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Evaluating Drought Vulnerability of Small Community Surface Water Supply Systems in the Midwest

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Institute of Natural Resource Sustainability
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Abstract

This report presents approaches and data availability for evaluating the drought vulnerability of small community water supply systems in the Midwest that obtain water from surface water bodies, such as rivers, streams, natural lakes, and man-made reservoirs. A description is provided of the various types of surface water sources from which 320 small community systems in the Midwest, each serving 10,000 or fewer people, obtain their water. The small community surface water system most commonly obtains its supply from one or two small impounding reservoirs. However, a substantial number of communities instead obtain their water from either direct river withdrawals or off-channel storage of water withdrawn from streams and rivers. Sixty of these 320 small community surface water systems were interviewed to gather information on the availability of data to determine the drought vulnerability of these systems. Although hydrologic and physical data exist for evaluating many of these systems, relatively few of the interviewed system managers could provide such pertinent information.

A summary of selected hydrologic data is provided that can be used to determine the relative severity of major historical drought periods for various portions of the Midwest. Focus is given to historical droughts and available data for the southern portion of the Midwest where most surface water supply systems are located, comprising parts of Kansas, Missouri, Iowa, Illinois, Indiana, and Ohio. Geographic differences in drought severity are described, as is the influence of the physical characteristics of a water supply on the “critical” drought duration that a community must consider.

Basic water budget analyses of water supplies and data needs are presented. Reservoir capacity measurements and estimates of inflow are the most critical data in reliable assessment of water supply adequacy. Depending on data availability, estimation of inflows may be straightforward to highly uncertain. For water supply systems that withdraw directly from a stream or river, the existence of long-term stream gage data on that river is particularly crucial to evaluate supply adequacy, and such data for larger streams and rivers are often available. With impounding reservoirs, which are typically located on smaller streams, data for that stream may often not exist; however, data from a “surrogate” gage that is considered to be hydrologically similar are often sufficient to estimate water supply yield. Systems that use off-channel reservoirs often withdraw water from smaller streams that do not have data for accurate depiction of their yield, and these systems also appear to be the most vulnerable to severe drought conditions. Case studies are presented to provide examples of yield calculations and innovative approaches that selected small communities have undertaken for addressing drought vulnerability. The role of demand management (drought response and water conservation) in evaluating drought vulnerability is also presented.

If hydrologic data and basic physical data such as storage capacity are lacking, it may be difficult for either system managers or experienced professionals to estimate a community system’s yield and potential drought impacts, particularly for off-channel reservoir and low channel dam systems. However, managers should attempt to understand the type of drought period likely to test the adequacy of the available supply and can begin recording basic system observations, such as daily withdrawal records and reservoir drawdown, in a readily-accessible form that will be useful for future evaluations.

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Introduction

Community water supply systems that obtain their water from surface water sources have the potential to be affected by severe drought conditions when streamflow amounts and the flow of shallow groundwater that feeds surface water bodies are reduced. Whereas some community surface water systems in the Midwest have needed to implement water-use restrictions during drought periods over the past 20 years, few communities have experienced a major drought during this time that seriously threatened their water supplies. For many communities, the lack of any serious drought threat in recent memory has fostered a sense of security concerning the adequacy of their supply. In many cases a sense of security is warranted; in other cases, it is not.

Major droughts have occurred in the past and will occur again in the future. The most recent example is the 2007–2008 drought that affected Alabama, Georgia, and the Carolinas. Portions of these states experienced the worst precipitation drought on record, with some records dating back to the late 1800s. From November 2006 through March 2008, the precipitation deficit for much of northeastern Alabama, for example, was 40 percent below normal. Hundreds of communities across the region were placed on mandatory water use restrictions, numerous communities needed to develop alternative supplies to avoid shortages (the most common solution was interconnecting with a larger nearby water supply system), and a small number of systems needed to haul water to their community. Many of those affected were small community systems. The predominant water supply concern for the region is Lake Lanier, which supplies water for 5 million people in Atlanta and other communities in northern Georgia. In December 2007, its water supply storage had been reduced to its lowest level on record, reportedly a 90-day supply, leading the State of Georgia to seek a reduction in the amount of water released from the lake for downstream uses. Although Lake Lanier does not represent a small water supply system, which is the focus of this report, the lesson to be learned is still the same. New droughts—worse than any previous droughts of record—can and will occur, causing unforeseen water management challenges.

Water supply planning in the United States is often focused on the potential recurrence of droughts similar to those observed in the past, but the Georgia experience identifies the potential necessity to plan for drought conditions that are a degree worse than those of the past century—even when recent history provides no hint of impending drought conditions. Based on Midwestern drought experiences from the mid-1900s, it is reasonable to assume that the Midwest would not escape a new drought of record without some small communities depleting their available water supply sources.

This study concentrates on the drought vulnerability of small community water supply systems in the Midwest that obtain their water from surface water bodies, such as rivers, streams, natural lakes, and man-made reservoirs. For this study, the Midwest is defined as the 10-state region serviced by the Midwest Technology Assistance Center (MTAC), comprising Illinois, Indiana, Iowa, Kansas, Michigan, Minnesota, Missouri, Nebraska, Ohio, and Wisconsin. More than 1.1 million residents in these states receive their water supply from 320 community surface water systems serving 10,000 people or fewer. Figure 1 shows the locations of these

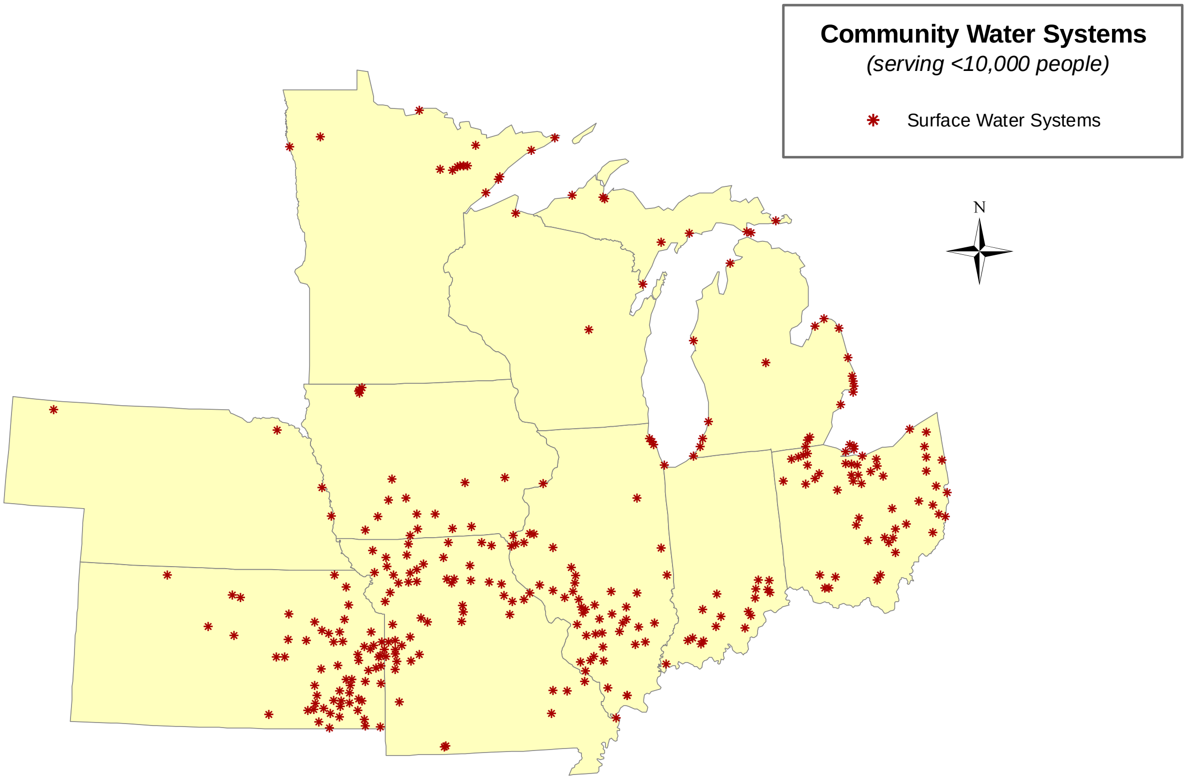

Figure 1. Location of small community surface water systems in the Midwest

communities. This map shows that the vast majority of surface water supplies are located in a relatively narrow band running from southeastern Kansas to east-central Ohio, passing through northern Missouri, southern Iowa, southern Illinois, and southern Indiana. Most small Midwestern communities outside this band, such as those in Michigan, Wisconsin, and Minnesota, obtain their water from groundwater supplies. Remaining surface water supplies outside this band typically receive their water from the Great Lakes or other sources that have a large supply, such that drought vulnerability is not considered a primary water supply issue. For this reason, much of the ensuing discussion on drought characteristics will focus on the southern tier of states in the Midwest where the majority of surface water supplies are located.

Although much attention has been devoted in recent years to securing reliable and safe water resources for community water supplies throughout the nation, most of this attention has been devoted to the quality of water and improving the technologies for water treatment and distribution. Comparatively less attention has been focused on the potential diminished capacity of systems to provide an adequate quantity of water during drought. The first step in addressing adequacy of supply involves examining the vulnerability of water supplies to drought impacts. However, the resources needed to analyze the potential vulnerability of community systems to severe drought are often not readily available or fully understood. Small community surface water systems also face a set of unique challenges:

- Many systems rely upon a single surface water source.
- Many small water systems have limited revenue from their modest customer base, as well as a high pipe length to customer ratio, making it more difficult to maintain and replace transmission and distribution lines as well as to afford treatment plant upgrades required to meet stricter U.S. Environmental Protection Agency (USEPA) surface water regulations.
- In some cases, the difficulty of funding treatment plant upgrades or augmenting their water supply sources influences a community's decision to purchase a portion of their supply from an external purveyor. In other cases, distances to nearby systems make the establishment of interconnections cost-prohibitive.
- Limited financial resources may constrain the amount of assistance they can receive from consulting engineers in devising a drought plan.
- These sources are also frequently smaller bodies of water that are more likely not to have stream gages or recent capacity measurements that allow managers to make informed decisions about their drought risk.

