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Evaluation of the Lakes and Impoundments Drought Index for the Massachusetts Drought Management Plan

Scientific Investigations Report 2024–5081

U.S. Department of the Interior
U.S. Geological Survey

Cover. Photographs of *left*, the masonry dam at Farnham Reservoir in the Pittsfield water supply reservoir system and *right*, the gage at the George H Nichols Reservoir on the Assabet River in Westborough.

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By Travis L. Smith

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
million gallons (Mgal)	3,785	cubic meter (m^3)
billion gallons (Ggal)	3,785	cubic kilometer (km^3)

Datums

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29), the North American Vertical Datum of 1988 (NAVD 88), the Boston City Base Datum, the City of Cambridge Datum, the City of Lynn Datum, and the City of Springfield Datum.

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum.

Supplemental Information

A water year is the 12-month period from October 1 through September 30 of the following year and is designated by the calendar year in which it ends.

Abbreviations

DCR	Massachusetts Department of Conservation and Recreation
EEA	Massachusetts Executive Office of Energy and Environmental Affairs
GNSS	global navigation satellite system
MWRA	Massachusetts Water Resources Authority
NGS	National Geodetic Survey
USGS	U.S. Geological Survey

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Abstract

The condition of surface water storage in lakes and impoundments is used as an index of drought in the Massachusetts drought management plan. The U.S. Geological Survey visited 28 of these lakes and impoundments at 14 single and multiple waterbody systems to evaluate their appropriateness for characterizing drought. The data collection and computation methods at each system were then reviewed and checked for consistency. The types of historical monthly data available varied by system and included water surface elevation, depth of water below the spillway, volume, or reservoir capacity (percent full). For this analysis, water surface elevations and reservoir capacities were converted to volumes to assess the interannual variability in lake volumes. As a second level of assessment, analysis was also done on water surface elevation variability. Systems that did not have enough differentiation in monthly values between lake volume or water surface elevations to clearly demarcate drought levels were identified as unsuitable for use in the drought index for that month. This report discusses the limitations of using the reviewed lakes and impoundments as a drought index, as well as a list of best practices for data collection techniques to improve the confidence and reliability of the data collected.

Introduction

The lakes and impoundments drought index is one of six indices in the Massachusetts drought management plan (Massachusetts Executive Office of Energy and Environmental Affairs, 2023) evaluated to determine monthly drought severity. The lakes and impoundments drought index characterizes the condition of surface water storage in selected lakes, ponds, and water supply reservoirs across the Commonwealth of Massachusetts. The drought index is not a measure of water available to meet water supply demands. The Commonwealth is divided into seven drought regions (fig. 1). No lakes or impoundments in the Islands region were identified by the Massachusetts Department of Conservation and Recreation (DCR) as potential drought index systems. Therefore, no systems were visited in the Islands region and only six regions are discussed in this report. Drought conditions in each region are categorized into five levels by using the volume of water in storage in lakes and impoundments (table 1), ranging from level 0 (normal) to level 4 (emergency). Data for the lakes and impoundments drought index are provided to the DCR by city and town municipalities, from U.S. Geological Survey (USGS) data, and from direct measurements by the DCR.

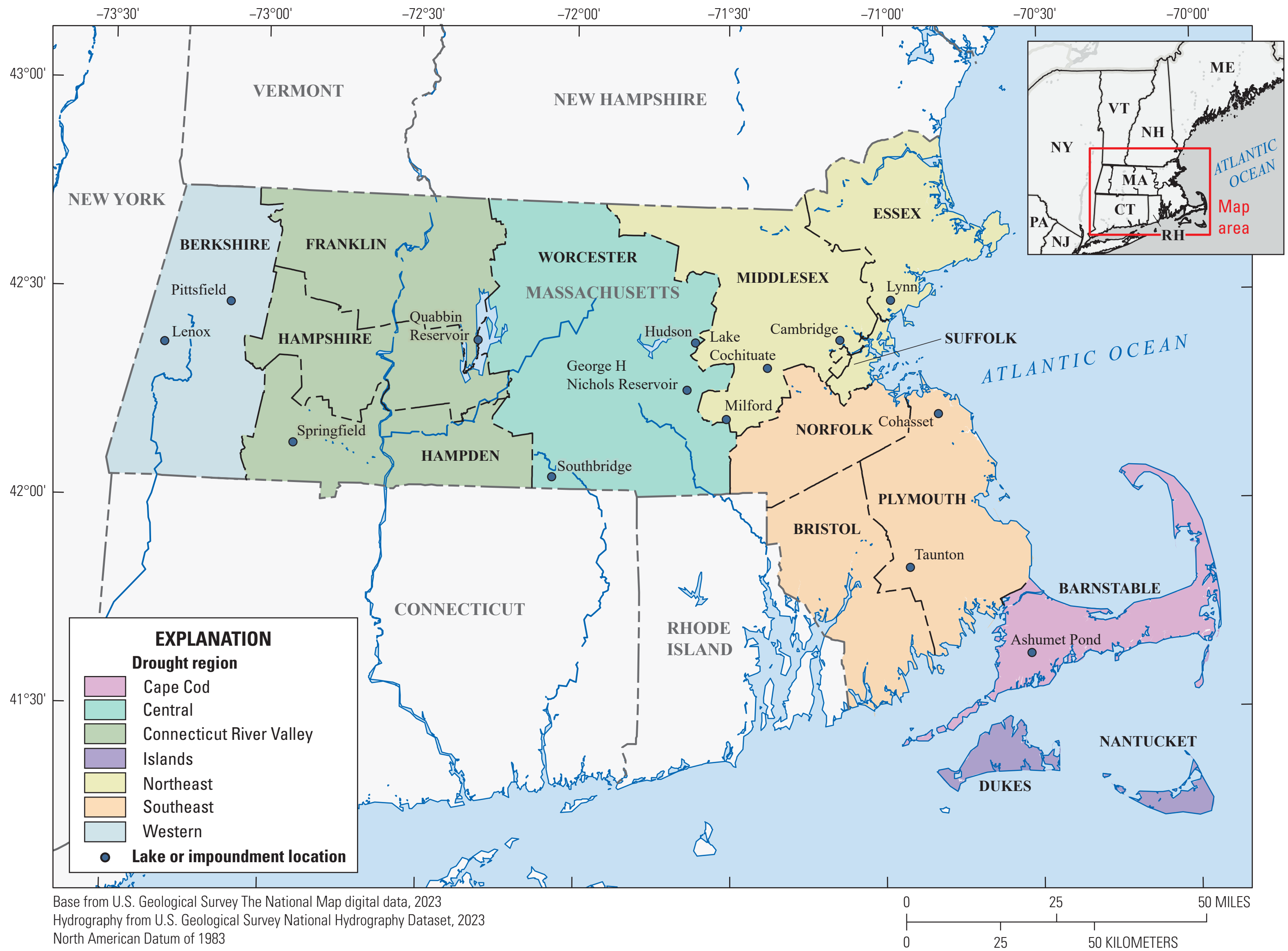

Figure 1. Map showing the Massachusetts drought regions, counties, and the lake and impoundment systems visited by the U.S. Geological Survey in water year 2023. Drought regions are from the Massachusetts Executive Office of Energy and Environmental Affairs (2023).

Table 1. Drought index severity levels and associated percentile ranges of the volume of water in lakes and impoundments from the Massachusetts drought management plan.

[The Massachusetts drought management plan is from the Massachusetts Executive Office of Energy and Environmental Affairs (2023). >, greater than; ≤, less than or equal to]

Drought index severity level	Drought condition	Percentile ranges
0	Normal	>30
1	Mild	>20–30
2	Significant	>10–20
3	Critical	>2–10
4	Emergency	≤2

Purpose and Scope

The purpose of this report is to evaluate the appropriateness of selected systems in the drought regions (table 2) being used in the Massachusetts lakes and impoundments drought index, document the methods used to collect the data, evaluate historical data for consistency, evaluate the methods currently [2023] used to analyze the systems, and provide best practices used by the USGS for collecting lake and impoundment data (Sauer and Turnipseed, 2010). Twenty-eight waterbodies comprising 14 systems were prioritized for review by the DCR and the USGS evaluated the data collected at these systems through the 2022 water year for this study. Eleven of the 14 systems are managed by municipal water departments as water supply systems and consist of between one and five waterbodies (table 3). The other three systems are not managed as water supply systems and consist of one waterbody each.

Table 2. Drought regions and associated counties in Massachusetts.

[Drought regions are from the Massachusetts Executive Office of Energy and Environmental Affairs (2023)]

Drought region	Counties
Cape Cod	Barnstable
Central	Worcester
Connecticut River Valley	Franklin, Hampshire, and Hampden
Islands	Nantucket and Dukes (including Elizabeth Islands)
Northeast	Essex, Middlesex, Suffolk (including Brookline)
Southeast	Bristol, Plymouth, Norfolk (except Brookline)
Western	Berkshire

Table 3. Lake or impoundment systems by drought region, water supply usage, dates and length of historical record, the number of waterbodies in the system, and the source and means of stage-volume ratings.

