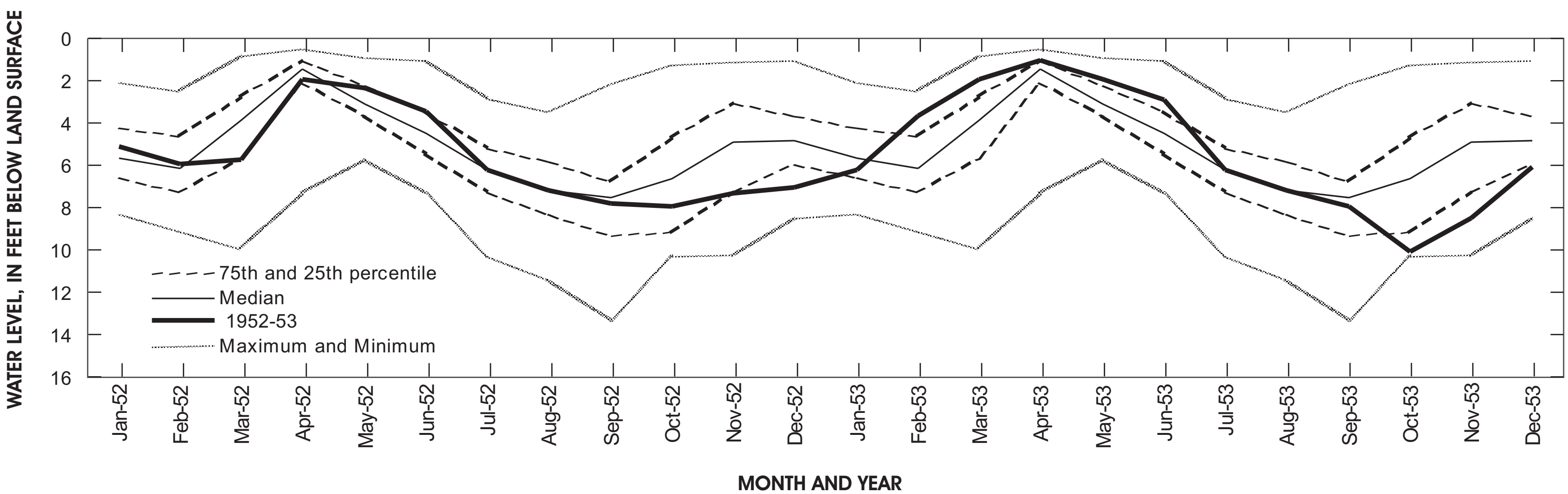

Figure 21. Comparison of 1952-53 month-end ground-water levels to historical median, maximum, and minimum month-end ground-water levels at U.S. Geological Survey wells OW 400 and OW 400A in Maine (444637070552301 and 443647070552302). [historical period of record is 1944-98]