This report focuses on how to evaluate a system's vulnerability to drought, with consideration to the supply challenges that small systems face. Chapter 2 presents background information on surface water supply droughts in the Midwest, using precipitation and streamflow data to compare geographic differences in drought severity and duration. Chapter 3 chronicles the geographic locations, population, and source types of all 320 community surface water systems in the Midwest. This chapter also contains an analysis of hydrologic data availability, drought impacts, planning efforts, and water demand reported from semi-structured telephone interviews with 60 systems selected via a stratified random sample. Chapter 4 presents basic methods and data that can be used to estimate the yield available to these systems during droughts of a given severity. Chapter 5 presents guidance for assessing specific water supply types, where possible, including approaches that can be used by systems possessing only rudimentary data. Chapter 6 reviews the role of demand management practices in evaluating drought vulnerability, and Chapter 7 presents a brief summary and recommendations.

Although this report is intended to provide water system managers with recommendations on how to self-evaluate the drought vulnerability of their system, in many cases a detailed evaluation of a system's yield and drought adequacy requires technical expertise. The information contained herein should, however, provide a system manager with a general understanding of the technical considerations in evaluating system adequacy.

Acknowledgments and Disclaimer

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Characteristics of Water Supply Drought in the Midwest

Drought is most simply defined as a period when deficient moisture or precipitation causes adverse impacts on people, animals, or vegetation. Although droughts are often discussed in meteorological terms, such as the amount of precipitation deficit over various time periods, it is the impacts that define the drought. A short-term period of very low precipitation, for example, can deplete soil moisture and affect its ability to initiate or sustain crop growth, thus resulting in an agricultural drought. However, short-term precipitation deficits are unlikely to cause adverse effects on surface and groundwater resources. The occurrence of a hydrologic drought, producing uncommonly low levels of streamflow, shallow groundwater, and/or reservoir storage, typically requires a prolonged period of precipitation deficit. Although low streamflow levels can occur following four to six months of low precipitation, the worst hydrologic droughts typically have occurred when precipitation has been below normal for several years in the eastern portion of the Midwest and as many as five to seven years in the western portion of the Midwest. Many types of water supply reservoirs must be designed to have sufficient carry-over storage to continue to provide for water use needs in the latter years of a multi-year drought period.

A water supply drought is a hydrologic drought that specifically causes threats to or concerns regarding the availability of water for human water supply systems. The susceptibility of a particular water supply system to drought impacts is not just a function of the lack of precipitation, but also is influenced by the type and size of water supply sources in the system and the characteristics of the watersheds and/or aquifers that feed those resources. Because of differences in watershed size, for example, it is possible for one community's reservoir to provide a fully adequate supply during a major drought, whereas a similarly sized reservoir at a nearby community would be vulnerable to shortages during a less severe drought.

Community water supply systems have typically developed supply sources that are capable of meeting water needs during moderate droughts, such as may occur on average every 10 to 20 years, but for some communities the adequacy of their system during major droughts may still be in question. Any observed vulnerability under a moderate drought condition, caused by either diminished capacity of the existing sources or an increase in water use, is a sign that the system may not have adequate resources during a major drought. Most community systems desire to provide an undiminished supply of water during all major droughts. In many cases, the *drought of record*—that being the worst drought for which regional hydrologic records are available—is used as the benchmark for determining adequacy of supply. In other cases, a hypothetical drought having an average recurrence frequency of 40, 50, or 100 years, as determined through analysis of the hydrologic records, may be used as the benchmark. Lessons learned from the 2007 drought in the Southeastern United States suggest that communities may want to examine the adequacy of their system for drought scenarios that are worse than the historical drought of record.

For most states, there is no predefined drought threshold that communities are required to surpass in developing their water supply sources. For very small communities, it may not be economically feasible to develop alternative water supplies capable of meeting water use during a drought of record. In these cases, hauling of water by tanker trucks from another water supply in the vicinity may be a feasible short-term option. Other small communities might have plans to interconnect with a nearby larger water supply system when they encounter potential shortages during a major drought. For communities where there are no existing alternative supply options, however, especially for larger communities, it is essential that existing resources are capable of meeting water needs during a major drought. Evaluating the adequacy of the current system is the first step in determining what plans and actions are needed.

Geographic Differences in Precipitation Droughts

Figure 2 shows a map of average annual precipitation across the Midwest. Precipitation is the most influential climate factor affecting the availability of surface water in the Midwest, although evapotranspirative losses (evaporation and plant transpiration), as influenced by air temperature, wind, humidity, and solar radiation, can also affect surface water supply availability. Figure 3 shows the annual potential evapotranspiration across the Midwest (the rate that would occur if the water supply from the ground surface was unlimited), with much higher potential water losses in the southern and western states within the region. For the western states, the actual amount of evapotranspiration is substantially less than the potential rate because of a limited availability of water. Even though the average precipitation for much of Kansas is not much different from that of the northern Midwest (Minnesota, Wisconsin, and Michigan), the climate in Kansas is considerably drier as a result of the higher evapotranspiration demands, thus

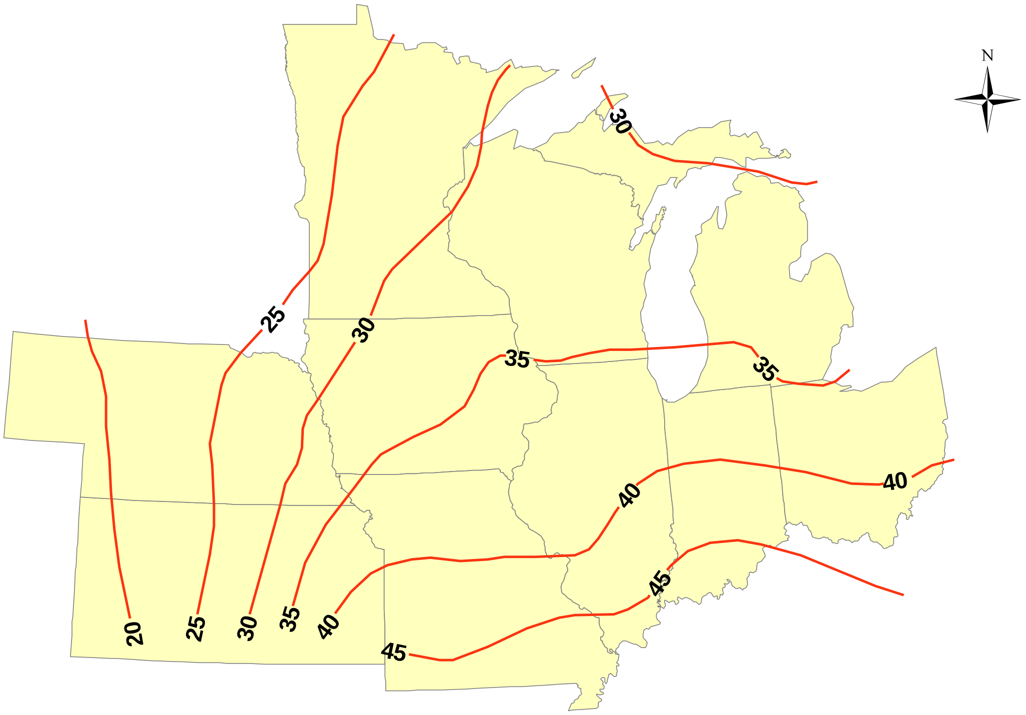

Figure 2. Normal annual precipitation (inches) based on the 1971–2000 average (from Winstanley et al., 2006)

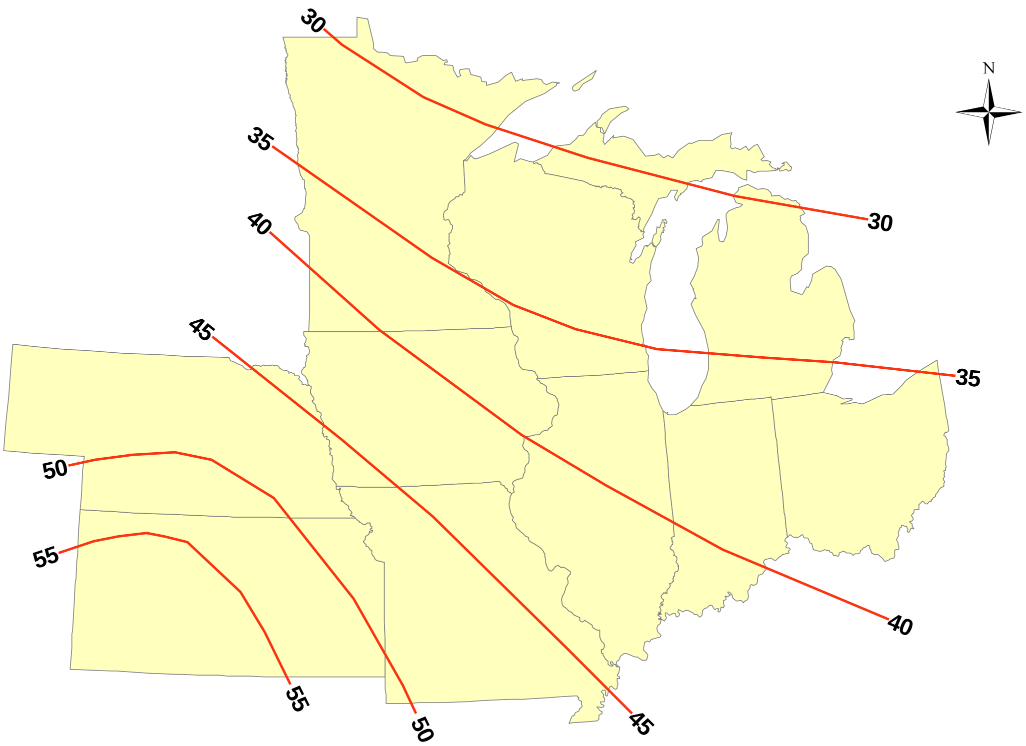

Figure 3. Average annual potential evapotranspiration (inches) in the Midwest based on estimates from the Midwestern Regional Climate Center using climate data collected at regional airports. Extrapolation to the western portions of Nebraska and Kansas follow Farnsworth et al. (1982).

reducing the overall availability of water for surface and groundwater resources. In Ohio, Michigan, and Wisconsin, 65 to 67 percent of all precipitation is returned to the atmosphere by way of evapotranspiration, with most of the remaining portion (one-third) eventually becoming streamflow. In Kansas, Nebraska, and western Minnesota, however, more than 80 percent of precipitation is returned to the atmosphere, leaving less than 20 percent for streamflow. These regional differences are reflected in the variations of the average annual streamflow (total runoff) for the Midwest, shown in Figure 4.