[Data are from Smith (2024). USGS, U.S. Geological Survey; DCR, Massachusetts Department of Conservation and Recreation]

Lake or impoundment system	Water supply system	Dates used	Length of record (years)	Number of waterbodies in system	Agency providing stage-volume ratings	Data collection means
Cape Cod drought region						
Ashumet Pond	No	1974–2000, 2002–22	48	1	USGS	USGS recording gage
Central drought region						
George H Nichols Reservoir	No	2006–11, 2013–22	17	1	DCR	Manually read by DCR
Hudson water supply reservoir system	Yes	1999–2007, 2008–22	24	1	USGS	Manually read by Hudson Department of Public Works
Southbridge water supply reservoir system	Yes	1999–2022	24	5	Southbridge Water Department	Manually read by Southbridge Water Department
Connecticut River Valley drought region						
Quabbin Reservoir system[1]	Yes	1948–2022	75	2	DCR	DCR recording gage
Springfield water supply reservoir system[1]	Yes	1999–2022	24	2	Springfield Water and Sewer Commission	Manually read by City of Springfield Water and Sewer Commission
Northeast drought region						
Cambridge water supply reservoir system	Yes	2002–22	21	3	USGS	USGS recording gages
Lake Cochituate	No	2010–22	13	1	USGS	USGS recording gage
Lynn water supply reservoir system	Yes	1992–2022	31	4	Lynn Water Sewer Commission	Manually read by Lynn Water and Sewer Commission
Milford water supply system	Yes	1995–2022	28	1	Milford Water Department	Manually read by Milford Water Department
Southeast drought region						
Cohasset water supply reservoir system[1]	Yes	2007–22	16	2	Cohasset Water Department	Manually read by Cohasset Water Department
Taunton and New Bedford water supply system[1]	Yes	1993–2002, 2010–22	23	6	Taunton Public Works, Water Division	Manually read by Taunton Public Works, Water Division
Western drought region						
Lenox water supply reservoir system	Yes	2006–22	17	2	Lenox Department of Public Works	Manually read by Lenox Department of Public Works
Pittsfield water supply reservoir system[1]	Yes	2002–08, 2011–15, 2016–22	19	5	USGS	Manually read by City of Pittsfield Water Division

[1]Not all waterbodies in the system are measured for drought severity levels index calculation.

Background

The DCR currently (2023) computes monthly percentiles for each lake and impoundment system from the available data over the system's period of record (Massachusetts Executive Office of Energy and Environmental Affairs, 2023). The various forms of monthly data recorded during physical site visits or from on-site instrumentation are provided to DCR by the managing municipality or agency. The types of data supplied include waterbody volume, percentage of reservoir capacity (also known as percent full, which is the terminology used in this report), and water surface elevation. Most of the systems examined do not have recording instruments; water surface elevations at these systems are measured manually. The frequency of these measurements ranges from once per day to once per month. The measurement intervals may change depending on the season (such as summer versus winter). Where multiple values were reported for a waterbody for any given month, only the last measured value in the month was used. For continuously collected data, the measurement recorded at 7 a.m. on the last day of the month was used. The DCR computes a monthly percentile of system volume, reservoir capacity, or water surface elevation for each individual system and then calculates a median percentile for all the systems in a drought region in order to assign a regional drought severity level (Massachusetts Executive Office of Energy and Environmental Affairs, 2023).

Other States' drought management plans were reviewed to identify if and how they use lakes and impoundments as a drought index. Of the other five New England States, only Connecticut, and Rhode Island use reservoir volume in their indexes to define drought severity levels, whereas Maine, New Hampshire, and Vermont do not. Connecticut monitors water supply reservoir levels and defines drought stages as a percentage below normal in each of their drought criteria (Connecticut Water Planning Council, 2022). Rhode Island monitors reservoir levels and defines drought phases by factoring in the size and percent capacity below average of the reservoir (Rhode Island Statewide Planning Program, 2012). In other nearby States, New York and New Jersey incorporate reservoir volumes into their drought severity levels, but Pennsylvania does not. New York assigns a score for lakes and reservoir storage levels that is determined from the normal seasonal patterns of the reservoirs in each region and is weighted to reflect regional characteristics. Reservoir scores carry a different weight depending on the region. This value is combined with the scores of other indices to determine drought stages (New York State Disaster Preparedness Commission, 2023). New Jersey monitors reservoir storage levels as a variation from normal within each drought region. The reservoir storage levels in each region are weighted according to a significance factor of the water supply source in order to determine a drought level (New Jersey Department of Environmental Protection, 2022). The use of reservoir volume in the calculation of a drought index differs slightly among States.

System Descriptions

Each system visited by the USGS as a part of this study is described alphabetically by region. The descriptions include the location, the managing organization, the method used to control the pool elevation, a general description of the waterbodies (including their size), and how pool water surface elevation is obtained (including the location, frequency, and accuracy of the water surface elevation measurements). The elevations are provided with the accuracy of the supplied data, which is not consistent across systems. Accuracy ranges from 0.01 foot (ft; one-hundredth of 1 ft) to 0.1 ft depending on the measuring instrument used and is described for each system in this section. Diagrams of the systems are available in Smith (2024).

Cape Cod Drought Region

Ashumet Pond.—Ashumet Pond is a natural kettle pond along the town lines of Mashpee and Falmouth. The pond is primarily fed by groundwater but there is a small inlet at its northern end. The pond is primarily used for recreation and is not a source of drinking water for local municipalities. There are no dams or spillways controlling the pond elevation.

Lake levels are recorded using USGS gage 413758070320501 (Ashumet Pond, Falmouth, Mass.) referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29). Between 1974 and 2022, the maximum recorded volume was 1,860 million gallons (Mgal), which is considered to be the maximum capacity of the pond. This capacity corresponds to a water surface elevation of 46.73 ft above the North American Vertical Datum of 1988 (NAVD 88; 47.77 ft above NGVD 29; Smith, 2024). The gage records water surface elevations to one-hundredth of 1 ft increments every 15 minutes from a pressure sensor in a stilling well. Elevations are verified by the USGS every 8 weeks by measuring from an outside measurement point near the pond.

Central Drought Region

George H Nichols Reservoir.—The George H Nichols Reservoir (also known as the George H Nichols flood control site or site A1) is in Westborough on the Assabet River. The reservoir is managed by the DCR and is used for flood control and recreation. The reservoir is controlled by an earthen dam with a capacity of 496 Mgal at the lower spillway crest, at an elevation of 310.00 ft above NGVD 29 (309.33 ft above NAVD 88). The reservoir was completed in 1969 and rehabilitated in 2012 (EA Engineering, Science, and Technology, Inc., 2010).

There is no recording instrumentation at the system. In 2006, the USGS installed a staff gage on the intake structure near the spillway. The datum at the staff gage was surveyed at 307.055 ft above NAVD 88. The staff plate is read to one-hundredth of 1-ft increments. Measurements are made monthly by the DCR.

Hudson Water Supply Reservoir System.—Gates Pond on Gates Pond Brook is in Berlin. This reservoir is managed by the Hudson Department of Public Works, Water Division as a water supply reservoir for Hudson. The reservoir is controlled by an earthen dam that was completed in 1915. It has a spillway elevation of 336.27 ft above NAVD 88 and a capacity of 195 Mgal.

There is no recording instrumentation at Gates Pond, and pool water surface elevation is manually read approximately 3 days per week by the Hudson Department of Public Works. Water surface elevations are read from a shaft encoder inside the gatehouse. The encoder is graduated in one-hundredth of 1-ft increments. Measurements are verified by tape-up measurements (in inches) from a measuring point on the weir.

Southbridge Water Supply Reservoir System.—The Southbridge water supply reservoir system is managed by the Southbridge Water Department at the Massachusetts-Connecticut border. The reservoir system consists of five reservoirs on two brooks that make up two separate watersheds, both of which originate in Connecticut; one of the two reservoirs (Hatchet Pond) is in Connecticut.

Four reservoirs are on Hatchet Brook and gravity feed from one to the next, in order: Hatchet Pond to Number 5 Reservoir (also known as Hatchet Brook Number 5 Reservoir) to Number 4 Reservoir (also known as Hatchet Brook Number 4 Reservoir) to Number 3 Reservoir (also known as Hatchet Brook Number 3 Reservoir). The Cohasse Reservoir is part of the Cohasse Brook system and is pumped into Number 4 Reservoir. There is no instrumentation at any of the reservoirs for recording water surface elevation, so measurements are made daily in inches from the spillway by the Southbridge Water Department.

Hatchet Pond is the reservoir farthest upstream on Hatchet Brook in Woodstock, Conn. The pond is controlled by an earthen dam built in 1879 and has a capacity of 133 Mgal at the concrete spillway crest (CR Environmental, Inc., 2016) at an elevation of 863 ft above NGVD 29 (Waldron and Archfield, 2006). Water surface elevation measurements are made from a staff plate near the spillway that is graduated in one-tenth of 1-ft increments with the 0-ft mark at the spillway crest. Measurements are converted from tenths of a foot to feet and inches by the Water Department.

Number 5 Reservoir is the second reservoir on Hatchet Brook and is gravity-fed by Hatchet Pond. The reservoir is controlled by an earthen dam built in 1938 and has a capacity of 161 Mgal at the concrete spillway crest (CR Environmental, Inc., 2016) at an elevation of 746.4 ft above NGVD 29 (Waldron and Archfield, 2006). Water surface elevation measurements are made from a staff plate on the gatehouse that is graduated in one-tenth of 1-ft increments, with the 0-ft mark set to the spillway crest. When the water surface elevation drops below the range of the staff plate, tape-down measurements are made from the floor of the gatehouse.