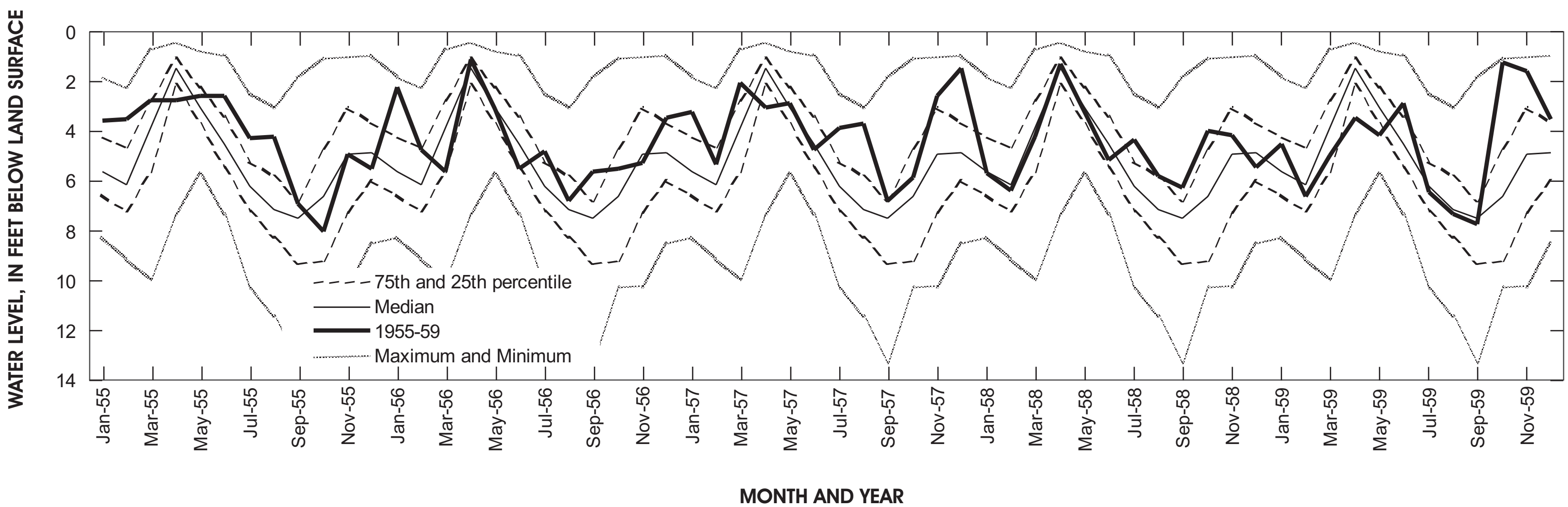

Figure 22. Comparison of 1955-59 month-end ground-water levels to historical median, maximum, and minimum month-end ground-water levels at U.S. Geological Survey wells OW 400 and OW 400A in Maine (444637070552301 and 443647070552302). [historical period of record is 1944-98]

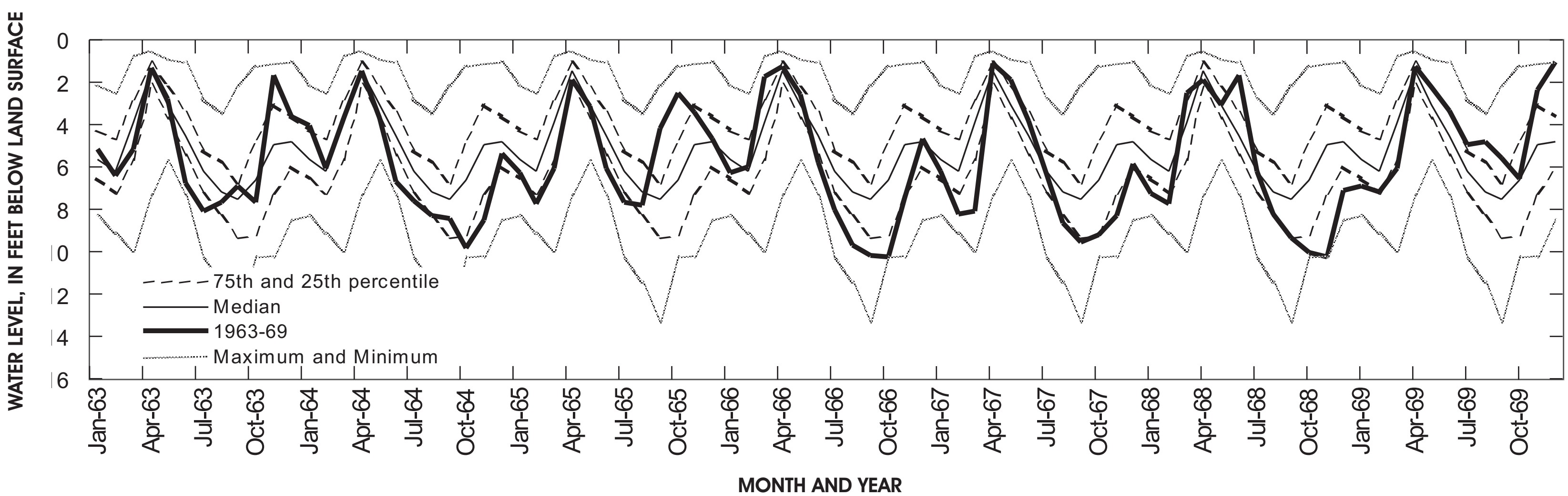

Figure 23. Comparison of 1963-69 month-end ground-water levels to historical median, maximum, and minimum month-end ground-water levels at U.S. Geological Survey wells OW 400 and OW 400A in Maine (444637070552301 and 443647070552302). [historical period of record is 1944-98]