Drought tends to accentuate regional differences in water availability throughout the Midwest. Although all Midwest regions experience drought periods, the regions that typically have a drier average climate are also more likely to experience droughts that are longer and produce a greater deficit in precipitation. Table 1 compares the precipitation deficit, expressed as a percentage of deviation from normal, during the worst precipitation drought on record for each of the Midwestern states. It shows that the states west of the Mississippi River have experienced the greatest percentage of precipitation deficits. Kansas is the Midwestern state most likely to experience a significant precipitation deficit, whereas Michigan is the least likely.

Prolonged precipitation droughts are never uniformly dry. During the driest periods in the drought, many consecutive weeks will have little or no precipitation. But dry periods will typically be interspersed with some wet periods when weekly or monthly precipitation may be close to or above normal. The sequence of dry and wet periods is different for each drought.

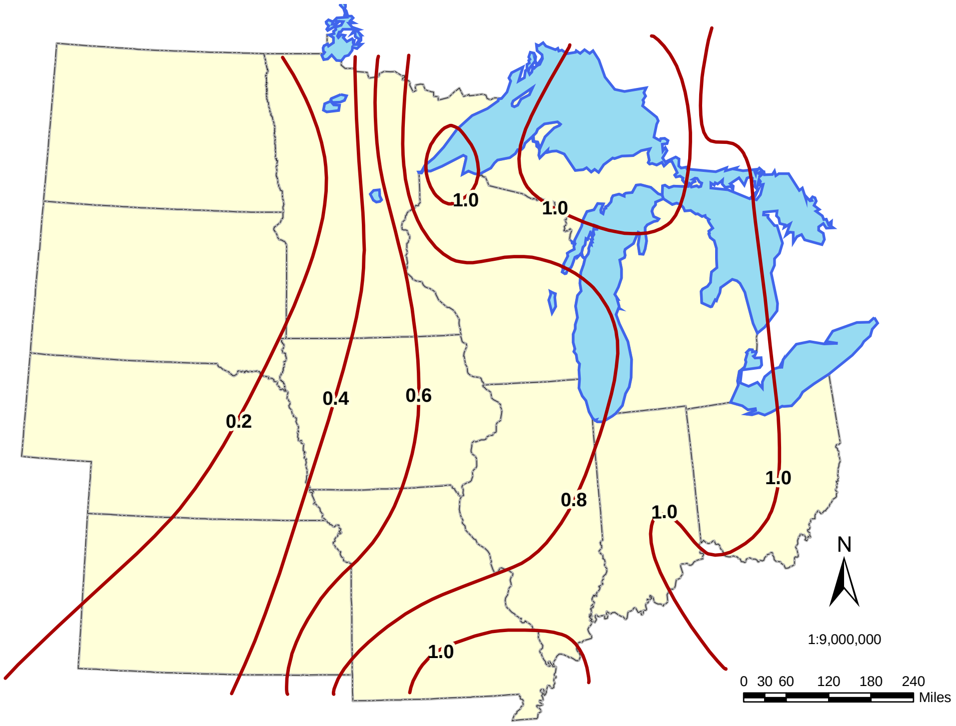

Figure 4. Long-term mean flow for streams in the Midwest, expressed in cfs per square mile (from Winstanley et al., 2006)

Table 1. Precipitation Deficits During the Drought of Record, Expressed as a Percent of Normal (1971-2000) Precipitation

	Drought duration				
	1-year	*2-year*	*3-year*	*4-year*	*5-year*
Kansas	-51	-39	-34	-31	-30
Nebraska	-48	-36	-28	-27	-26
Missouri	-47	-34	-28	-26	-24
Iowa	-48	-35	-26	-24	-21
Minnesota	-47	-30	-25	-23	-21
Illinois	-46	-32	-24	-19	-17
Indiana	-43	-29	-22	-17	-16
Ohio	-43	-28	-22	-19	-17
Wisconsin	-41	-29	-22	-19	-17
Michigan	-38	-29	-21	-17	-15

Source of data: Composite precipitation data for Midwestern climate divisions obtained from the Midwestern Regional Climate Center (mrcc.sws.uiuc.edu).

For this reason, a drought that produces the worst 9-month precipitation deficit in a region may not necessarily be the same drought that produces the worst 6- or 12-month precipitation deficit, for example. Precipitation also shows considerable geographic variation in a drought. A storm event in the middle of a drought may produce a substantial amount of rain in some locales, but entirely miss nearby regions.

Because of the precipitation variability inherent in droughts, comparing different historical drought periods in many ways can be similar to a horse race. During various stages within most races, the lead may be held by different horses. In some races, a horse may bolt out to an early lead, only to fade later in the race. In other races, the strongest horse may lead from start to finish, and run away from the field. Such is the case with comparing droughts. All droughts contain significant short-term precipitation deficits, but there are comparatively few historical droughts in which that deficit continues to build beyond the first year. In many geographic locations in the Midwest, such as Illinois and Indiana, several different historical droughts may be considered the drought of record depending on which drought duration is being analyzed. In other locations, such as in Kansas and much of Missouri, one specific drought period (1952–1958) dominates all records regardless of duration.

Figures 5–8 identify the precipitation droughts of record for climate divisions across the Midwest for four different drought durations: 12, 24, 36, and 60 months. Note that a large number of different drought periods qualify as the 12-month drought of record depending on which location in the Midwest is being considered. However, as the duration of the drought increases to five years, only a few droughts stand out as the worst on record.

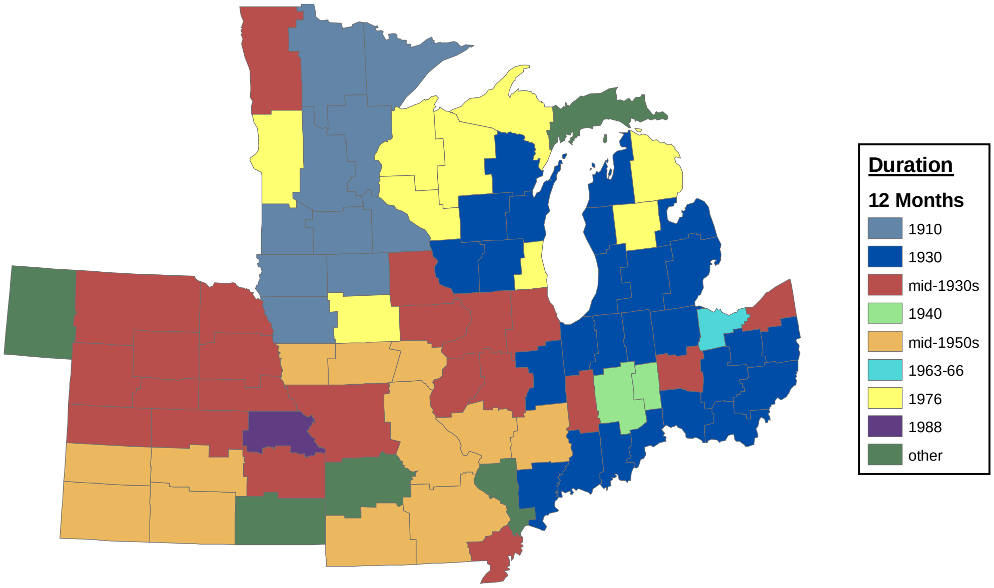

Figure 5. Drought that had the greatest precipitation deficit over a period of 12 months

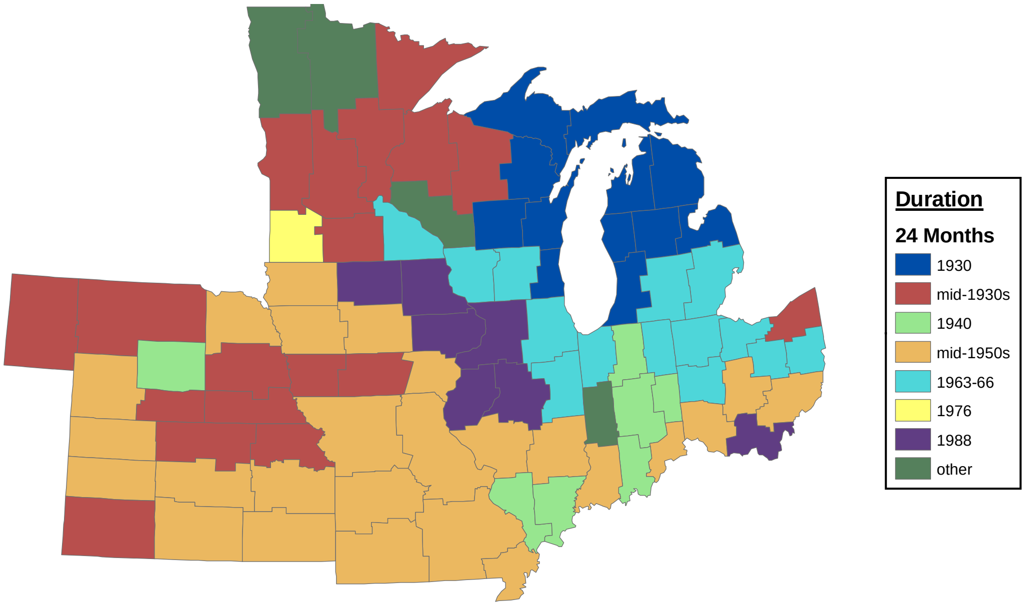

Figure 6. Drought that had the greatest precipitation deficit over a period of 24 months