Number 4 Reservoir is the third reservoir on Hatchet Brook and is gravity-fed by Number 5 Reservoir. Water from the Cohasse Brook Reservoir is also pumped into Number 4 Reservoir. The reservoir is controlled by an earthen dam built in 1906 and has a capacity of 248 Mgal at the concrete spillway crest (CR Environmental, Inc., 2016) at an elevation of 705.6 ft above NGVD 29 (Waldron and Archfield, 2006). Water surface elevation measurements are made from a staff plate on the gatehouse that is graduated in one-tenth of 1-ft increments. When the water surface elevation drops below the range of the staff plate, tape-down measurements are made from the floor of the gatehouse.

Number 3 Reservoir is the fourth and last reservoir on Hatchet Brook before the treatment plant and is gravity-fed by Number 4 Reservoir. The reservoir is controlled by an earthen dam built in 1894 and has a capacity of 89.5 Mgal at the concrete spillway crest (CR Environmental, Inc., 2016) at an elevation of 678.1 ft above NGVD 29 (Waldron and Archfield, 2006). Water surface elevation measurements are made from a staff plate on the gatehouse that is graduated in one-tenth of 1-ft increments, with the 0-ft mark set to the spillway crest. When the water surface elevation drops below the range of the staff plate, tape-down measurements are made from the top of a graded walkway on the gatehouse.

Cohasse Brook Reservoir, on Cohasse Brook, is pumped into Number 4 Reservoir. The reservoir is controlled by an earthen dam built in 1967 and has a capacity of 335 Mgal at the concrete spillway crest (CR Environmental, Inc., 2016) at an elevation of 632 ft above NGVD 29 (Waldron and Archfield, 2006). Water surface elevations are made from tape-down measurements from a measuring point inside the gatehouse.

Connecticut River Valley Drought Region

Springfield Water Supply Reservoir System.—The Springfield water supply reservoir system is managed by the City of Springfield Water and Sewer Commission. The system comprises two reservoirs in Blandford, Granville, and Russell. Both reservoirs are on the Little River and are managed as water supply reservoirs. Borden Brook Reservoir is upstream and gravity feeds into Cobble Mountain Reservoir; it has a capacity of 2.45 billion gallons (Ggal) at the concrete spillway crest at an elevation of 1,068.9 ft above the City of Springfield Datum (Levin and others, 2011); and is controlled by an earthen dam that was completed in 1909. No water surface elevation data were supplied for Borden Brook Reservoir. Cobble Mountain Reservoir is the larger of the two reservoirs with a capacity of 22.8 Ggal at the spillway crest (Elise Tarnauskas, Springfield Water and Sewer Commission, unpub. data, January 24, 2023), at an elevation of 952 ft above the City of Springfield Datum (Levin and others, 2011), and is controlled by an earthen dam that was completed in 1933. The water surface elevation of Cobble Mountain Reservoir is recorded daily by the City of Springfield Water and Sewer Commission from a surge tank used for hydropower. Water from the reservoir is piped into the surge tank and allowed to equalize overnight before being used to generate power the next day. The water surface elevation in the surge tank is checked weekly to one-tenth of 1-ft increments from the measuring point on the gatehouse floor.

Quabbin Reservoir System.—The Quabbin Reservoir, on the Swift River, is the largest reservoir in Massachusetts and supplies drinking water to the Boston metropolitan area and a few systems in the Chicopee area. The reservoir is controlled by Winsor Dam in Belchertown, which was completed in 1939, and has a capacity of 412 Ggal at the upper spillway crest at an elevation of 530 ft above Boston City Base Datum (DCR, 2007). Management of the reservoir is divided between the DCR and the Massachusetts Water Resources Authority (MWRA). The DCR manages the water quality and physical property of the reservoir and the land around it. The MWRA is responsible for the transfer of water from the Quabbin Reservoir through the Quabbin Aqueduct to the Wachusett Reservoir, the transfer of water to the Chicopee Valley Aqueduct, and the seasonal transfer of water into the Quabbin Reservoir from the Ware River.

A gage house at Winsor Dam has a shaft encoder that records water surface elevation every 5 minutes to one-hundredth of 1-ft increments and is checked weekly by the DCR. These data from the shaft encoder were used in this analysis. An auxiliary staff gage is at the spillway and is graduated to one-tenth of 1-ft increments. The spillway and the gage house are about 2 miles (mi) apart.

Northeast Drought Region

Cambridge Water Supply Reservoir System.—The Cambridge water supply reservoir system is managed by the Cambridge Water Department, Watershed Division. The system comprises three reservoirs, two of which (Hobbs Brook and Stony Brook Reservoirs) are in the Charles River Basin. Water from Stony Brook Reservoir is transferred through an underground pipeline to the third reservoir, Fresh Pond, in the Mystic River Basin. Water is treated at Fresh Pond before being pumped to the Payson Park Reservoir, an underground storage treatment facility in Belmont.

Hobbs Brook Reservoir (also known as Cambridge Reservoir) is in Lincoln, Lexington, and Waltham, and has a storage capacity of 2,520 Mgal at the spillway crest, at an elevation of 181.34 ft above the City of Cambridge Datum. The reservoir is controlled by an earthen dam in Waltham that was completed in 1897. Water from the Hobbs Brook Reservoir gravity feeds into the Stony Brook Reservoir. USGS gage 01104430 (Hobbs Brook below Cambridge Reservoir near Kendall Green, Mass.; USGS, 2023) is near the dam and records water surface elevation to one-hundredth of 1 ft increments every 15 minutes. Recorded water surface elevations are checked by the USGS against a staff gage to one-hundredth of 1-ft increments every 8 weeks.

Stony Brook Reservoir is downstream of Hobbs Brook Reservoir on the Waltham-Weston town line. The reservoir has a storage capacity of 412 Mgal at the spillway crest, at an elevation of 80.70 ft above the City of Cambridge Datum, and is controlled by an earthen dam that was completed in 1887. Water from the reservoir flows through a 7.7-mi-long pipeline (an aqueduct) to Fresh Pond. USGS gage 01104480 (Stony Brook Reservoir at Dam Near Waltham, Mass.; USGS, 2023) is near the dam and records the water surface elevation to one-hundredth of 1 ft increments every 15 minutes. Recorded water surface elevations are checked by the USGS against a staff gage to one-hundredth of 1-ft increments every 8 weeks.

Fresh Pond is a kettle pond in Cambridge where the water is treated. The targeted capacity of the reservoir is 1,500 Mgal (City of Cambridge, 2011), at a water surface elevation of 16.77 ft above the City of Cambridge Datum. Inflows to the pond are controlled to keep the pool water surface elevation at an optimal operational level and to reduce localized contamination (City of Cambridge, 2011). USGS gage 422302071083801 (Fresh Pond in Gatehouse at Cambridge, Mass.; USGS, 2023) is near the town's water treatment facility and records water surface elevations to one-hundredth of 1-ft increments every 15 minutes. Recorded water surface elevations are checked by the USGS against a staff gage to one-hundredth of 1-ft increments every 8 weeks.

Lake Cochituate.—Lake Cochituate has a capacity of 4,910 Mgal at the principal spillway crest, at an elevation of 136.23 ft above NAVD 88 (Pare Corp., 2015). The lake, along the town lines of Framingham, Natick, and Wayland, is divided into three major sections connected by navigable culverts. The lake was originally dammed to serve as a water supply reservoir for the city of Boston using the Cochituate aqueduct but was discontinued for that purpose in the 1930s. Since then, the lake has primarily been used for recreation.

The lake level is controlled by the Lake Cochituate Dam in Framingham owned by the DCR. The masonry-and-earthen dam was completed in 1920. USGS gage 01098499 (Lake Cochituate at Framingham, Mass.; USGS, 2023) is near the dam, at an elevation of 128.04 ft above NAVD 88 and records water surface elevations to one-hundredth of 1-ft increments every 15 minutes. Recorded water surface elevations are checked by the USGS against a staff gage to one-hundredth of 1-ft increments every 8 weeks.

Lynn Water Supply Reservoir System.—The Lynn water supply reservoir system consists of four interconnected reservoirs: Hawkes Pond, Walden Pond, Breeds Pond, and Birch Pond that are fed from the Ipswich and Saugus Rivers. Hawkes Pond Reservoir is fed from the Saugus River and is then pumped into Walden Pond Reservoir. Walden Pond is also seasonally fed (December–May) by water pumped from the Ipswich River. From Walden Pond, the water is either gravity-fed into Birch Pond Reservoir or pumped into Breeds Pond Reservoir. Both Breeds Pond and Birch Pond Reservoirs gravity feed into the water treatment plant. There is no recording equipment at any of the reservoirs. Water surface measurements are made at measuring points in feet and inches by the Lynn Water and Sewer Commission (Zarriello, 2002).

Hawkes Pond Reservoir is on the Saugus River and is the smallest pond in this system with a capacity of 309 Mgal at the concrete spillway crest, at an elevation of 25.17 ft above the City of Lynn Datum (Richard Dawe, Lynn Water and Sewer Commission, unpub. data, February 16, 2023). This reservoir is controlled by an earthen dam in Saugus that was completed in 1895. Water surface elevation measurements are made daily from a measuring point at the top of the concrete structure at the gate. Measurements are made with a standard measuring tape in feet and inches.