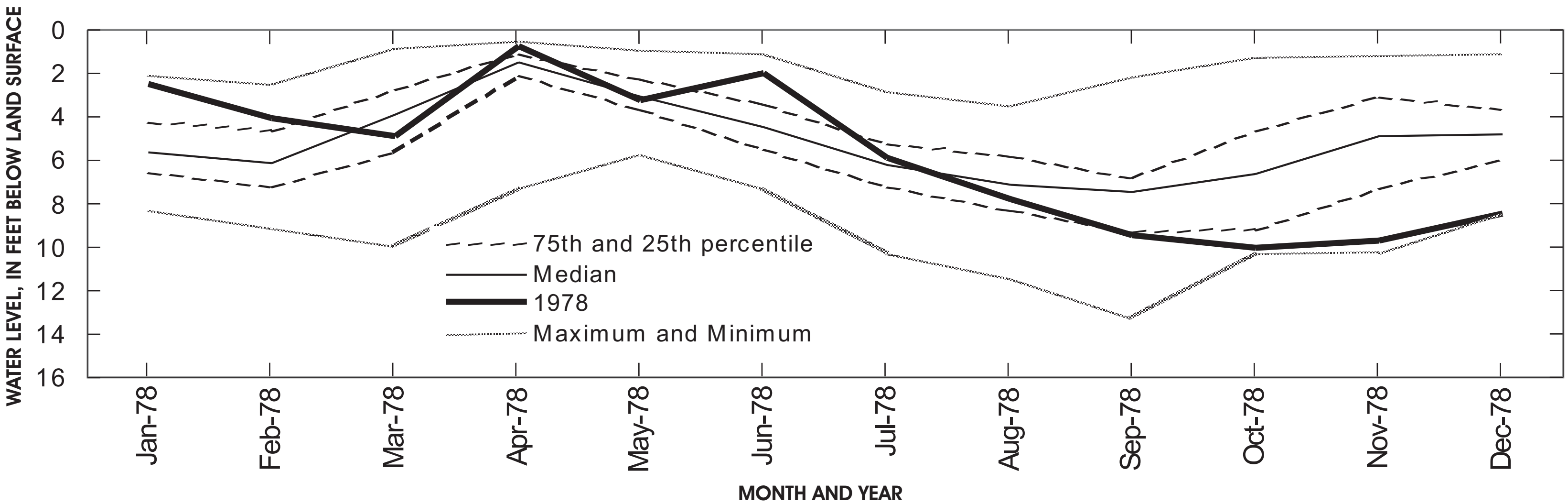

Figure 24. Comparison of 1978 month-end ground-water levels to historical median, maximum, and minimum month-end ground-water levels at U.S. Geological Survey wells OW 400 and OW 400A in Maine (444637070552301 and 443647070552302). [historical period of record is 1944-1998]