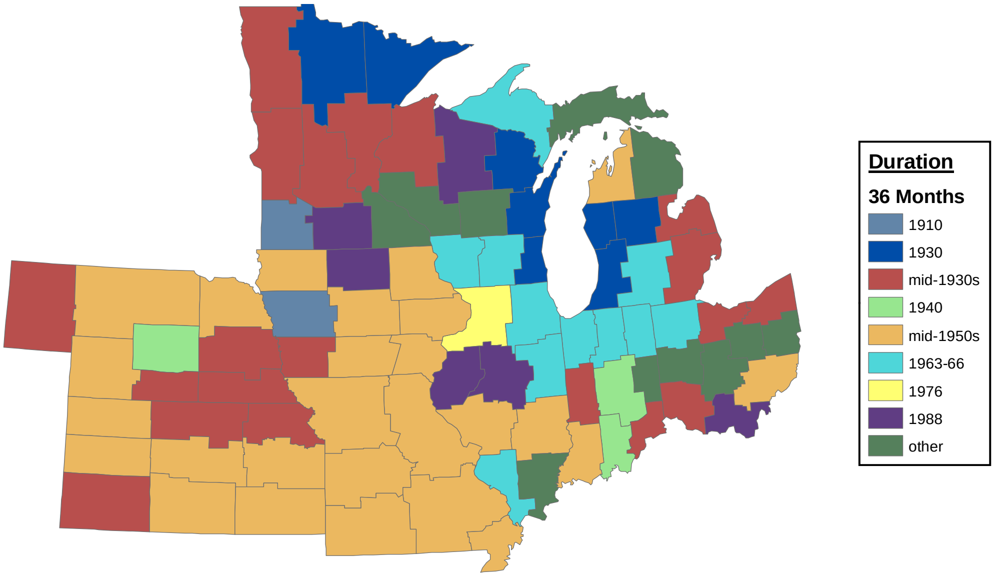

Figure 7. Drought that had the greatest precipitation deficit over a period of 36 months

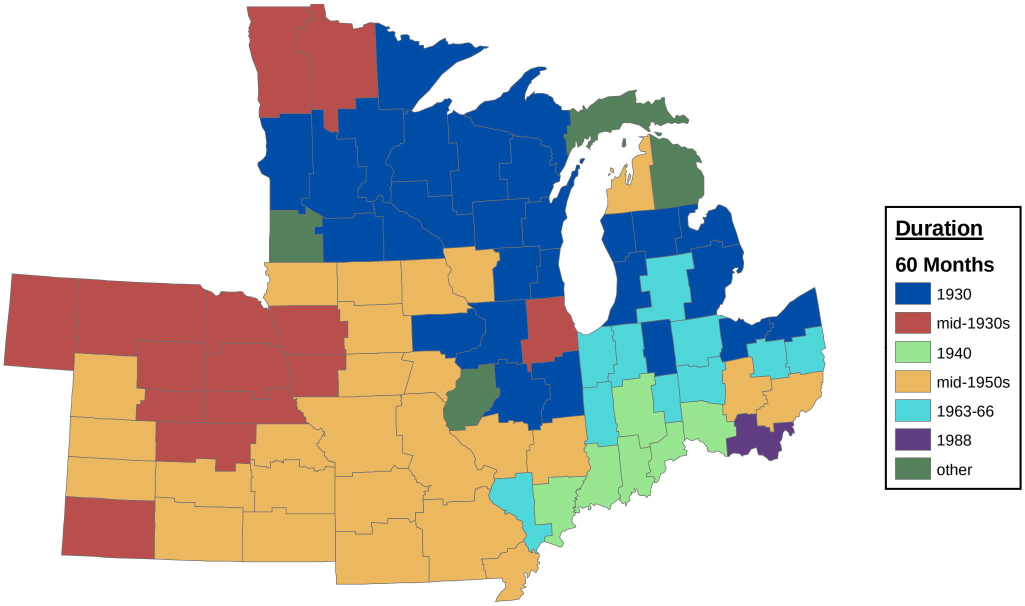

Figure 8. Drought that had the greatest precipitation deficit over a period of 60 months

Palmer Drought Index

The most standard measure of drought impacts using only climate (precipitation and temperature) data is the Palmer Drought Index. This index uses a generic monthly water balance assessment of soil moisture, estimating evapotranspirative losses from the soil as well as water added through precipitation. Based on the relative amount of available moisture for a given location, a monthly numerical index is created, ranging from extreme drought (-4) to extremely moist (+4), with zero as the long-term normal condition. Monthly estimates of the Palmer Drought Index using historical climate data from 1900 to 2008 can be obtained at: http://www.ncdc.noaa.gov/oa/climate/research/drought/palmer-maps/. The relative severity and duration of past droughts for any region of the Midwest can be compared using these historic index values.

An examination of the historic Palmer Index identifies two great drought periods within the past 100 years: the 1930–1936 and 1952–1958 periods. For most locations in the Midwest, the 1930–1936 period actually contains three distinct drought periods (1929–1930, 1933–1934, and 1936), each separated by a recovery period but typically viewed collectively. In contrast, the 1950s drought was more continuously dry, marked by its persistence. As also shown in Figures 5–8, a number of other drought periods, such as 1900–1901, 1910, 1913–1915, 1939–1941, 1962–1964, 1976–1977, 1987–1989, 1999–2000, and 2005 that, according to the Palmer Drought Index, have produced extreme drought conditions in certain regions of the Midwest.

Precipitation records alone rarely accurately identify the relative impact of hydrologic droughts. Long-term precipitation and streamflow data from 30 different locations across the Midwest were examined to determine the correspondence between low precipitation and low streamflow. When looking at longer drought periods, such as two years or longer, the hydrologic drought of record corresponded with the precipitation drought of record in only about 50 percent of cases examined. The linkage between the occurrence of precipitation and hydrologic drought was stronger in regions such as Kansas and Missouri, where the record drought of the 1950s was noticeably more severe than for other droughts, and weaker elsewhere.

Precipitation records are also clearly not able to rank hydrologic drought events beyond the most severe events or estimate streamflow amounts during drought. Although streamflow amount is most directly related to precipitation amount, other factors affect flow amount, such as: 1) hydrogeology of the watershed; 2) seasonal timing of precipitation deficit; and 3) watershed conditions leading into the drought period.

Phases of a Water Supply Drought

Although water supply droughts and subsequent system responses vary in timing, they all pass through a specific series of phases:

1. *Initial Precipitation Deficit—Drying out*—This is the initial period during which precipitation is below normal and soils begin to dry. Although it is possible that agricultural impacts may become noticeable during this phase, streamflow and reservoir levels are still in the range of normal conditions. The precipitation deficit may occur for four months or longer before hydrologic impacts are apparent. If this first drying out phase occurs in fall or winter, there may be no agricultural impacts and the onset of hydrologic impacts may be less pronounced.
2. *Hydrologic Deficit—Decline in water levels and observation*—Streamflow and reservoir levels have fallen below normal, but at this point may not be noticeably different from low levels that might be experienced once every three to five years. Water supply system operators typically monitor the conditions but are not yet concerned about any threat to the water supply. Even as water levels decline further, there may still be a reluctance to impose restrictions as the condition may likely become a false alarm (the crying wolf syndrome). Summer water use during this phase typically remains very high. Depending on the system and drought characteristics, this phase may last well into the full drought duration.
3. *Hydrologic Deficit—Response*—This stage typically must be reached before a drought condition is considered a “water supply drought.” A threat to water supplies is now apparent, even if a critical condition is not imminent. Communities begin to conserve water, usually beginning with voluntary restrictions of outdoor water use and enforcing mandatory restrictions as conditions worsen. For communities with direct stream withdrawals, these restrictions may be short-term as needed to avoid low water levels in the stream. For communities with reservoir systems, restrictions are longer in term, aimed at reducing overall water use for the duration of the drought. At some point as water levels continue to decline, emergency measures may be taken to obtain supplemental water sources or more greatly restrict certain domestic, commercial, and industrial water users. If conditions progress to a very severe drought condition, actual water shortages may occur.

4. *Recovery*—Drought recovery begins after minimum levels in the stream and/or reservoirs have been reached. There is usually a lag between when precipitation starts returning to normal and when water supply sources begin to show recovery, similar to the way that the onset of the hydrologic deficit lagged behind the precipitation deficit. In some cases, the recovery to water supply systems may be swift, provided by a "drought-breaking" series of precipitation events. In other cases, particularly for water supply reservoirs, the recovery (refill) may take longer than the period during which the water supplies were in decline.

The following analysis of hydrologic drought and its impact on community water supplies focuses almost entirely on the second and third drought phases described above.

Geographic Differences in Hydrologic Impacts

Streamflow during Major Historical Droughts

The occurrence and severity of water supply droughts is ordinarily identified using available long-term hydrologic records. For most situations, the only such data available are those provided by streamgage records maintained by the U.S. Geological Survey (USGS). The amount of streamflow passing by each gage is most commonly expressed in units of cubic feet per second (cfs). The daily amount of accumulated flow is often expressed as an average flow rate over the entire day (cfs-day). The cumulative flow amount over the course of a longer drought period is often converted to a volumetric measure such as acre-feet or millions of gallons. When comparing flow amounts from different watersheds, it is useful to express the cumulative flow in *inches of runoff*. One inch of runoff represents the same water volume created if the entire watershed area upstream of the gage was inundated by an inch of water.

Table 2 and Figure 9 identify 27 USGS streamflow gages selected to provide representative examples of drought flows in the Midwest. The gaging records were selected to achieve broad coverage over the southern portion of the Midwest where surface water supplies are most common, with emphasis on long flow records from locations that are not noticeably affected by human-induced factors such as reservoirs, flow diversions, or large water uses. The selection of gages that are relatively unaffected by human activities is based partly, but not entirely, on the Hydro-Climatic Data Network (HCDN), established by Slack and Landwehr (1994). Additional effort was made to select gages on comparatively smaller watersheds of the type that might be used to evaluate water supplies for small communities. It is noted that many small community water supply systems are located on streams much smaller than those presented in Table 2, with watershed sizes less than 30 square miles. However, long-term flow records on small streams such as these are rarely available.

Table 3 lists the four lowest minimum one-day flow amounts and the four lowest cumulative flow quantities observed over various drought durations at the selected streamgages. There is a clear increasing trend particularly in the cumulative flow quantities (or drought flows) as gage locations move from west to east. For example, during the worst drought of record for Cedar Creek in Kansas (the most western site listed in Table 3), the lowest 12 months of streamflow produced a total volume equivalent to only 0.07 inches of runoff.