Walden Pond is the largest of the four reservoirs with a capacity of 1,940 Mgal at the concrete spillway crest, at an elevation of 39.25 ft above the City of Lynn Datum (Rick Dawe, Lynn Water and Sewer Commission, unpub. data, February 16, 2023). Waldon Pond Reservoir is controlled by two dams: the outlet dam in Saugus, which was completed in 1890, and the east-end dam in Lynn, which was completed in 1905. Water surface elevation measurements are made daily from a staff gage mounted to a concrete structure in the reservoir off Walden Pond outlet dam. The staff gage is graduated in one-tenth of 1-ft increments.

Breeds Pond Reservoir, on Moore's Brook, is the primary water supply pond with a capacity of 1,600 Mgal at the concrete spillway crest, at an elevation of 55.0 ft above the City of Lynn Datum (Rick Dawe, Lynn Water and Sewer Commission, unpub. data, February 16, 2023). The reservoir is controlled by an earthen and concrete dam in Lynn that was completed in 1870. Water surface elevation measurements are made daily from either the upper or the lower staff gage. The upper staff gage is on a concrete footer close to shore and the lower staff gage is on a concrete pier further out into the reservoir. Both staff gages are graduated in one-tenth of 1-ft increments.

Birch Pond Reservoir on Birch Brook has a capacity of 356 Mgal at the Well Hole inlet at an elevation of 22.0 ft. above the City of Lynn Datum. The concrete spillway crest has a capacity of 397 Mgal at an elevation of 23.0 ft above the City of Lynn Datum, (Rick Dawe, Lynn Water and Sewer Commission, unpub. data, February 16, 2023). The reservoir is controlled by an earthen dam in Lynn that was completed in 1873. Water surface elevation measurements are made daily from two measuring points marked with blue paint. The higher measuring point, on the stone retaining wall off Walnut Street and Birchwood Avenue, covers a range from 44 to 48 ft. The second measuring point, approximately 500 ft farther upstream, on a ledge outcrop, is used for water surface elevations below 44 ft. Measurements are taken with a standard measuring tape in feet and inches.

Milford Water Supply System.—Echo Lake Reservoir is on the Charles River in Hopkinton. The lake is operated by the Milford Water Department as a water supply reservoir with a capacity of 524 Mgal at the stone spillway crest, at an elevation of 354.2 ft above NGVD 29 (CR Environmental, Inc., 2013). The lake is controlled by a masonry dam that was completed in 1898. In 1987, the dam was raised to 357.1 ft with stop planks to increase the capacity to 634 Mgal (CR Environmental, Inc., 2013). There is no recording equipment at the lake. Water surface elevation measurements are taken about three times per week by the Milford Water Department from a measuring point that is equal to the top of the overflow spillway using a standard measuring tape in feet and inches.

Southeast Drought Region

Cohasset Water Supply Reservoir System.—The Cohasset water supply reservoir system is managed by the Cohasset Water Department. The system has two gravity-fed reservoirs: Aaron River Reservoir and Lily Pond. Aaron River Reservoir flows downstream to a dam downstream of the junction of Herring Brook and Bound Brook. The dam directs the flow into Lily Pond or Bound Brook. Only data from Aaron River Reservoir were used because of the complexity of the relationship between Lily Pond and Bound Brook Dam.

Aaron River Reservoir, on the Aaron River, is the larger of the two reservoirs. It has a capacity of 481 Mgal (479 Mgal usable) at the concrete spillway crest (Jonathan Loja, Cohasset Water Department, unpub. data, March 1, 2023), at an elevation of 65.0 ft above NGVD 29 (U.S. Army Corps of Engineers, 1980). The pool is controlled by an earthen dam in Cohasset that was completed in 1976. The water surface elevation is measured weekly by the Cohasset Water Department from a measuring point at the top of the intake pipe on the fish ladder with an engineer's ruler in one-hundredths of 1-ft increments.

Lily Pond is a natural pond on Herring Brook in Cohasset and Hingham. The pond has a capacity of 79 Mgal at an elevation of 43.0 ft above NGVD 29 (Jonathan Loja, Cohasset Water Department, unpub. data, March 1, 2023). It is controlled by the Bound Brook dam control structure, which was completed in 1999. No water surface elevation data were supplied for Lily Pond.

Taunton and New Bedford Water Supply System.—Assawompset Pond, in Lakeville, is the water supply reservoir for New Bedford and Taunton. It is the largest of a system of five interconnecting ponds—along with Great Quittacas Pond, Little Quittacas Pond, Long Pond, and Pocksha Pond—along the borders of Freetown, Lakeville, Middleborough, and Rochester. The Taunton Water Division pumps water for Taunton directly from Assawompset Pond in Lakeville and the Town of New Bedford Water Division pumps water for New Bedford from the Little Quittacas Pond in Rochester.

Assawompset and Pocksha Ponds were combined into one waterbody with a capacity of 14,400 Mgal at an elevation of 52.82 ft above NAVD 88 (Jodi Raposa, City of Taunton Water Division, unpub. data, March 1, 2023). The ponds are controlled by an earthen dam in Middleborough on the Nemasket River that was completed in 1894. Water surface elevation measurements are taken from a measuring point on the pump house floor. Measurements are made daily by the Taunton Public Works with a tape graduated to one-hundredth of 1 ft.

Western Drought Region

Lenox Water Supply Reservoir System.—The Lenox water supply reservoir system is managed by the Department of Public Works in Lenox. The property was built and managed by the Lenox Water Company until 1956, when it was sold to the town. The system comprises two reservoirs—the Lower Root and the Upper Root—that function in tandem to supply water to Lenox.

The Upper Root Reservoir is 400 ft upstream from the Lower Root Reservoir and gravity feeds into the lower reservoir. Water is then transferred from the Lower Root Reservoir to the treatment plant. Excess flow leaves the system through a concrete spillway into Lenox Mountain Brook. There are no recording instruments in this system, so measurements are made to the tenth of 1 ft manually at the end of each month by the Lenox Department of Public Works.

Upper Root Reservoir has a capacity of 79 Mgal at the concrete spillway crest (William J. Gop, Lenox Department of Public Works, unpub. data, October 25, 2022), at an elevation of 1,487.0 ft above NGVD 29 (U.S. Army Corps of Engineers, 1981); 3 ft of flashboards can be added, increasing the elevation to 1,490.0 ft to increase the capacity to 94 Mgal (William J. Gop, Lenox Department of Public Works, unpub. data, October 25, 2022). The water is controlled by an earthen dam that was completed in 1960. The water surface elevation of the reservoir is measured in feet above or below the spillway from a staff plate graduated in one-tenth of 1-ft increments mounted on the right-hand vertical wingwall of the weir. The 0-ft mark is at the elevation of the spillway crest. When the water surface elevation is below the range of the staff plate, survey equipment is used to determine the elevation to one-hundredth of 1 ft.

The Lower Root Reservoir has a capacity of 74 Mgal at the concrete spillway crest, at an elevation of 1,457.0 ft above NGVD 29. A 0.12-ft flashboard can be added to increase the elevation to 1,457.12 ft and the capacity to 75 Mgal (William J. Gop, Lenox Department of Public Works, unpub. data, October 25, 2022). The water is controlled by an earthen dam that was completed in 1861. The water surface elevation of the reservoir is measured in feet above or below the spillway (the 0-ft mark) from a staff plate graduated in one-tenth of 1-ft increments mounted on the side of the gatehouse.

Pittsfield Water Supply Reservoir System.—The Pittsfield water supply reservoir system comprises six reservoirs managed by the City of Pittsfield's Water Division. Water from these reservoirs is treated at two plants before being distributed to the city (City of Pittsfield, 2022). Of these, Cleveland Brook Reservoir is the largest and Upper Sackett Reservoir is the smallest.

Water from the Cleveland Brook Reservoir is treated at the Cleveland Water Treatment Plant in Hinsdale. The Ashley Lake, Farnham, Sandwash, and Upper Sackett Reservoirs are treated at the Ashley Water Treatment Plant in Dalton. Water is sent directly to the two water treatment plants from all the reservoirs except the Sandwash Reservoir, which gravity-feeds into Farnham Reservoir and Roaring Brook. The sixth waterbody in the system, the lower Ashley intake reservoir, was not included in the study in this report because it is a mixing pond for the Ashley Water Treatment Plant and is always kept full. There are no stage recorders at any of the reservoirs, so measurements are made daily by the City of Pittsfield Water Division in feet and inches. Cleveland Brook Reservoir and Farnham Reservoir are the primary reservoirs used for drinking water because of their water quality and accessibility. There are no pipes at the gatehouse connecting Ashley Lake to the Ashley Water Treatment Plant. Water flows down Ashley Brook, eventually making it to the lower Ashley intake reservoir.