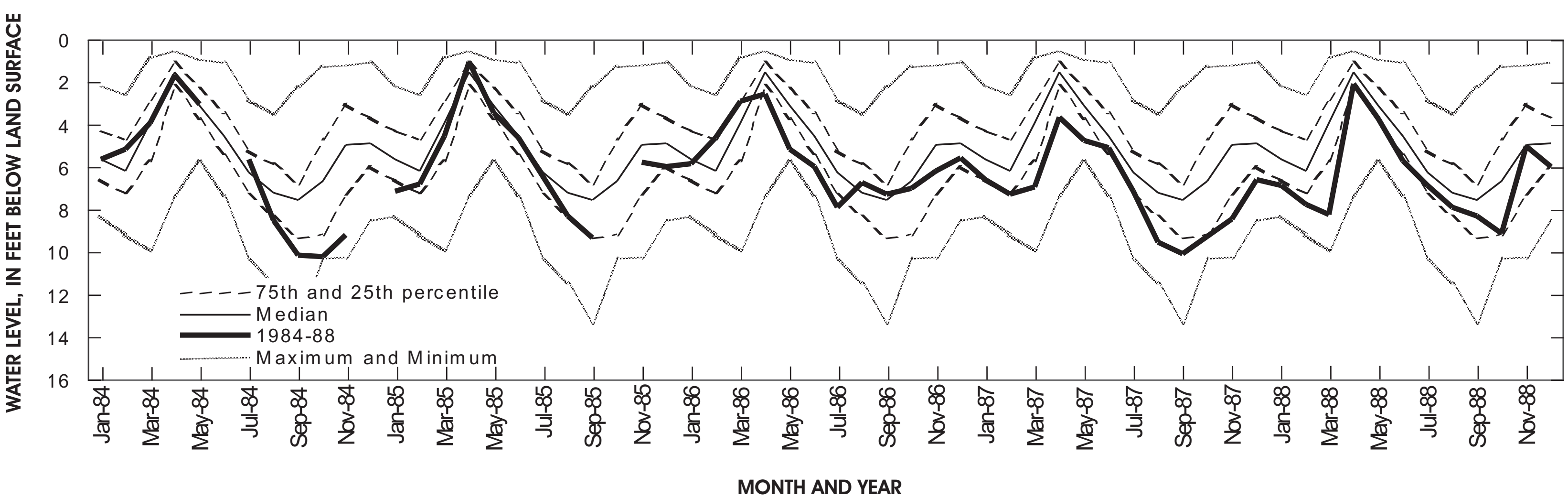

Figure 25. Comparison of 1984-88 month-end ground-water levels to historical median, maximum, and minimum month-end ground-water levels at U.S. Geological Survey wells OW 400 and OW 400A in Maine (444637070552301 and 443647070552302). [historical period of record is 1944-98]

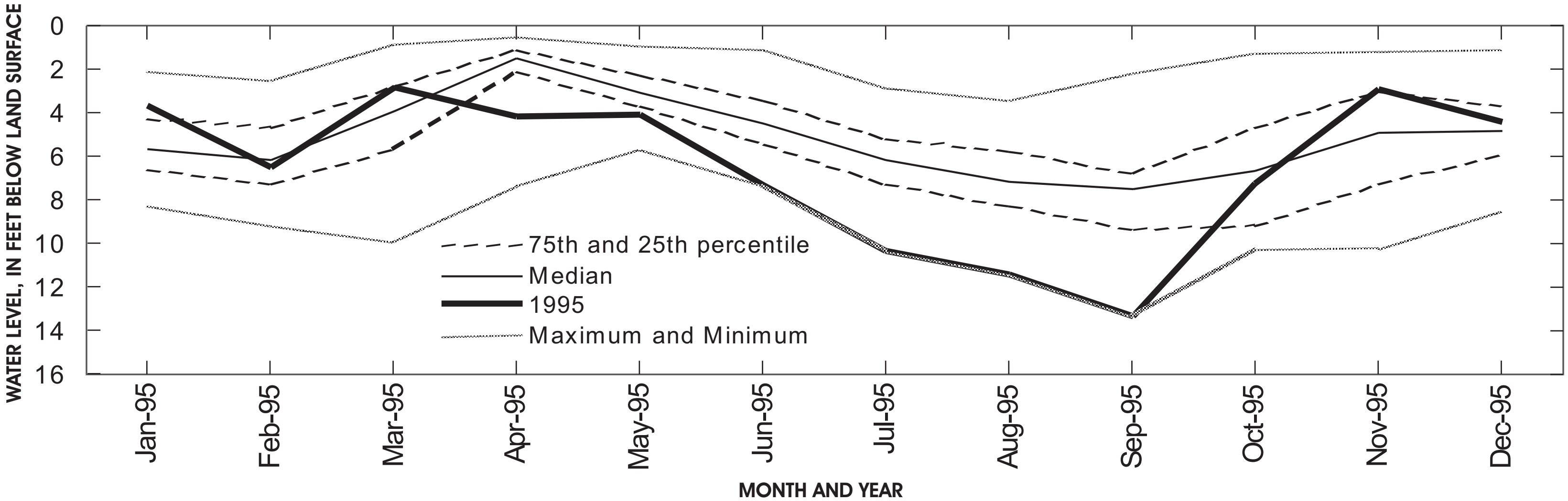

Figure 26. Comparison of 1995 month-end ground-water levels to historical median, maximum, and minimum month-end ground-water levels at U.S. Geological Survey wells OW 400 and OW 400A in Maine (444637070552301 and 443647070552302). [historical period of record is 1944-98]