Table 2. Selected Long-Term USGS Streamgage Records

	USGS gage number	*Location description*	*Drainage area (sq mi)*	*Period of record*	*Mean flow (cfs)*
1	07180500	Cedar Creek near Cedar Point, KS	110	1938-2007	57.4
2	07167500	Otter Creek at Climax, KS	129	1946-2007	86.4
3	06608500	Soldier Creek at Pisgah, IA	407	1940-2007	152
4	06889500	Soldier Creek near Topeka, KS	290	1929-1932, 1935-2007	156
5	06911500	Salt Creek near Lyndon, KS	111	1939-2007	66.0
6	06819500	One Hundred and Two River at Maryville, MO	515	1932-1990, 2001-2007	232
7	05470000	South Skunk River near Ames, IA	315	1920-1927, 1933-2007	176
8	06900000	Medicine Creek near Galt, MO	225	1922-1975, 1978-1990	145
9	06908000	Blackwater River at Blue Lick, MO	1120	1922-1933, 1938-1985, 1994-2007	795
10	05504800	South Fork Salt River above Santa Fe, MO	233	1939-2007	190
11	05455500	English River at Kalona, IA	574	1940-2007	385
12	05495000	Fox River at Wayland, MO	400	1922-2007	264
13	05512500	Bay Creek at Pittsfield, IL	39.4	1940-2007	27.2
14	05466000	Edwards River near Orion, IL	155	1941-2007	113
15	05588000	Indian Creek at Wanda, IL	36.7	1940-2007	26.4
16	05572000	Sangamon River at Monticello, IL	550	1914-2007	418
17	03380500	Skillet Fork at Wayne City, IL	464	1914-1921, 1928-2007	412
18	03346000	North Fork Embarras River near Oblong, IL	318	1941-2007	272
19	03339500	Sugar Creek at Crawfordsville, IN	509	1938-2007	497
20	03303000	Blue River near White Cloud, IN	476	1931-2007	666
21	03363500	Flatrock River at St. Paul, IN	303	1931-2007	326
22	03324000	Little River near Huntington, IN	263	1944-2007	244
23	03272000	Twin Creek near Germantown, OH	275	1914-1923, 1927-2007	273
24	03237500	Ohio Brush Creek near West Union, OH	387	1927-1935, 1941-2007	458
25	04196500	Sandusky River near Upper Sandusky, OH	256	1921-1935, 1938-1981, 2000-2007	256
26	03144000	Wakatomika Creek near Frazeysburg, OH	140	1937-2007	155
27	04213000	Conneaut Creek at Conneaut, OH	175	1922-1935, 1950-2007	277

Table 3. Watershed Runoff (Cumulative Flow) during Severe Droughts

Cedar Creek near Cedar Point, KS		Watershed runoff in inches (drought year)							
	1-day Low flow (cfs)	Drought duration in months							
		6	9	12	18	24	30	42	60
Drought of record	0.00	0.00	0.00	0.07	0.11	0.29	0.64	0.75	3.70
		(1956)	(1956)	(1956)	(1954)	(1954)	(1954)	(1954)	(1954)
2nd worst drought	0.00	0.00	0.04	0.10	0.43	4.80	4.86	14.35	22.81
		(1954)	(1954)	(1954)	(1956)	(1963)	(1956)	(1976)	(1988)
3rd worst drought	0.00	0.01	0.07	0.44	1.64	4.90	7.39	14.78	23.34
		(1953)	(1953)	(1955)	(1991)	(1956)	(1940)	(2000)	(2000)
4th worst drought	0.00	0.04	0.28	0.62	1.66	5.12	8.16	14.78	25.57
		(1939)	(1963)	(1963)	(2006)	(1988)	(1966)	(1966)	(1976)

Otter Creek at Climax, KS		Watershed runoff in inches (drought year)							
	1-day Low flow (cfs)	Drought duration in months							
		6	9	12	18	24	30	42	60
Drought of record	0.00	0.00	0.00	0.04	0.06	0.33	0.34	0.87	2.44
		(1953)	(1953)	(1963)	(1954)	(1954)	(1954)	(1954)	(1954)
2nd worst drought	0.00	0.00	0.00	0.04	0.12	0.62	3.31	11.17	17.51
		(1954)	(1956)	(1954)	(1956)	(1956)	(1963)	(1991)	(1963)
3rd worst drought	0.00	0.00	0.00	0.10	0.27	1.77	4.88	11.38	22.19
		(1956)	(1963)	(1956)	(1963)	(1963)	(1980)	(1980)	(1988)
4th worst drought	0.00	0.00	0.00	0.26	0.62	2.30	7.11	14.40	26.45
		(1963)	(1980)	(1991)	(1991)	(1991)	(1991)	(1966)	(1980)

Soldier Creek at Pisgah, IA		Watershed runoff in inches (drought year)							
	1-day Low flow (cfs)	Drought duration in months							
		6	9	12	18	24	30	42	60
Drought of record	2.00	0.19	0.37	0.71	1.11	1.56	2.87	4.62	8.42
	(1944)	(1956)	(1957)	(1956)	(1956)	(1956)	(1956)	(1956)	(1956)
2nd worst drought	2.50	0.20	0.40	0.75	1.26	2.56	3.65	8.98	15.08
	(1958)	(1958)	(1956)	(1957)	(1981)	(1981)	(1981)	(1976)	(1976)
3rd worst drought	2.80	0.22	0.53	0.86	2.19	3.39	5.03	9.19	15.34
	(1957)	(1957)	(1976)	(1981)	(1976)	(1976)	(1976)	(1940)	(1967)
4th worst drought	3.30	0.24	0.59	0.97	2.35	3.86	6.58	9.43	18.57
	(1956)	(1976)	(1981)	(1976)	(1958)	(1958)	(1967)	(1967)	(1940)

Table 3. Continued

Soldier Creek near Topeka, KS

	1-day Low flow (cfs)	Watershed runoff in inches (drought year) Drought duration in months 6	9	12	18	24	30	42	60
Drought of record	0.00	0.00 (1953)	0.00 (1953)	0.00 (1953)	0.04 (1956)	0.15 (1956)	0.28 (1956)	0.94 (1956)	2.18 (1956)
2nd worst drought	0.00	0.00 (1955)	0.00 (1955)	0.04 (1956)	0.11 (1953)	0.16 (1953)	4.12 (1953)	13.15 (1991)	20.06 (1963)
3rd worst drought	0.00	0.00 (1956)	0.00 (1966)	0.16 (1952)	0.55 (1991)	3.24 (1991)	5.00 (1963)	13.81 (1966)	20.99 (1988)
4th worst drought	0.00	0.00 (1966)	0.02 (1956)	0.21 (1988)	0.88 (1954)	3.47 (1964)	5.31 (1966)	14.64 (1980)	24.71 (1976)

Salt Creek near Lyndon, KS

	1-day Low flow (cfs)	Watershed runoff in inches (drought year) Drought duration in months 6	9	12	18	24	30	42	60
Drought of record	0.00	0.00 (1956)	0.00 (1956)	0.00 (1956)	0.04 (1956)	0.15 (1956)	0.28 (1956)	0.94 (1956)	2.18 (1956)
2nd worst drought	0.00	0.00 (1953)	0.00 (1953)	0.04 (1953)	0.11 (1953)	0.16 (1953)	4.12 (1953)	13.15 (1991)	20.06 (1964)
3rd worst drought	0.00	0.00 (1955)	0.00 (1955)	0.16 (1952)	0.55 (1991)	3.24 (1991)	5.00 (1964)	13.81 (1966)	20.99 (1988)
4th worst drought	0.00	0.00 (1956)	0.02 (1956)	0.21 (1988)	0.88 (1954)	3.47 (1964)	5.31 (1966)	14.64 (1980)	24.71 (1976)

One Hundred and Two River at Maryville, MO

	1-day Low flow (cfs)	Watershed runoff in inches (drought year) Drought duration in months 6	9	12	18	24	30	42	60
Drought of record	0.00	0.01 (1988)	0.04 (1956)	0.11 (1988)	0.84 (1988)	1.63 (1956)	2.61 (2003)	4.81 (1956)	9.40 (1956)
2nd worst drought	0.00	0.02 (1956)	0.05 (1988)	0.13 (1956)	1.03 (1956)	2.29 (2003)	3.72 (1956)	6.82 (1948)	11.52 (1938)
3rd worst drought	0.00	0.03 (1940)	0.17 (1938)	0.42 (1977)	1.19 (1968)	2.92 (1934)	4.11 (1934)	9.25 (1948)	15.21 (1968)
4th worst drought	0.00	0.04 (1938)	0.18 (1954)	0.49 (1934)	1.20 (2003)	3.16 (1980)	5.02 (1940)	9.79 (1968)	20.41 (2003)

Table 3. Continued

South Skunk River near Ames, IA

	1-day	Watershed runoff in inches (drought year)							
		Drought duration in months							
	Low flow (cfs)	6	9	12	18	24	30	42	60
Drought of record	0.00	0.00	0.07	0.14	0.35	1.62	3.44	8.11	15.15
		(1956)	(1956)	(1956)	(1956)	(1956)	(1956)	(1956)	(1940)
2nd worst drought	0.00	0.01	0.17	0.19	0.89	2.16	5.27	10.22	15.94
		(1954)	(1976)	(1976)	(1988)	(1988)	(1988)	(1940)	(1956)
3rd worst drought	0.00	0.01	0.18	0.47	1.02	3.37	6.35	12.50	22.22
		(1976)	(1954)	(1934)	(1934)	(1934)	(1940)	(1934)	](1925)
4th worst drought	0.00	0.02	0.20	0.50	1.06	3.60	6.59	12.57	24.21
		(1940)	(1967)	(1988)	(1999)	(1925)	(1934)	(1948)	(1967)

Medicine Creek near Galt, MO

	1-day	Watershed runoff in inches (drought year)							
		Drought duration in months							
	Low flow (cfs)	6	9	12	18	24	30	42	60
Drought of record	0.00	0.04	0.10	0.39	0.73	2.23	2.40	5.64	9.24
		(1954)	(1956)	(1988)	(1938)	(1956)	(1956)	(1956)	(1956)
2nd worst drought	0.00	0.06	0.11	0.56	1.12	3.47	6.12	9.12	15.95
		(1956)	(1954)	(1934)	(1956)	(1938)	(1938)	(1938)	(1938)
3rd worst drought	0.00	0.06	0.20	0.62	1.83	3.87	7.44	17.47	27.69
		(1957)	(1938)	(1956)	(1988)	(1988)	(1954)	(1964)	(1964)
4th worst drought	0.00	0.06	0.25	0.63	2.37	4.46	8.20	18.32	32.62
		(1940)	(1988)	(1938)	(1954)	(1934)	(1988)	(1940)	(1930)