Cleveland Brook Reservoir has a capacity of 1,580 Mgal at the concrete spillway crest, at an elevation of 1,435 ft above NGVD 29, and is controlled by an earthen dam that was completed in 1949. Four feet of boards can be added to the spillway to raise the pool elevation to 1,439 ft above NGVD 29 and increase the capacity to 1,860 Mgal (Waldron and Archfield, 2006). Typically, the boards are removed during the winter months. Measurements are made daily at the spillway except during the winter months when, because of ice buildup on the weir, measurements are made at the pump house. Water surface elevation measurements from the spillway are made from visual inspections from painted, unlabeled 1-ft line markers on the left wingwall. The markers cover a 6-ft range from 1,434 ft to 1,440 ft. Water surface elevations are recorded either in one-tenth of 1-ft increments or in inches. Water surface elevation measurements made at the pump house are from two measuring points. One measuring point is on the walkway to the pump house in front of the door and the other is from a cement block under the trap door. Readings are made with standard measuring tape in feet and inches.

Ashley Lake has a capacity of 612 Mgal at the concrete spillway crest, at an elevation of 1,924 ft above NGVD 29, and is controlled by an earthen and masonry dam that was completed in 1902. Boards can be added to the spillway to raise the pool elevation by 2 ft to 1,926 ft above NGVD 29, increasing the capacity to 672 Mgal (Waldron and Archfield, 2006). Water surface elevations are recorded in feet and inches above or below the spillway. Monthly water surface elevations are made using a standard measuring tape in feet and inches from the low point of the spillway.

Upper Sackett Reservoir has a capacity of 165 Mgal at the concrete spillway crest, at an elevation of 1,520 ft above NGVD 29 (Waldron and Archfield, 2006), and is controlled by an earthen and masonry dam that was completed in 1947. Remediation work completed at the reservoir and spillway in 2017 did not change the elevation of the spillway. Water surface elevations are recorded in feet and inches above or below the spillway. Monthly water surface elevations are measured from the low point of the spillway using a standard measuring tape in feet and inches.

Sandwash Reservoir has a capacity of 261 Mgal at the concrete spillway crest, at an elevation of 1,895 ft above NGVD 29 (Waldron and Archfield, 2006), and is controlled by an earthen dam that was completed in 1936. Water surface elevations are recorded in feet and inches above or below the spillway. Monthly water surface elevations are measured from the low point of the spillway using a standard measuring tape in feet and inches.

Farnham Reservoir has a capacity of 450 Mgal at the concrete spillway crest, at an elevation of 1,585 ft above NGVD 29, and is controlled by a masonry dam completed in 1910. Boards can be added to the spillway to raise the elevation by 2 ft to 1,587 ft above NGVD 29, increasing the capacity to 480 Mgal (Waldron and Archfield, 2006). Monthly water surface elevations above or below the spillway are measured from the walkway above the spillway using a standard measuring tape in feet and inches.

Historical Data

The municipalities and agencies that manage each system have provided a variety of historical data, including water surface elevations, individual waterbody or systemwide volumes, and percent-full (reservoir capacity) data. The full dataset, including how the volumes were obtained for each waterbody, is compiled in the “Data Adjustment Factors by Waterbody” table in Smith (2024). Measurements are reported with the level of precision provided for each system. Elevations, referenced to NGVD 29, NAVD 88, or local municipal datums, were left in the datum supplied unless they needed to be converted to correspond with the water surface elevation measurements. Data for stage-volume ratings were obtained from multiple sources and were referenced to NGVD 29, NAVD 88, local municipal datums, or the spillway elevation. These measurements were converted to the datum required to calculate historical monthly volumes.

Some systems only provided reservoir capacity as percent-full data. For these systems, monthly volumes were computed from the reservoir’s maximum capacity. Data for stage-volume ratings are available for all waterbodies in Smith (2024) so that volumes can be computed from water surface elevations if those measurements are provided in the future.

The historical record ranges from 75 years at Quabbin Reservoir to 13 years at Lake Cochituate. A summary of the data for each lake or impoundment system is listed in table 3. The complete historical datasets for each system are available in Smith (2024).

The data were also evaluated for consistency regarding pool level management. Data were omitted from the analysis for months when the pool level management practice changed, or the pool was lowered for maintenance (Smith, 2024). For example, if the pool was lowered in December to repair the spillway, then the volume and elevation for that month would be artificially low because of the construction, not because of the environmental conditions, and therefore, was not included in the calculations. Data were analyzed by water year.

Occasionally, it was unclear how volumes were originally computed. When volumes could not be recomputed because of missing information, those values were removed from the dataset (Smith, 2024). When stage-volume rating data were not available, they were developed for this study. All the data described in this section and the code used to create them, where applicable, are available in Smith (2024).

Cape Cod Drought Region

Ashumet Pond.—Forty-eight years of water surface elevation data, in feet above NGVD 29 (July 1974–November 2000 and July 2002–September 2022), were obtained from USGS gage 413758070320501 (Ashumet Pond, Falmouth, Mass.; USGS, 2023). Before July 2002, the water surface elevation was measured twice a month. If no measurement was taken on the last day of the month, a water surface elevation taken within 3 days of the end of the month was used. If no measurements were taken during that period, no water surface elevation data were used for that month. After July 2002, water surface elevation data were collected from the 7 a.m. measurement recorded on the last day of the month or the closest water surface elevation measurement in a 3-day window from the end of the month. There are some gaps in the data because of gage malfunctions.

No stage-volume rating data were available for Ashumet Pond, so these were developed by combining bathymetric data (Jason Stolarski, Massachusetts Division of Fisheries and Wildlife, unpub. data, April 14, 2023) with local lidar data along the shoreline in ArcGIS Pro (Esri, undated). Water surface elevations to one-hundredth of 1-ft increments were interpolated by using the Aquarius Rating Development toolbox (Aquatic Informatics, Inc., 2023). Data for stage-volume ratings are in feet above NAVD 88. Water surface elevations from the Ashumet Pond gage are published in feet above NGVD 29 (USGS, 2023) and converted to feet above NAVD 88 by subtracting 1.04 ft.

Central Drought Region

George H Nichols Reservoir.—Seventeen years of water surface elevation data in feet above the local datum (April 2006–September 2011 and October 2013–September 2022) were provided by the DCR for the George H Nichols Reservoir (Erin Graham, DCR, unpub. data, September 15, 2022). There are large gaps in the data when no measurements were made. There are no data from March 2016 to March 2017. Data are missing for individual months during water years 2007, 2008, 2013, and 2019. Data from the 2012 water year were removed due to construction at the dam.

Data for stage-volume ratings had previously been developed by using the conic method in feet above NGVD 29 (EA Engineering, Science, and Technology, Inc., 2010). To compute volume data, the stage-volume rating data and the water surface elevation measurement data were adjusted to

NAVD 88. The staff plate was surveyed at 307.055 ft above NAVD 88 using global navigation satellite system (GNSS) survey-grade equipment. A NGVD 29 to NAVD 88 correction of −0.669 ft was applied to the stage-volume rating data by using the National Geodetic Survey (NGS) Coordinate Conversion and Transformation tool (National Oceanic and Atmospheric Administration, 2022).

Hudson Water Supply Reservoir System.—Twenty-four years of water surface elevation in feet above local datum (October 1999–September 2022) were provided by the DCR and the Town of Hudson (Erin Graham, DCR, unpub. data, September 16, 2022; Bob Moriarty, Town of Hudson Department of Public Works, unpub. data, February 2, 2023). Data are missing for a few months during water years 2012 and 2013. Monthly water surface elevations from August 2007 to February 2008 were omitted from the analysis because the pool was lowered for maintenance.

There were no stage-volume rating data available for Gates Pond, so data were developed by using a geographic information system (GIS) bathymetry estimation tool using maximum depth (Hollister and Milstead 2010) and shoreline lidar data. ArcPro (Esri, undated) was used to create stage-volume rating data in 1-ft increments above NAVD 88. Elevations to one-hundredth of 1-ft increments were interpolated by using the Aquarius Rating Development toolbox (Aquatic Informatics, Inc., 2023).

The maximum depth of Gates Pond is 20.25 ft, which is the same elevation as the weir measuring point in feet above the local datum (Bob Moriarty, Town of Hudson Department of Public Works, unpub. data, February 2, 2023). The measuring point was surveyed using (GNSS) survey-grade equipment at 336.266 ft above NAVD 88, producing a gage datum of 316.016 ft above NAVD 88. Stage measurements (local datum) were added to the gage datum to determine water surface elevation in feet above NAVD 88 in order to compute the volume of the reservoir.

Southbridge Water Supply Reservoir System.—The DCR and the Southbridge Water Department provided 24 years of water surface elevation measurements, in inches above or below the spillway (January 1999–September 2022), for each of the five reservoirs (Erin Graham, DCR, unpub. data, January 17, 2023; Jonathan Harris, Southbridge Water Department, unpub. data, February 7, 2023). Data are missing for some months during water years 2013, 2014, and 2015.

Data for stage-volume ratings, developed by CR Environmental, Inc. (2016) and provided for each of the five reservoirs by the Southbridge Water Department, are referenced to feet below the concrete spillway. All water surface elevations from each reservoir were converted from inches to feet, as needed, and applied to their corresponding 2016 stage-volume rating data to determine the monthly volumes. The total volume for the Southbridge water supply reservoir system is the sum of the five individual reservoirs.