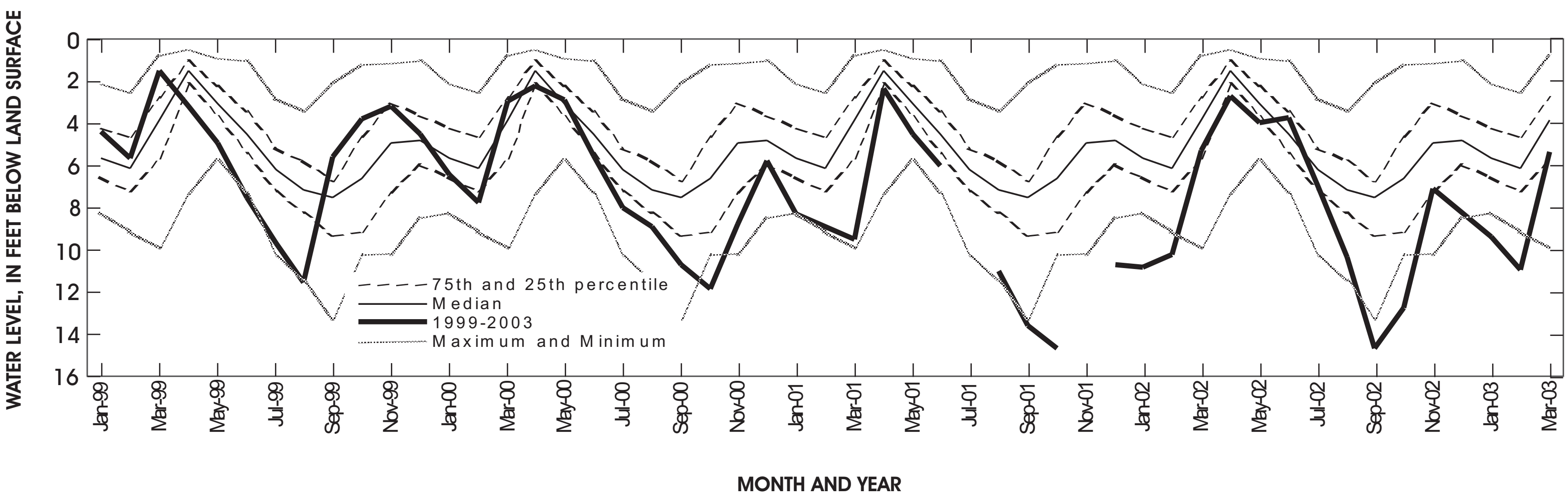

Figure 27. Comparison of 1999-2003 month-end ground-water levels to historical median, maximum, and minimum month-end ground-water levels at U.S. Geological Survey wells OW 400 and OW 400A in Maine (444637070552301 and 443647070552302). [historical period of record is 1944-98]

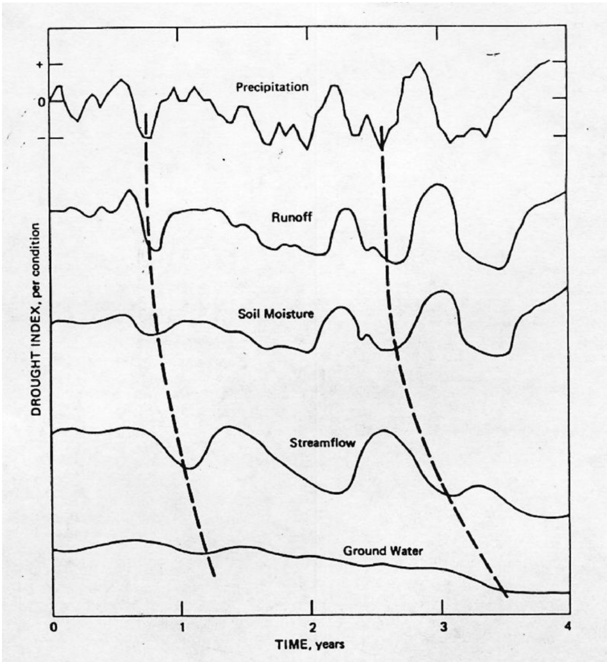

Figure 28. Precipitation deficits propagated in runoff, soil moisture, streamflow, and ground water over time (from: Changnon, 1987). [Dashed lines link precipitation deficit to deficits in other hydrologic indicators]