Blackwater River at Blue Lick, MO

	1-day	Watershed runoff in inches (drought year)							
		Drought duration in months							
	Low flow (cfs)	6	9	12	18	24	30	42	60
Drought of record	0.00	0.01	0.08	0.61	0.81	2.22	4.24	6.72	10.36
	(1980)	(1956)	(1954)	(1930)	(1956)	(1956)	(1956)	(1956)	(1956)
2nd worst drought	0.10	0.03	0.16	0.62	1.73	2.72	5.06	9.90	22.91
	(1956)	(1954)	(1956)	(1956)	(1954)	(1963)	(1954)	(1930)	(1980)
3rd worst drought	0.12	0.03	0.17	0.64	1.74	3.62	6.19	14.22	29.11
	(1976)	(1963)	(1963)	(1954)	(1930)	(1930)	(1930)	(1980)	(1963)
4th worst drought	0.20	0.08	0.23	0.73	1.83	3.63	6.27	14.58	30.07
	(1954)	(1940)	(1976)	(1980)	(1963)	(1980)	(1963)	(1940)	(1988)

Table 3. Continued

South Fork Salt River above Santa Fe, MO

		Watershed runoff in inches (drought year)							
		Drought duration in months							
	1-day Low flow (cfs)	6	9	12	18	24	30	42	60
Drought of record	0.00	0.03 (1954)	0.14 (1954)	0.49 (1954)	1.07 (1963)	1.98 (1963)	4.93 (1954)	11.04 (1954)	18.29 (1954)
2nd worst drought	0.00	0.06 (1963)	0.30 (1963)	0.71 (1963)	1.48 (1954)	3.50 (1980)	5.09 (1963)	14.12 (1963)	19.60 (1966)
3rd worst drought	0.00	0.06 (1966)	0.32 (1980)	1.10 (2005)	2.64 (1980)	3.80 (1954)	7.46 (1988)	14.32 (1988)	29.76 (1988)
4th worst drought	0.00	0.08 (1956)	0.34 (1999)	1.14 (1988)	3.55 (988)	5.62 (1988)	12.02 (1966)	26.75 (1966)	36.01 (1980)

English River at Kalona, IA

		Watershed runoff in inches (drought year)							
		Drought duration in months							
	1-day Low flow (cfs)	6	9	12	18	24	30	42	60
Drought of record	0.66 (1976)	0.04 (1956)	0.17 (1956)	0.36 (1956)	1.24 (1956)	1.94 (1956)	2.74 (1956)	5.58 (1956)	9.11 (1956)
2nd worst drought	0.80 (1977)	0.07 (1954)	0.22 (1954)	0.69 (1976)	1.80 (1954)	3.31 (1988)	6.46 (1988)	14.45 (1940)	30.88 (1999)
3rd worst drought	1.10 (1955)	0.14 (1976)	0.36 (1988)	0.74 (1988)	1.96 (1988)	4.49 (1940)	7.81 (1963)	14.51 (1988)	32.18 (1988)
4th worst drought	1.20 (1956)	0.14 (1950)	0.46 (1976)	0.75 (1954)	2.88 (1940)	5.41 (1980)	7.92 (1967)	18.63 (1953)	33.86 (1940)

Fox River at Wayland, MO

		Watershed runoff in inches (drought year)							
		Drought duration in months							
	1-day Low flow (cfs)	6	9	12	18	24	30	42	60
Drought of record	0.00	0.01 (1954)	0.13 (1963)	0.26 (1956)	0.60 (1956)	1.39 (1988)	3.55 (1988)	8.22 (1954)	14.51 (1954)
2nd worst drought	0.00	0.01 (1956)	0.13 (1988)	0.35 (1988)	0.63 (1988)	1.93 (1956)	3.68 (1956)	8.70 (1988)	18.38 (1963)
3rd worst drought	0.00	0.03 (1940)	0.16 (1954)	0.83 (1963)	1.89 (1999)	3.83 (1940)	5.77 (1963)	9.99 (1940)	19.77 (1940)
4th worst drought	0.00	0.05 (1988)	0.20 (1956)	0.92 (1934)	2.07 (1940)	4.21 (1963)	7.26 (1940)	13.59 (1963)	22.55 (1988)

Table 3. Continued

Bay Creek at Pittsfield, IL

		Watershed runoff in inches (drought year) Drought duration in months							
	1-day Low flow (cfs)	6	9	12	18	24	30	42	60
Drought of record	0.00	0.04	0.11	0.60	1.44	2.72	5.77	10.70	16.95
		(1954)	(1954)	(1954)	(1940)	(1954)	(1954)	(1954)	(1954)
2nd worst drought	0.00	0.12	0.35	0.70	1.81	3.90	7.12	13.91	24.39
		(1999)	(1988)	(1988)	(1956)	(1940)	(1988)	(1988)	(1988)
3rd worst drought	0.00	0.14	0.38	0.95	1.84	4.96	10.90	19.08	30.94
		(1950)	(1999)	(1940)	(1954)	(1988)	(1963)	(1948)	(1948)
4th worst drought	0.00	0.18	0.56	1.26	1.98	5.51	12.11	20.32	35.80
		(1968)	(1950)	(1999)	(1988)	(1956)	(1956)	(1958)	(1976)

Edwards River near Orion, IL

		Watershed runoff in inches (drought year) Drought duration in months							
	1-day Low flow (cfs)	6	9	12	18	24	30	42	60
Drought of record	0.40	0.13	0.42	0.93	3.07	5.98	7.19	14.89	24.73
	(1976)	(1956)	(1956)	(1956)	(1956)	(1956)	(1956)	(1956)	(1956)
2nd worst drought	0.40	0.16	0.71	1.03	3.67	6.85	7.91	19.11	28.53
	(1977)	(1954)	(1954)	(1976)	(1954)	(1988)	(1988)	(1940)	(1999)
3rd worst drought	1.20	0.25	0.71	1.40	4.48	8.65	12.69	21.96	35.17
	(1956)	(1976)	(1988)	(1988)	(1988)	(1940)	(1963)	(1988)	(1988)
4th worst drought	1.20	0.32	0.96	2.24	5.09	8.72	13.48	23.61	36.44
	(1955)	(1950)	(1976)	(1954)	(1940)	(1980)	(1967)	(1954)	(1940)

Indian Creek at Wanda, IL

		Watershed runoff in inches (drought year) Drought duration in months							
	1-day Low flow (cfs)	6	9	12	18	24	30	42	60
Drought of record	0.00	0.00	0.01	0.15	1.56	3.09	3.68	5.76	17.16
		(1954)	(1954)	(1954)	(1954)	(1964)	(1964)	(1954)	(1954)
2nd worst drought	0.00	0.07	0.48	0.83	1.69	3.54	3.93	8.64	19.47
		(1960)	(1964)	(1956)	(1964)	(1954)	(1954)	(1964)	(1964)
3rd worst drought	0.00	0.08	0.50	1.07	2.09	3.96	7.02	18.03	32.66
		(1988)	(1956)	(1964)	(1956)	(1980)	(1980)	(1980)	(1988)
4th worst drought	0.00	0.13	0.50	1.61	2.60	6.69	10.61	19.15	38.19
		(1999)	(1999)	(1940)	(1980)	(1988)	(1976)	(1958)	(1980)

Table 3. Continued

Sangamon River at Monticello, IL

	1-day Low flow (cfs)	Watershed runoff in inches (drought year) Drought duration in months 6	9	12	18	24	30	42	60
Drought of record	0.00	0.07	0.25	0.84	2.10	5.12	6.41	11.04	23.65
	(1988)	(1914)	(1930)	(1930)	(1954)	(1954)	(1954)	(1954)	(1954)
2nd worst drought	0.30	0.09	0.34	1.51	2.54	6.25	6.59	17.27	25.61
	(1954)	(1930)	(1963)	(1934)	(1930)	(1930)	(1930)	(1930)	(1930)
3rd worst drought	0.40	0.11	0.48	1.68	3.23	6.62	10.77	18.54	30.25
	(1940)	(1954)	(1940)	(1954)	(1934)	(1940)	(1963)	(1988)	(1963)
4th worst drought	0.80	0.13	0.68	1.82	3.55	8.70	11.57	18.70	36.09
	(1953)	(1976)	(1976)	(1914)	(1940)	(1988)	(1999)	(1963)	(1914)

Skillet Fork at Wayne City, IL

	1-day Low flow (cfs)	Watershed runoff in inches (drought year) Drought duration in months 6	9	12	18	24	30	42	60
Drought of record	0.00	0.01	0.03	0.49	1.36	5.72	6.90	13.87	26.04
		(1954)	(1954)	(1954)	(1954)	(1954)	(1954)	(1954)	(1954)
2nd worst drought	0.00	0.03	0.14	0.76	2.56	6.05	7.92	19.18	30.38
		(1980)	(1934)	(1980)	(1980)	(1940)	(1940)	(1940)	(1963)
3rd worst drought	0.00	0.06	0.30	0.76	2.60	7.74	10.10	19.69	34.31
		(1999)	(1980)	(1934)	(1940)	(1980)	(1980)	(1963)	(1940)
4th worst drought	0.00	0.07	0.43	1.25	2.89	9.25	10.65	21.87	40.37
		(1940)	(1940)	(1940)	(1934)	(1976)	(1976)	(1976)	(1930)

North Fork Embarras River near Oblong, IL

	1-day Low flow (cfs)	Watershed runoff in inches (drought year) Drought duration in months 6	9	12	18	24	30	42	60
Drought of record	0.00	0.02	0.08	0.17	0.36	3.04	5.34	10.10	23.89
		(1954)	(1954)	(1954)	(1954)	(1954)	(1954)	(1954)	(1954)
2nd worst drought	0.00	0.05	0.28	1.79	2.61	5.72	7.36	11.86	25.81
		(1976)	(1976)	(1940)	(1976)	(1965)	(1965)	(1965)	(1965)
3rd worst drought	0.00	0.06	0.36	2.09	3.51	8.87	12.30	24.18	38.90
		(1964)	(1964)	(1976)	(1965)	(1976)	(1976)	(1976)	(1976)
4th worst drought	0.00	0.06	0.53	2.26	5.56	8.90	13.55	26.51	47.36
		(1960)	(1944)	(1965)	(1963)	(1963)	(1971)	(1988)	(1988)