Connecticut River Valley Drought Region

Quabbin Reservoir System.—A total of 75 years of water surface elevation data (January 1948–September 2022) were available; data for 1948 to 1980 were provided by the MWRA (Mathew Walsh, MWRA, unpub. data, June 5, 2023), and for 1980 to 2022, by the DCR (Drew Forest, DCR, unpub. data, October 19, 2022). There are no missing monthly water surface elevation data. Although both agencies made monthly water surface elevation measurements, the MWRA took them on the first day of the month and the DCR on the last day of the month. The MWRA measurements were assigned to the previous month to match DCR end-of-month records. Data for stage-volume ratings were provided by the DCR (Drew Forest, DCR, unpub. data, October 19, 2022) referenced in feet above the Boston City Base Datum and were used to calculate monthly volumes from the monthly water surface elevation measurements.

Springfield Water Supply Reservoir System.—Twenty-four years of percent-full (reservoir capacity) data (July 1999–September 2022) for the Cobble Mountain Reservoir were generated by the Springfield Water and Sewer Commission and provided by the DCR (Erin Graham, DCR, unpub. data, September 1, 2022; Elise Tarnauskas, Springfield Water and Sewer Commission, unpub. data, January 24, 2023). Data are missing for individual months during water years 2000, 2001, 2006, 2007, 2009, 2011, 2012, 2013, and 2015. No data were provided for the smaller Borden Brook Reservoir upstream from Cobble Mountain Reservoir. Monthly volumes were computed from a total percent-full value of Cobble Mountain's maximum capacity of 22,829 Mgal.

Data for stage-volume ratings for the Cobble Mountain Reservoir, referenced to feet above the City of Springfield Datum, were provided by the Springfield Water and Sewer Commission (Elise Tarnauskas, Springfield Water and Sewer Commission, unpub. data, January 24, 2023) and Levin and others (2011). The maximum capacity reported by the Springfield Water and Sewer Commission was 22.8 Ggal and by Levin and others (2011) was 21.8 Ggal. Data for stage-volume ratings at a maximum capacity of 22.8 Ggal are included in Smith (2024).

Northeast Drought Region

Cambridge Water Supply Reservoir System.—Twenty-one years of volume data (March 2002–September 2022) were obtained from the system's three USGS gages (Fresh Pond in gatehouse at Cambridge, Mass., 422302071083801; Hobbs Brook below Cambridge Reservoir near Kendall Green, Mass., 01104430; and Stony Brook Reservoir at dam near Waltham, Mass., 01104480; USGS, 2023). Data are missing for individual months during water years 2008, 2010, 2012, 2014, and 2015 because of gage malfunctions.

The volume data compiled from Fresh Pond, Hobbs Brook, and Stony Brook Reservoirs were taken from the 7 a.m. measurement or the closest measurement in a 3-day window from the end of the month. Volumes for each of the three reservoirs were determined from stage-volume rating data generated from USGS bathymetric surveys in feet above the City of Cambridge Datum. The combined volume for all three reservoirs was used as the total monthly volume for the Cambridge water supply system.

Lake Cochituate.—Thirteen years of water surface elevations, in feet above the local datum (August 2010–September 2022), were obtained from USGS gage 01098499 (Lake Cochituate at Framingham, Mass.; USGS, 2023). There are no missing monthly water surface elevations in the dataset. Compiled monthly water surface elevations were taken from the 7 a.m. measurement recorded on the last day of the month or the closest water surface elevation measurement in a 3-day window from the end of the month.

The published datum of USGS gage is 129 ft above NAVD 88, as estimated from a topographic map (USGS, 2023). To get a more accurate elevation, the gage was surveyed by using GNSS survey-grade equipment and found to be 128.04 ft above NAVD 88, which was the value used in the study.

No stage-volume rating data were available for Lake Cochituate; stage-volume rating data for this analysis were developed by combining bathymetric data (Jason Stolarski, Massachusetts Division of Fisheries and Wildlife, unpub. data, April 14, 2023) with lidar data along the shoreline. ArcPro (Esri, undated) was used to create stage-volume rating data, in 1-ft increments above NAVD 88. Elevations to one-hundredth of 1-ft increments were interpolated by using the Aquarius Rating Development toolbox (Aquatic Informatics, Inc., 2023). Monthly water surface elevation measurements to the local datum were added to the gage datum of 128.04 ft above NAVD 88 and applied to the stage-volume rating data to obtain monthly volumes.

Lynn Water Supply Reservoir System.—Thirty-one years of percent-full (reservoir capacity) data for the Lynn water supply reservoir system (January 1992–September 2022) were provided for all four reservoirs by the DCR and the Lynn Water and Sewer Commission (Erin Graham, DCR, unpub. data, September 15, 2022; Richard Dawe, Lynn Water and Sewer Commission, unpub. data, November 4, 2022). Monthly water surface elevation data for the individual reservoirs in the system were not available in an easily analyzable format (such as a spreadsheet). There are no missing values in the dataset. Monthly volumes were computed from the percent-full values from the maximum system capacity of 4,204.5 Mgal.

Data for stage-volume ratings were provided by the Lynn Water and Sewer Commission for all four reservoirs—Birch Pond, Breed Pond, Hawkes Pond, and Walden Pond—in feet above the City of Lynn Datum. These data were not used to compute monthly volumes for the historical record; however, they were included in Smith (2024) for future reference. If water surface elevation data become available in the future, then they could be used with these data to determine monthly volumes at the four reservoirs and then summed to get the total volume for the Lynn water supply reservoir system.

Milford Water Supply System.—Twenty-eight years of data (March 1995–September 2022) measuring the depth above or below the spillway, in inches, were provided by the Milford Water Department (David Condrey, Milford Water Department, unpub. Data, February 28, 2023). One monthly measurement (May 2019) was omitted because the pool level was lowered for maintenance. Data for stage-volume ratings, in feet above NGVD 29, previously developed by CR Environmental, Inc. (2013) from a bathymetric survey, were used to compute monthly volumes for the historical record. Measurements above and below the spillway were added to the gage datum of 354.2 ft to determine water surface elevation in feet above NAVD 29 in order to compute the volume of the reservoir.

Southeast Drought Region

Cohasset Water Supply Reservoir System.—Sixteen years of percent-full (reservoir capacity) data (January 2007–September 2022) for the Aaron River Reservoir were provided by the DCR and the Cohasset Water Department (Erin Graham, DCR, unpub. data, August 19, 2022; Jonathan Loja, Cohasset Water Department, unpub. data, March 1, 2023). The monthly water surface elevation data for Aaron River Reservoir were not available. No monthly data were supplied for Lily Pond downstream from Aaron River Reservoir. Data are missing for individual months during water years 2007 and 2008. Monthly volumes were computed from the percent-full value of usable (above the intake) maximum capacity of 479 Mgal for Aaron River Reservoir.

Data for stage-volume ratings were provided by the Cohasset Water Department, referenced to feet above NGVD 29 (Smith, 2024). Monthly water surface elevation in feet above NGVD 29 can be used with this table to determine monthly volume.

Taunton and New Bedford Water Supply System.—Data for Assawompset Pond were provided by the Taunton Public Works (Jodi Raposa, City of Taunton Water Division, unpub. data, March 1, 2023) and the town of Lakeville (Town of Lakeville, 2023), including 30 years of percent-full data (December 1993–September 2022) and 23 years of water surface elevation data (December 1993–February 2002 and January 2010–September 2022). The water surface elevations from December 1993 through April 2013 were referenced to feet above NGVD 29. After April 2013, water surface elevations were referenced to feet above NAVD 88. No historical water surface elevation data were available between March 2002 and December 2010. An undocumented adjustment (to account for silt in the system from an unknown origin) was applied to part of the historical percent-full volume data, making that full set of data (December 1993–September 2022) unusable for the purposes of this study.

Data for stage-volume ratings from March 28, 1988, referenced to feet above NGVD 29, were provided by the Taunton Public Works (Jodi Raposa, City of Taunton Water Division, unpub. data, March 1, 2023). A survey done by the USGS while performing work to update flood hazard maps found the conversion from NGVD 29 to NAVD 88 to be −1.18 ft (Schwartz, 2013). This correction was applied to the stage-volume rating data and the water surface elevations in feet above NGVD 29 to convert all data to feet above NAVD 88. The updated stage-volume rating data, in feet above NAVD 88, were used to determine monthly volumes (Smith, 2024).

Western Drought Region

Lenox Water Supply Reservoir System.—Twenty-four years of percent-full data for the Lenox water supply system (January 1999–September 2022) were provided by the DCR and the Lenox Department of Public Works for the two reservoirs Upper Root and Lower Root Reservoirs (Erin Graham, DCR, unpub. data, September 1, 2022; William J. Gop, Lenox Department of Public Works, unpub. data, October 25, 2022). However, because of a change in how the pool water surface elevation was managed before and after 2006, the data before 2006 were omitted from the analysis. As a result, only 17 years of data (October 2006–September 2022) were used in this study. Monthly volumes were computed from the percent-full of the maximum capacity of 169 Mgal for both reservoirs.

Data for stage-volume ratings for each reservoir were provided by the Lenox Department of Public Works, in feet above NGVD 29 (William J. Gop, Lenox Department of Public Works, unpub. data, October 25, 2022). Monthly water surface elevations, in feet above NGVD 29, can be used with these stage-volume rating data to determine monthly volumes and then summed to provide the total system volume.