In order to determine the interaction between ground water and surface-water at this location over 50 years, annual minimum month-end ground-water levels, and annual 7-day surface water lows are shown with identified periods of hydrologic drought (fig. 29). This relation shows the interaction between the ground water and surface water for multi-year periods. The 1955-59 drought is not highlighted because it was a regional drought affecting primarily southern Maine. Low annual minimums in both the ground water and surface water match periods of drought in 1949, 1953, 1964, 1968, 1978, 1984, 1987, 1995, 2001, and 2002. In many cases, the annual surface-water minimum preceded the low ground-water level by a year, such as in 1952-53 and in 1960-61. There also were cases, such as in 2000, where the surface water recovered, but the ground-water levels continued to fall, leading to extremely low surface-water and ground-water levels in 2001 and 2002. Years such as 1975 had low ground-water and surface-water minimums, but were not in an established drought period. In these cases, the drought was a local condition, and was not evident at other stations in Maine.

Record lows during 1995, 2001, and 2002 in annual minimum ground-water levels and surface-water flows could be due in part to a downward trend shown in the last 10-15 years. Downward trends in the data indicate that it probably is most appropriate to examine these data compared to the data immediately surrounding them, as opposed to over the entire period of record and to be cautious about conclusions made with the data. To examine the interaction among precipitation, surface water, and ground water more closely during the 1999-2002 drought, departures from monthly mean data for all three data sets were normalized and plotted for the sites near Middle Dam, Maine (fig. 30). The departure from the mean for each month was calculated as the difference between the monthly mean and the long-term monthly mean, divided by the long-term standard deviation for that month. A positive value indicates above-normal conditions and a negative value indicates below-normal conditions.

The sites at Middle Dam show the lag of ground-water response to precipitation as compared to surface water response to precipitation. For 1999, the precipitation gage shows its lowest dimensionless departure from the monthly mean in April, whereas the lowest departure from the monthly mean for the year was in May for surface water and August for ground water (fig. 15). Even in months at the end of year 2000 and the beginning of 2001, when precipitation was above normal and surface water rose to above normal at times, the ground-water level did not rise back to normal. This lack of recovery indicates that ground-water responded more slowly than surface water to precipitation, and that the drought may have extended through the moderately dry year of 2000 in the ground water at this location, as indicated in figure 29. Another example of the lag of ground-water levels in response to precipitation is shown in 2001. Although precipitation was consistently at or below the monthly mean starting in the spring of 2001, ground-water levels did not reach record lows until the fall, when precipitation was starting to recover. Surface water responded and recovered more quickly during this period.

SUMMARY AND CONCLUSIONS

Dry conditions were present in Maine from 1999 to 2002, with a severe drought in 2001-2002. Hydrologic drought, defined as reduced streamflow,