Table 3. Continued

Sugar Creek at Crawfordsville, IN

	1-day	Watershed runoff in inches (drought year)							
		Drought duration in months							
	Low flow (cfs)	6	9	12	18	24	30	42	60
Drought of record	2.40	0.29	0.82	1.65	2.16	5.78	6.69	16.24	36.19
	(1941)	(1944)	(1940	(1940)	(1940)	(1940)	(1940)	(1940)	(1940)
2nd worst drought	3.10	0.29	0.84	2.36	5.08	11.28	13.68	26.43	45.29
	(1954)	(1940)	(1999)	(1999)	(1999)	(1999)	(1988)	(1963)	(1963)
3rd worst drought	4.00	0.30	1.05	3.20	5.94	11.62	15.38	28.36	50.74
	(1940)	(1999)	(1941)	(1976)	(1954)	(1988)	(1999)	(1954)	(1954)
4th worst drought	6.50	0.39	10.70	3.85	6.75	13.13	16.07	28.99	50.41
	(1966)	(1976)	(1963)	(1954)	(1965)	(1954)	(1965)	(1999)	(1999)

Blue River near White Cloud, IN

	1-day	Watershed runoff in inches (drought year)							
		Drought duration in months							
	Low flow (cfs)	6	9	12	18	24	30	42	60
Drought of record	9.60	0.50	1.63	3.29	5.32	14.54	17.34	32.31	55.71
	(1964)	(1943)	(1940)	(1940)	(1940)	(1940)	(1940)	(1934)	(1940)
2nd worst drought	10.00	0.61	1.94	3.63	6.18	16.32	18.67	32.66	62.61
	(1952)	(1954)	(1963)	(1954)	(1954)	(1954)	(1954)	(1940)	(1954)
3rd worst drought	11.00	0.63	2.09	4.59	6.30	17.79	22.01	36.97	65.70
	(1943)	(1940)	(1954)	(1934)	(1934)	(1963)	(1934)	(1954)	(1963)
4th worst drought	11.00	0.77	2.13	7.10	9.24	19.40	24.92	40.18	71.88
	(1992)	(1963)	(1934)	(1991)	(1991)	(1934)	(1988)	(1963)	(1934)

Flatrock River at St. Paul, IN

	1-day	Watershed runoff in inches (drought year)							
		Drought duration in months							
	Low flow (cfs)	6	9	12	18	24	30	42	60
Drought of record	0.60	0.26	0.56	1.47	3.67	9.70	12.84	23.09	43.74
	(1931)	(1934)	(1934)	(1934)	(1940)	(1934)	(1954)	(1954)	(1954)
2nd worst drought	0.70	0.27	0.94	1.82	4.36	10.65	12.93	27.47	46.26
	(1941)	(1999)	(1940)	(1940)	(1954)	(1940)	(1934)	(1940)	(1940)
3rd worst drought	0.71	0.29	1.09	3.34	5.56	11.71	13.53	28.45	49.28
	(1999)	(1944)	(1963)	(1930)	(1934)	(1954)	(1940)	(1934)	(1934)
4th worst drought	0.80	0.42	1.46	3.40	8.11	15.52	19.06	30.23	49.81
	(1963)	(1940)	(1954)	(1954)	(1966)	(1963)	(1976)	(1963)	(1963)

Table 3. Continued

Little River near Huntington, IN	1-day Low flow (cfs)	Watershed runoff in inches (drought year) Drought duration in months							
		6	9	12	18	24	30	42	60
Drought of record	1.10 (1946)	0.21 (1962)	0.65 (1962)	2.78 (1953)	3.72 (1963)	6.66 (1963)	10.06 (1963)	18.97 (1963)	31.31 (1963)
2nd worst drought	1.70 (1947)	0.29 (1946)	0.77 (1963)	3.00 (1966)	4.63 (1966)	10.45 (1954)	15.35 (1954)	28.03 (1954)	43.41 (1954)
3rd worst drought	1.90 (1944)	0.30 (1963)	0.95 (1954)	3.28 (1963)	5.53 (1954)	12.31 (1994)	18.40 (1946)	29.68 (1976)	48.04 (1976)
4th worst drought	2.50 (1962)	0.31 (1960)	1.04 (1976)	3.39 (1962)	8.29 (1946)	12.42 (1966)	19.45 (1966)	30.05 (1946)	54.51 (1968)

Twin Creek near Germantown, OH	1-day Low flow (cfs)	Watershed runoff in inches (drought year) Drought duration in months							
		6	9	12	18	24	30	42	60
Drought of record	2.00 (1941)	0.15 (1944)	0.61 (1963)	1.69 (1934)	2.55 (1954)	7.84 (1954)	8.85 (1954)	18.60 (1954)	36.42 (1954)
2nd worst drought	2.50 (1999)	0.22 (1954)	0.64 (1930)	1.79 (1930)	3.77 (1930)	8.13 (1934)	10.47 (1934)	23.05 (1934)	40.78 (1934)
3rd worst drought	2.60 (1963)	0.25 (1999)	0.65 (1954)	2.09 (1954)	4.54 (1934)	11.55 (1940)	14.50 (1940)	24.90 (1940)	42.11 (1940)
4th worst drought	2.80 (1964)	0.25 (1963)	0.95 (1934)	3.30 (1960)	5.71 (1940)	11.57 (1960)	15.12 (1930)	26.69 (1963)	43.39 (1963)

Ohio Brush Creek near West Union, OH	1-day Low flow (cfs)	Watershed runoff in inches (drought year) Drought duration in months							
		6	9	12	18	24	30	42	60
Drought of record	0.00 (1955)	0.11 (1930)	0.33 (1930)	2.92 (1930)	6.27 (1954)	12.26 (1954)	15.34 (1954)	30.33 (1954)	58.25 (1954)
2nd worst drought	0.10 (1953)	0.13 (1999)	0.84 (1954)	3.20 (1954)	7.66 (1969)	14.86 (1941)	21.91 (1969)	36.92 (1969)	61.40 (1988)
3rd worst drought	0.10 (1964)	0.17 (1988)	1.15 (1999)	4.82 (1941)	7.89 (1930)	17.51 (1988)	22.77 (1930)	37.01 (1988)	64.02 (1930)
4th worst drought	0.11 (1988)	0.19 (1944)	1.52 (1988)	5.69 (1969)	9.51 (1944)	17.64 (1930)	23.77 (1988)	37.92 (1930)	64.34 (1940)

Table 3. Concluded

Sandusky River near Upper Sandusky, OH	1-day Low flow (cfs)	Watershed runoff in inches (drought year) Drought duration in months							
		6	9	12	18	24	30	42	60
Drought of record	0.60	0.16	0.47	2.33	4.02	8.42	10.85	20.40	38.62
	(1955)	(1963)	(1934)	(1934)	(1934)	(1934)	(1953)	(1953)	(1953)
2nd worst drought	0.60	0.17	0.70	3.17	5.16	10.08	13.36	26.26	41.58
	(1963)	(1934)	(1963)	(1930)	(1953)	(1953)	(1934)	(1934)	(1934)
3rd worst drought	1.00	0.28	0.96	3.18	6.72	11.41	17.02	274.41	44.86
	(1934)	(1953)	(1930)	(1953)	(1944)	(1963)	(1940)	(1940)	(1963)
4th worst drought	1.00	0.28	1.06	4.27	7.26	12.10	18.00	29.50	50.05
	(1939)	(1944)	(1940)	(1940)	(1940)	(1965)	(1963)	(1963)	(1940)

Wakatomika Creek near Frazeysburg, OH	1-day Low flow (cfs)	Watershed runoff in inches (drought year) Drought duration in months							
		6	9	12	18	24	30	42	60
Drought of record	2.60	0.39	0.82	3.99	6.31	11.62	12.89	23.50	48.13
	(1963)	(1963)	(1963)	(1992)	(1954)	(1954)	(1954)	(1954)	(1954)
2nd worst drought	2.70	0.46	1.21	4.73	8.92	17.06	22.52	35.50	56.78
	(1953)	(1954)	(1992)	(1954)	(1992)	(1963)	(1999)	(1999)	(1963)
3rd worst drought	3.10	0.49	1.22	7.30	10.90	19.30	23.24	36.12	59.01
	(1944)	(1992)	(1954)	(1971)	(1999)	(1988)	(1963)	(1963)	(1999)
4th worst drought	3.20	0.60	1.85	7.37	11.42	19.40	24.02	38.15	61.04
	(1939)	(1952)	(1956)	(1963)	(1988)	(1999)	(1988)	(1988)	(1988)

Conneaut Creek at Conneaut, OH	1-day Low flow (cfs)	Watershed runoff in inches (drought year) Drought duration in months							
		6	9	12	18	24	30	42	60
Drought of record	0.30	0.42	3.66	9.19	11.73	22.08	23.57	35.78	59.94
	(1934)	(1991)	(1930)	(1930)	(1930)	(1934)	(1934)	(1934)	(1930)
2nd worst drought	0.30	0.56	3.94	10.18	11.77	24.18	26.41	44.10	79.29
	(1933)	(1923)	(1935)	(1934)	(1934)	(1930)	(1930)	(1962)	(1962)
3rd worst drought	1.00	0.62	4.06	11.42	15.13	25.76	28.94	51.06	84.35
	(1930)	(1934)	(1991)	(1998)	(1998)	(1962)	(1962)	(1930)	(1998)
4th worst drought	1.30	0.71	4.40	11.70	15.15	29.31	36.39	52.47	96.43
	(1932)	(1930)	(1960)	(1994)	(1963)	(1998)	(1998)	(1998)	(1951)

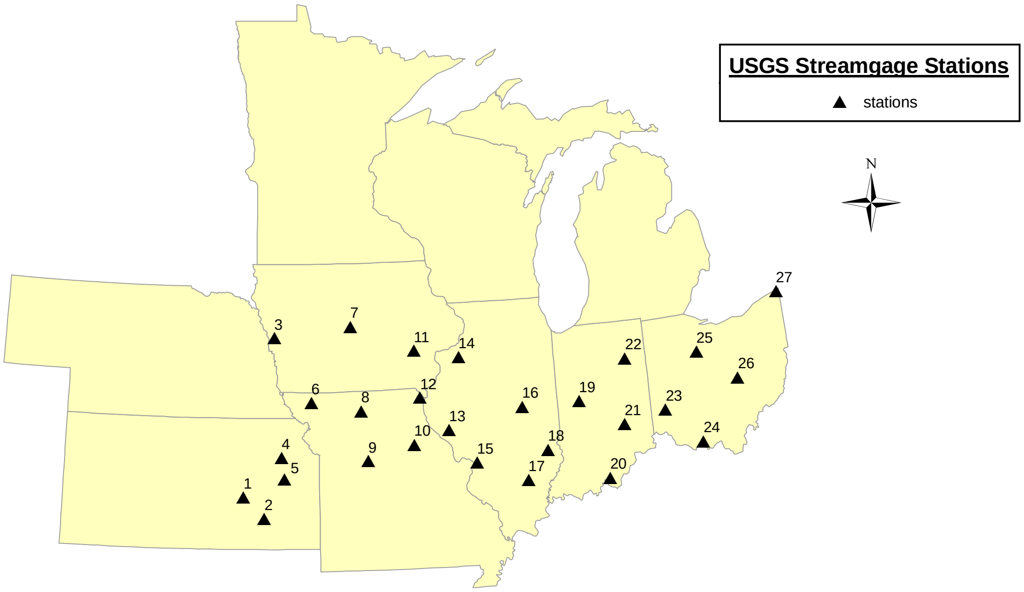

Figure 9. Selected USGS streamflow gages for which drought flows are computed

In contrast, the lowest 12 months of streamflow for Conneaut Creek in Ohio, the most eastern site listed in Table 3, was equivalent to 9.19 inches of runoff. Also shown in both cases is the year in which the worst 12-month low flow occurred: 1954 for Cedar Creek and 1930 for Conneaut Creek. In cases where the drought duration is longer than 12 months, the year listed in Table 3 is the commonly identified "worst year" within that particular drought period.