Pittsfield Water Supply Reservoir System.—Twenty-one years of data measuring the depth below the spillway, in feet (January 2002–September 2022) were provided by the DCR for the five reservoirs where measurements were taken (Erin Graham, DCR, unpub. data, September 1, 2022). Monthly measurements from September 2008 through March 2011 were omitted because Ashley Lake was lowered for dam repair and from January 2015 through June 2016 because the Upper Sackett Reservoir was lowered for repairs. There are also multiple months with missing data during water years 2016, 2017, 2018, and 2020.

Data for stage-volume ratings for each of the five reservoirs are available, in feet above NGVD 29 (Waldron and Archfield, 2006). The monthly volume of each reservoir was determined by subtracting the measured depth below the spillway from the spillway's elevation in feet above NGVD 29 and then applied to the stage-volume rating. The volumes for each reservoir were added together to get the total monthly volume for the Pittsfield water supply reservoir system.

The capacities of Ashley Lake, Cleveland Brook, and Farnham Reservoirs can change with the addition of boards to the spillway. The capacity of Cleveland Brook Reservoir, for example, fluctuates seasonally as flashboards are added during the summer months and removed during the winter months. Flashboards are not added regularly or seasonally at the other two reservoirs. The data provided to the DCR did not specify the number of boards installed at the time of the measurements. This analysis assumed a monthly volume with no boards installed at the time of measurement at all reservoirs.

Methods

The USGS visited 28 lakes and impoundments at 14 single or multiple waterbody systems to evaluate their appropriateness for characterizing drought. Historical data available varied by system and included one or more of the following: monthly water surface elevations, depths below spillways, volume, and percent-full volume. The data were compiled from the various sources described in the "System Descriptions" section of this report. The historical data are described in the "Historical Data" section and listed in the "Data Adjustment Factors by Waterbody" table of Smith (2024).

Monthly volumes were computed from the monthly water surface elevation measurements and the stage-volume rating data provided in Smith (2024) at all sites. At some systems, water surface elevation data needed to be converted to a consistent datum prior to calculating volumes. For other systems, where water surface elevations were not available, volume was computed from percent-full data and maximum capacity values. A summary of these adjustments is listed in the "Data Adjustment Factors by Waterbody" table of Smith (2024). As a final step, the monthly volumes were used to compute percentiles of volume for the systems in each drought region to be used as an index.

Percentiles of reservoir volume were computed in R (R Foundation, 2015) for each system for each month that data were available by using the Weibull (1939) plotting position quantile function (type 6; Helsel and others, 2020), and these percentiles of reservoir volume are used to characterize drought. Although the R function refers to quantiles as opposed to percentiles, the term percentile is used throughout this report for consistency with the Massachusetts drought management plan (Massachusetts Executive Office of Energy and Environmental Affairs, 2023). As a secondary step in evaluating the drought index method, percentiles of water surface elevations also were computed, and comparisons were made between levels in a way that accounted for the uncertainty in the water surface elevation measurements. Both methods are described further below.

There is not currently a commonly used or known distribution to fit lakes and reservoir data. It is challenging to determine if the data are normally distributed and (or) test additional distributions that rely on the assumption of normality for small datasets. Further, a sample size of 20 to 30 observations is needed for a statistical test such as the Shapiro-Wilks test for normality to be valid (Helsel and others, 2020). Five of the 14 systems analyzed in this study have less than 20 years of data and 6 have between 20 and 30 years of data. Therefore, it was assumed that the data were non-normal for the purposes of this study and nonparametric statistical methods were used in all analyses that follow.

The Weibull plotting position is a nonparametric data distribution for analyzing extreme values, such as those produced during droughts, that does not assume a normal distribution of the data (Helsel and others, 2020). It is recommended for use with continuous hydrologic data because it recognizes the existence of a nonzero probability of surpassing the maximum value, resulting in unbiased exceedance probabilities (Helsel and others, 2020). This allows for a future monthly volume to be larger or smaller than the highest or lowest volume in the historical record. The R code for computing the percentiles using the Weibull plotting position is provided in Smith (2024).

Percentiles of 0.5, 0.3, 0.2, 0.1, and 0.02 correspond to the median (50th percentile) reservoir volume and the designated drought severity thresholds of 30, 20, 10, and 2 percent, respectively, and were computed from the monthly value recorded at or near the end of each month for each year in the period of record (for example, table 4). Monthly volumes that were equal to or less than the 30th percentile for the period of record, qualify as a mild drought (level 1); volumes equal to or less than the 20th percentile qualify as a significant drought (level 2); volumes equal to or less than the 10th percentile qualify as a critical drought (level 3); and volumes equal to or less than the 2d percentile qualify as an emergency drought (level 4; table 1).

Two conditions were identified that indicate how sensitive a system is to drought and limit its usefulness as an indicator for the drought index for a given month. In the first instance, the computed volumes were the same between drought levels, suggesting little sensitivity. In the second, the difference in water surface elevations between two drought levels was within the uncertainty of the water surface elevation measurements, suggesting that the data were not suitable for measuring discernible change.

In the case of volumes, if the median value was not greater than the mild drought threshold (30th percentile), then the system was identified as having minimal applicability as a part of the drought index. In the case of water surface elevations, USGS best practices for collecting water surface elevations recommend that elevation measurements should be reported with an estimate of their uncertainty (Sauer and Turnipseed, 2010). Each system was evaluated to ensure that the differences in percentiles computed were meaningful for each month. Months that did not show a difference were excluded, as listed in table 5.

In cases where the supplied data did not include water surface elevations, values were back-computed to allow for a comparison of the elevation differences between drought severity percentiles and the estimated uncertainty of the measurements. For most systems, the uncertainty of the measurement was not recorded. An uncertainty of 0.05 ft was assumed to be a reasonable value to account for the effects of waves on water surface elevation measurements made from the exposed staff plates and measuring points used at these systems. Systems where the difference between two drought threshold water surface elevations was equal to or less than 0.05 ft were identified as having insufficient differentiation to determine a drought level. This analysis was only performed for single waterbody systems because of the greater challenges associated with computing water surface elevation percentiles for multiple waterbody systems. Historical monthly water surface elevations and the percentiles computed from these systems are published in Smith (2024). These elevation percentiles were only used to evaluate the appropriateness of the drought index for a given site in any given month. Elevation percentiles were not used to determine final drought levels, which are determined solely by the volume percentiles.

Monthly water surface elevations at Cobble Mountain Reservoir in Springfield and Aaron River Reservoir in Cohasset were determined by using the stage-volume rating data and the monthly volume data. The water surface elevation data for these systems were derived from reservoir capacity values. Because these computed water surface elevation values may not represent the exact water surface elevations because of rounding errors or the accuracy of the stage-volume rating data, they were not included in the historical records for those systems. Including an uncertainty value in field measurements helps to better define the minimum water surface elevation threshold (see "Limitations of the Drought Severity Level" section of this report).

Table 4. Monthly storage volumes computed for Cobble Mountain Reservoir, Springfield, Massachusetts, and their associated drought severity levels.

		Volume (million gallons)											
Percentile	**Drought level**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
50th	0. Normal	17,600	18,800	19,200	20,300	20,100	20,500	21,700	21,200	21,100	20,100	19,400	18,000
30th	1. Mild	16,900	16,500	17,100	18,000	17,700	19,200	21,200	21,000	19,400	18,600	17,600	16,400
20th	2. Significant	16,000	15,400	16,700	16,200	16,200	17,100	20,000	20,400	19,200	17,900	16,300	15,200
10th	3. Critical	13,700	13,900	14,900	15,900	15,800	15,400	18,500	17,200	18,100	16,800	15,200	13,800
2d	4. Emergency	12,900	12,300	13,900	15,100	14,400	15,100	14,800	15,500	17,100	16,200	14,400	12,300

Table 5. Months suitable for use as a drought index by reservoir system on the basis of percentile thresholds computed through the 2022 water year.

[Data are from Smith (2024). ✓, suitable for use; X, not suitable for use]

Lake or impoundment reservoir system	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Cape Cod drought region												
Ashumet Pond	X	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Central drought region												
George H Nichols Reservoir	X	✓	X	X	X	X	X	X	X	X	✓	✓
Hudson water supply reservoir	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Southbridge water supply reservoir system	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Connecticut River Valley drought region												
Quabbin Reservoir system	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Springfield water supply reservoir system	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Northeast drought region												
Lake Cochituate	✓	X	X	X	X	X	X	X	X	X	X	✓
Cambridge water supply reservoir system	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Milford water supply system	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Lynn water supply reservoir system	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Southeast drought region												
Cohasset water supply reservoir system	✓	✓	✓	X	X	✓	X	✓	✓	✓	✓	✓
Taunton and New Bedford water supply system	✓	✓	X	✓	✓	✓	✓	✓	✓	X	✓	✓
Western drought region												
Lenox water supply reservoir system	✓	✓	✓	X	X	X	X	X	✓	✓	X	✓
Pittsfield water supply reservoir system	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Results

Seven systems had at least 1 month of data that were deemed not appropriate for use in the drought index, either because of a lack of variability in the computed volume percentiles or because there was not enough range between water surface elevations (table 5). In the Cape Cod drought region, computed volumes at Ashumet Pond resulted in an indistinguishable drought threshold volume in October. This is the only system in the Cape Cod region resulting in no usable system to characterize drought levels for October. In the Central drought region, computed volumes for the George H Nichols Reservoir resulted in indistinguishable drought threshold volumes in December, April, and May. The reservoir also lacked sufficient differentiation in water surface elevation between drought severity thresholds and the 50th percentile (median) in October, December, January, February, March, April, May, June, and July. However, both the Hudson and Southbridge water supply systems are suitable for characterizing drought in the Central drought region for all months.