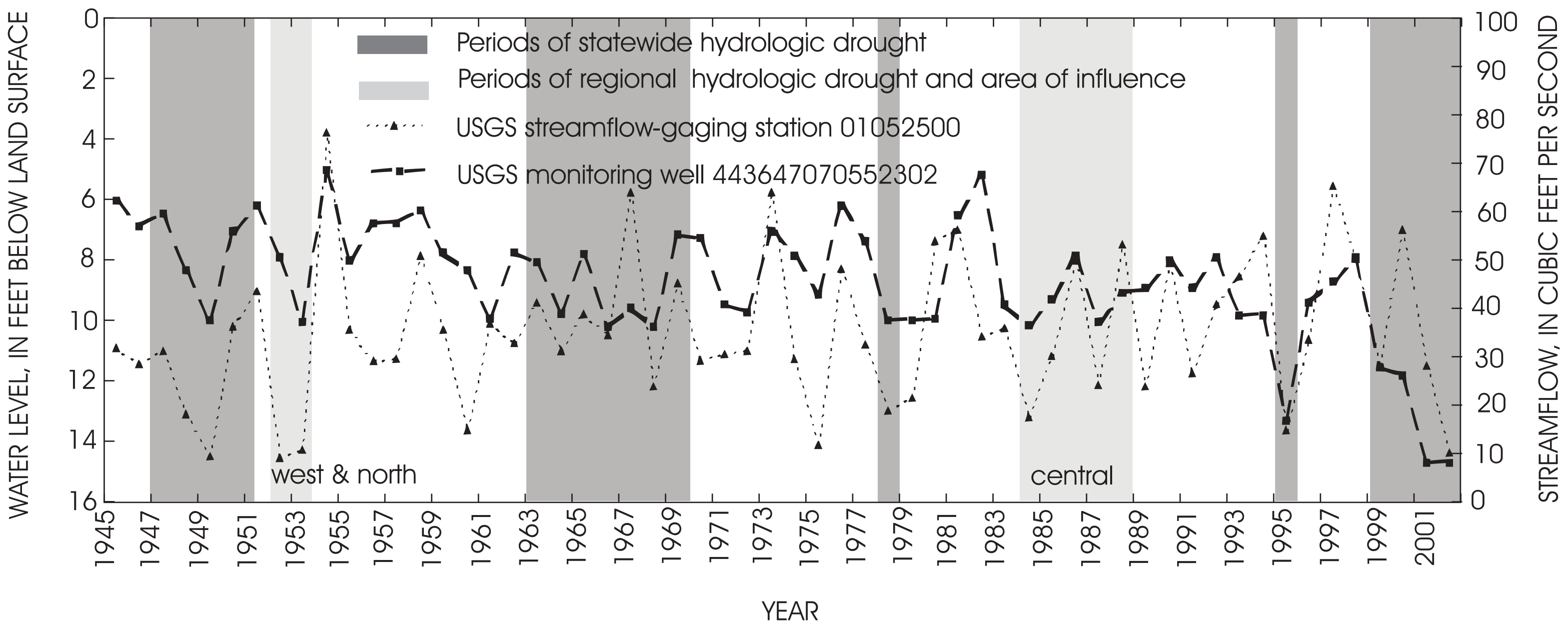

Figure 29. Annual minimum month-end ground-water levels and annual 7-day surface-water lows plotted with periods of surface-water drought near Middle Dam, Lower Richardson Lake, Maine, 1945-2002. [1955-59 not shown as period of drought because it did not affect the central region of State]

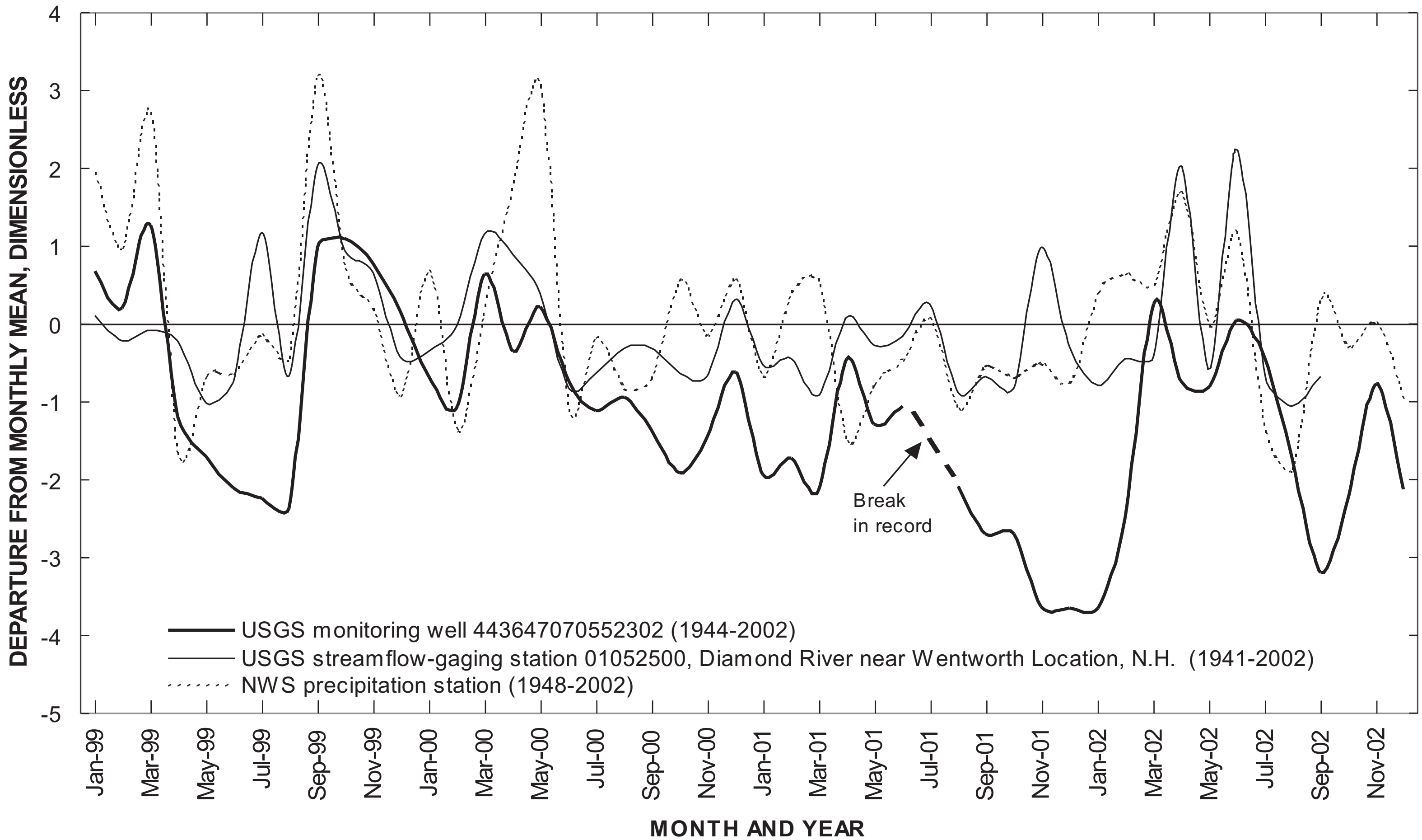

Figure 30. Precipitation, surface water, and ground water departures from monthly means near Middle Dam, Lower Richardson Lake, Maine, 1999 -2002. [USGS, US Geological Survey; NWS, National Weather Service]

declining ground-water levels, and (or) reductions in lake or reservoir levels, is a temporary aberration, relative to some long-term (tens of years) average condition, and is a normal, recurring feature in all climatic regimes. This report, prepared by the US Geological Survey, presents precipitation, surface-water, and ground-water records compared to historical statistics to give an overall picture of the drought years 1999-2002 in Maine, and to put these recent years into context with historical droughts. Little work has been done previously in Maine that integrates these records during periods of extreme low flow.

Examination of precipitation, surface-water, and ground-water records across the State helped to characterize the most recent period of drought. Record lows were set in all three data sets at select locations in central Maine in April 1999. Although the surface water recovered at most locations during 2000, ground-water levels in the central region did not recover. Low water levels could have been carried over into 2001 when the central region had surface-water recurrence intervals greater than 100 years. The drought spread north and west in 2002 with record lows being set in both of these regions in the fall of 2002. Initial examination of the interaction among precipitation, surface water, and ground water at one location in central/western Maine indicated that streamflow responded fairly quickly to below-normal precipitation across Maine in 1999 and in 2001-2002. Streamflow also recovered fairly quickly in between these periods (during 2000). Ground water was slower to respond to low levels of precipitation and slower to recover than streamflow, with a potential lag time of up to one year.

Study results show that 1999-2002 was the most severe drought on record in Maine based on statewide 7-day annual surface-water low flows and one ground-water record in central Maine. The period of record was approximately 50 years across stations. The period from 1947 to 1950 may have been the only comparable period of drought statewide. The 1960s drought, although extreme in the northern and southern regions of the State, was most severe in its duration in the central, western, and coastal regions of the State. The drought in 1995 was unique in that it had some of the lowest streamflows statewide for a single year, second only to 2002. Year 2002 was the lowest single year on record in terms of statewide surface-water levels, with 7-day annual low-flow recurrence intervals of greater than 100 years at four locations. Other historical drought periods, including 1952-53, 1955-59, and 1984-88, were severe regional droughts. A mild statewide drought occurred in 1978.

Further work would be needed to quantify the extent to which hydrologic droughts carry over from year to year in ground-water levels and to determine the timing and amount of precipitation that was necessary to end historical droughts. The linking of hydrologic droughts with climatological droughts (for example percentage of normal precipitation) could potentially allow water-resource managers to characterize droughts while in the middle of a drought period. An in-depth examination of the progression of hydrologic droughts in the ground water over many years of record would be needed for this examination. Studying the interactions of ground water and surface water will be important to determine if assumptions can be made about late summer low flows based on the timing and the magnitude of spring ground-water levels.

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