In the Connecticut River Valley drought region, the Quabbin Reservoir system and the Springfield water supply reservoir system produced results sufficient to characterize droughts for all months. For the Northeast drought region, computed volumes at Lake Cochituate resulted in indistinguishable drought threshold volumes in December, February, March, April, June, and July. The median (50th percentile) volume was equal to the 30th percentile volume (mild drought) in December and March. Lake Cochituate lacked sufficient differentiation in water surface elevation between drought severity levels and volume at the median (50th percentile) for all months except September and October. However, the Cambridge, Milford, and Lynn water supply reservoir systems produced results sufficient to characterize droughts for all months.

In the Southeast drought region, the computed volumes at the Cohasset water supply reservoir system were distinct for each month, but the water surface elevations lacked sufficient differentiation between drought severity thresholds for January, February, and April. Computed volumes at the Taunton and New Bedford water supply system have indistinguishable drought thresholds for December and July. The Taunton and New Bedford system also lacked sufficient differentiation in water surface elevation between drought thresholds for December. The Cohasset and Taunton and New Bedford water supply systems are the only systems in the Southeast drought region; although both have months that include data that cannot be used to characterize droughts, there is at least one system that can characterize drought severity for every month of the year.

In the Western drought region, computed volumes at the Lenox water supply reservoir system resulted in indistinguishable drought threshold volumes in January, February, March, April, May, and August. Computed volumes at the Pittsfield water supply reservoir system resulted in indistinguishable drought threshold volumes for March. These are the only two systems in the Western drought region, leaving no system able to characterize drought severity levels for March.

Limitations of the Drought Severity Level

This report was designed to help the DCR evaluate the lakes and impoundments drought index as a part of the Massachusetts drought management plan (Massachusetts Executive Office of Energy and Environmental Affairs, 2023). The data are not intended to be used as a measure of water supply availability. Each system is managed according to the needs of its community, and therefore, management practices may differ between systems. Some of the limitations of the dataset are outlined below.

England and others (2018) recommend that at least 10 years of data be collected at a system before computing statistical analysis. Four lakes or impoundments prioritized for evaluation (John Pierce Lake, Watson Pond, North Brookfield Water Supply Reservoir, and Lake Cochichewick) had a data record with fewer than 10 years of data recorded for most of the 12 months each year. For this reason, these systems were not included in these analyses.

Eleven of the 14 systems are regulated water supply systems. Lake or impoundment levels at these systems are heavily controlled to maximize water availability. If the reservoir structure or water management procedures of these systems change, the data from that point forward may no longer be comparable with the historical record. Ideally, in such cases, an additional 10 years of records would be collected before monthly percentiles are recomputed based on the new data alone.

In general, the monthly variability in volumes at the 11 regulated water supply systems is greater than the volume changes at the three non-water-supply (natural) systems. One possible cause of this difference is that the water supply demand, which usually increases during droughts, may amplify the drought effects on these waterbodies. Other natural waterbodies could be studied to see if their use may be a better drought index system as they are not being regulated for alternative usage and would more directly reflect the effects of climate-related conditions on drought severity levels.

Five of the 14 systems are multisystem networks. If any one of the waterbodies in the system is under construction or a measurement is missed, then the total monthly volume of the system cannot be computed. Such occurrences increase the number of gaps in the historical record. In addition, the correlation between water surface elevations and drought severity levels is harder to evaluate.

A single measurement on the last day of the month was assigned as the monthly value. This monthly value may not accurately represent the average volume for a particular month. Typically, lake and reservoir volumes do not change much throughout a month, but the timing of a rainstorm or daily release may cause the measurement to misrepresent the average monthly volume. Continuous data collection at lake and impoundment systems would allow for more accurate monthly averages as opposed to single data points.

This report is a snapshot of the 14 systems through the 2022 water year. New data can be added to the historical datasets to better reflect long-term averages. Percentiles with the latest data can be recomputed to determine up-to-date drought severity levels. Additional sites may be included as more data become available for analysis.

Monthly water surface elevations sent to the DCR by the cooperating municipalities or agencies may be used in the future to compute monthly volumes from the stage volume rating data (Smith, 2024). The new volume data can be combined with the historical dataset and new percentiles can be computed (Smith, 2024) to determine updated drought severity levels.

The monthly drought severity level for each of the drought regions is computed as the median percentile of all systems in the region. Systems that do not have data able to characterize drought for that month (for example, as listed in table 5) should be excluded from analysis for that month. These systems could be reassessed once more data become available.

This report does not include an evaluation and analysis of all waterbodies used to determine the Massachusetts lakes and impoundments drought index. Other systems currently used in the drought index or that might be considered for inclusion in the future could be evaluated to increase the number of systems in each region.

Best Practices for Data Collection

It is important that data collection activities are carried out in a consistent and reproducible manner to minimize errors and to help ensure that the data are comparable across sites. Best practices listed below are not all inclusive and should be used together with the listed references for complete guidance. Specific techniques that could improve the confidence and reliability of the data collected at these systems include:

- Define a well-marked measuring point.
- Periodically verify that the elevation of staff gages and measuring points have not changed.
- Document the uncertainty for each measurement.
- Install automated lake gages.
- Review and store data at a central location.

In addition, field data referenced to a permanent staff gage or measuring point other than the spillway could help ensure a higher level of accuracy of the data by decreasing potential errors. The addition of flashboards to the concrete spillway could result in misleading or misreading water surface elevation measurements; thus, the presence or absence of flashboards should be documented every time data are collected. For improved accuracy, measuring points should be clearly defined, recognizable, described, and clearly marked so they can be easily located.

Sauer and Turnipseed (2010) recommend that the primary gage height, as recorded during a site visit, be compared with a secondary gage height from a reference gage near the primary recorder. It is recommended that the gages be close enough to be read at the same time, measuring the water surface elevation of the same pool. The secondary gage can be a staff plate, wire-weight gage, or measuring point.

Kenney (2010) recommends routinely running levels at water surface gages in relation to measuring points and staff plates every 3–5 years. The elevations of the measuring points and staff plates used to determine water surface elevations can shift over time. Routine levels run from a set of reference marks can confirm that the elevations of measuring points and staff plates have not changed. Measuring points typically are located in areas that allow easy access to the water surface but might be vulnerable to damage or ground shifting. Reference marks differ from measuring points as they are placed in more stable locations that are unlikely to shift or be disturbed.

Including an uncertainty estimate in field measurements helps to better define the minimum water surface elevation threshold. Conditions such as high winds and waves affecting the water surface elevation measurements during field inspections could impact the quality of the data collected for the analysis of the drought severity level. Systems with small differentiations between drought levels can be significantly affected by the uncertainty of the water surface elevation measurement. For example, in August, the George H Nichols Reservoir had a critical drought severity threshold of 466 Mgal and an emergency drought severity threshold of 463 Mgal. The corresponding difference in water surface elevations between these two volumes was 0.07 ft. Wave action on the staff gage during the inspection, resulting in a measurement uncertainty of 0.10 ft could result in difficulty in defining the drought severity level. If the uncertainty in the field inspection measurements were found to be typically around 0.10 ft after many inspections, then the threshold in the difference in water surface elevations at the system may need to be adjusted to ensure that these accuracies are less than the difference in water surface elevations between the drought severity levels. The use of stilling wells at measurement locations can significantly decrease the uncertainty of water level measurements.

Water surface elevations obtained directly from a recording gage or routinely measured by trained personnel can also improve accuracy. Water surface elevation data compiled and stored by a single entity are more easily quality-assured than data from multiple entities

Summary

Fourteen systems with a total of 28 waterbodies were evaluated for their appropriateness as a part of the lakes and impoundments drought index in the Massachusetts drought management plan (Massachusetts Executive Office of Energy and Environmental Affairs, 2023). Each system was visited by the U.S. Geological Survey to document the methods used by system personnel to collect the data and to evaluate the methods currently used to analyze the system’s data. Additionally, the historical data were evaluated for consistency.

Historical monthly data were used to compute monthly percentiles of the system’s volume associated with drought severity levels ranging from level 0 (normal) to level 4 (emergency) in the Massachusetts drought management plan. Data for stage-volume ratings are provided for all waterbodies in these systems that can be used to compute drought severity levels.

Percentiles of monthly volumes were computed from the total combined volumes for each system by using the Weibull plotting position, a nonparametric data distribution for analyzing extreme values, such as those produced during droughts. Monthly values at some systems were not appropriate for use as a drought index because of a lack of differentiation between the thresholds.

There are many limitations to using lakes and impoundments as a drought severity index. Most of these systems are primarily used as water supply reservoirs and are heavily regulated. Adherence to best practices for data collection could increase the accuracy of and confidence in the data being collected to evaluate drought conditions in Massachusetts. Collecting additional data at existing systems and including additional systems in each drought region could improve the robustness of using lakes and impoundments for the drought severity index.

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