With the exception of the four gages in Indiana, the 1950s drought provides the drought of record for longer durations (greater than or equal to 18 months) at most selected gages. This indicates that, if that streamgage record is to be used in analyzing water supply conditions during severe droughts, it is very important for that gage's period of record to include the 1950s. Note that Table 3 includes only gages within the southern tier of Midwestern states that contain the largest number of community surface water systems. The drought of record in Michigan, Wisconsin, and Minnesota is likely to have been in the 1930s or 1960s.

As mentioned earlier, the values in Table 3 illustrate that the eastern Midwest states have considerably more flow during drought periods than states in the western Midwest, with a progressive increase in flows across the region from west to east. The geographic difference in drought flows has a profound influence on the types of surface water supply systems used across the Midwest, as discussed in Chapter 3, *Description of Small Community Surface Water Supplies in the Midwest.*

Reservoir Refill Capacity during Droughts

Water supply reservoirs represent the most common surface water source for small community systems, and the amount of streamflow flowing into the reservoir is an important element in determining the drought vulnerability of the system. Reservoir storage capacity is often expressed in units of either million gallons or acre-feet; 1 million gallons is equivalent to roughly 3.07 acre-feet. However, another very useful measure of capacity is to express this number as the equivalent inches of runoff over the watershed that contributes flow to the reservoir. The equivalent inches of runoff can be computed from the reservoir capacity and the contributing watershed area as follows:

Equivalent runoff (inches) = Capacity (acre-feet) x 12 / Watershed Area (acres)

If a reservoir stored the equivalent of 2 inches of runoff, then it would seem to be very easy for one or two heavy rainfall events to create enough runoff to fill up the reservoir. During a drought period, however, most rainfall is soaked into the soil and very little runs off into streams. It is not unusual, for example, for a 1.0-inch rain during a dry summer to cause little or no increase in the flows of nearby streams, and it may take a considerable amount of time for a watershed to accumulate 2 inches of total runoff.

The average water supply reservoir in the Midwest stores the equivalent of 5 inches of runoff; roughly two-thirds of all water supply reservoirs store between 1.5 and 10 inches of runoff. If a reservoir with 5 inches of storage was empty, during a normal year it would take roughly six months to fill (ranging from less than four months in eastern Ohio to more than nine months in central Kansas). But during a drought of record it would take nearly 18 months for that reservoir to fill in Ohio (not counting evaporation losses and water withdrawals), as shown in Table 3. For many locations in Illinois it would take that same reservoir 24–30 months to refill, and in Kansas it would take more than five years to refill.

The time that it would take the reservoir to refill during this lowest flow period is denoted as the *refill duration index*. This is not a common term, but one adopted in this study for purposes of reference. Note that during reservoir operation in real drought conditions, the time required for reservoir recovery could either be longer or shorter than the refill duration index because: 1) concurrent water withdrawals and evaporation can prolong the refill of the reservoir and 2) the recovery of the reservoir level (at the end of the drought) doesn’t usually correspond to the period when inflows are at their lowest.

Critical Duration of Drawdown

One of the more important variables in the determination of reservoir yield is the duration of the critical drawdown period (Stall, 1964), also termed the *critical duration*. The critical duration is the period between when the reservoir first starts falling below full pool in the early stage of the drought and when the reservoir reaches its lowest level prior to recovery. The critical duration is not directly related to the refill duration index as described in the preceding paragraph; however, comparisons of the two values indicate that they often are similar in duration. Thus, the refill duration index is recommended as an initial approximation of the critical duration. The amount of reservoir capacity needed to sustain the reservoir through the critical drawdown period (often termed *carry-over storage* for multi-year drought periods) is determined by the cumulative amount of water used from the reservoir during the critical duration, the net amount of water that would be lost from the reservoir from evaporation or seepage, and the expected amount of inflow into the reservoir. This is described in more detail in Chapter 4: "Data and Methods for Assessing Water Supply Availability."

It is possible that two adjacent water supplies may have differences in critical duration, often because of differences in reservoir size relative to watershed inflow. In such cases, the drought of record also may be different for the two supplies.

Effect of Local Hydrogeology on Drought Flows

Even within regions that are considered to have hydrologic similarity, there can be local differences in baseflow amounts, particularly where a stream interfaces with a groundwater resource. This can happen, for example, if the stream cuts through a highly permeable bedrock formation or flows through an area of extensive shallow sand-and-gravel deposits. In Table 3, Soldier Creek in western Iowa and Blue Creek in southern Indiana provide the two most obvious examples of minimum lows that are substantially higher than other watersheds in their region. In the latter case, the stream's watershed includes areas of karst topography. Shallow sand-and-gravel deposits can occur in certain glaciated landscapes, particularly where there has been glacial outwash. However, in such cases where a local groundwater source is present, it is likely that the community is using groundwater for its water supply source instead of the stream.

Description of Small Community Surface Water Supplies in the Midwest

The United States Environmental Protection Agency (USEPA) considers water systems that serve more than 25 people or 15 connections year-round to be community water systems. Community surface water systems regularly draw from at least one surface water source and must have a treatment facility that meets USEPA surface water regulations. Surface water systems are more vulnerable to pollution than their groundwater counterparts and consequently must be subject to more rigorous treatment standards. For this reason, the USEPA classifies systems that rely upon both surface and groundwater sources as surface water systems.

Community surface water systems supply 320 community water systems serving 10,000 or fewer people in the ten-state MTAC region. The list of systems was compiled from the USEPA Safe Drinking Water Information System (SDWIS) and correspondence with state agencies and individual systems in the MTAC region. These multiple inquiries identified inconsistencies among these lists. In such cases, telephone calls were placed to water systems to ascertain their regular use of a surface water source. For instance, the Rend Lake Intercity Water System in Illinois was listed as serving only 3,000 people when, in fact, 65 communities and rural water districts in southern Illinois with an estimated population of 165,000 rely upon this source. All respondents from systems sampled in our survey were initially asked about their total service area populations. Systems whose total service area population exceeded the 10,000 threshold were removed from both the sampled subset of 60 stations and the entire census of surface water systems in the Midwest. However, the total service area populations for many non-sampled community water systems often could not be verified.

Geographic Distribution of Surface Water Supplies

Figure 1 shows that there are prominent clusters of surface water supplies in the Midwest including:

- Southeastern Kansas and west-central Missouri
- Southwestern and south-central Illinois
- Northern Missouri and southern Iowa
- Northwestern Ohio
- Southern Indiana
- Northern Minnesota
- Great Lakes communities

This clustering of surface water systems tends to occur in regions with poor groundwater resources. Groundwater is often the preferred water supply choice for small community systems, and communities will typically develop reservoirs or other surface water systems only when groundwater sources are insufficient. The exception is when there exists a high-quality source of surface water such as the Great Lakes, other large naturally formed lakes, or major rivers.

Table 4 presents the total number of systems in each MTAC state. Kansas has the greatest number of systems (63), Missouri is second with 59 systems, while Ohio and Illinois follow with 58 and 50 systems, respectively. In contrast, there are only two community surface water systems in Wisconsin that serve 10,000 people or fewer. Table 4 also lists the total number of people that these systems serve in each state, and the percentage of each state's population dependent on small surface water systems. Ohio's small community surface water systems serve the greatest number of people at 232,346, while Illinois (212,607) was the only other state to eclipse the 200,000 threshold. Wisconsin has the lowest population served and is followed, in ascending order, by Nebraska and Minnesota, all of which have fewer than 50,000 residents dependent upon small community surface water supplies.

Figure 10 shows the average service population of small community surface water supplies by state; Nebraska and Wisconsin were not included because they have a small number of systems. In general, systems in the eastern half of the Midwest serve larger populations than systems in the western half of the Midwest. Part of the disparity is related to geographic differences in population density. However, in recent years, there has also been a trend for many of the smallest communities to abandon their surface water supplies and instead purchase water from other nearby communities (Hecht and Knapp, 2008). This trend has been primarily triggered by economic considerations such as when communities cannot easily afford treatment plant upgrades required to meet stricter USEPA surface water regulations, mandated in 1996 amendments to the Safe Drinking Water Act. Purchasing water from nearby communities may be more economically feasible in the eastern Midwest where there is less distance between communities than in the western Midwest. However, in other cases the interconnection to a larger, more reliable water system has been necessary because of inadequate supply in the smaller system. Small community systems in Missouri that have been forced to connect to neighboring systems are now more drought-proofed than in their previous circumstances (Personal communication, Steve McIntosh, Missouri Department of Natural Resources, June 10, 2009.)

Table 4. Number of Small Community Surface Water Systems and Populations Served

State	*Number of systems*	*Total population served*	*2006 state population estimate (U.S. Census Bureau)*	*Percent of state population*
Illinois	50	212,607	12,831,970	1.7%
Indiana	20	74,076	6,313,520	1.2%
Iowa	17	61,863	2,982,085	2.1%
Kansas	63	161,385	2,764,075	5.8%
Michigan	32	128,283	10,095,643	1.3%
Minnesota	15	43,100	5,167,101	0.8%
Missouri	59	183,951	5,842,713	3.1%
Nebraska	4	23,638	1,768,331	1.3%
Ohio	58	232,346	11,478,006	2.0%
Wisconsin	2	10,355	5,556,506	0.2%

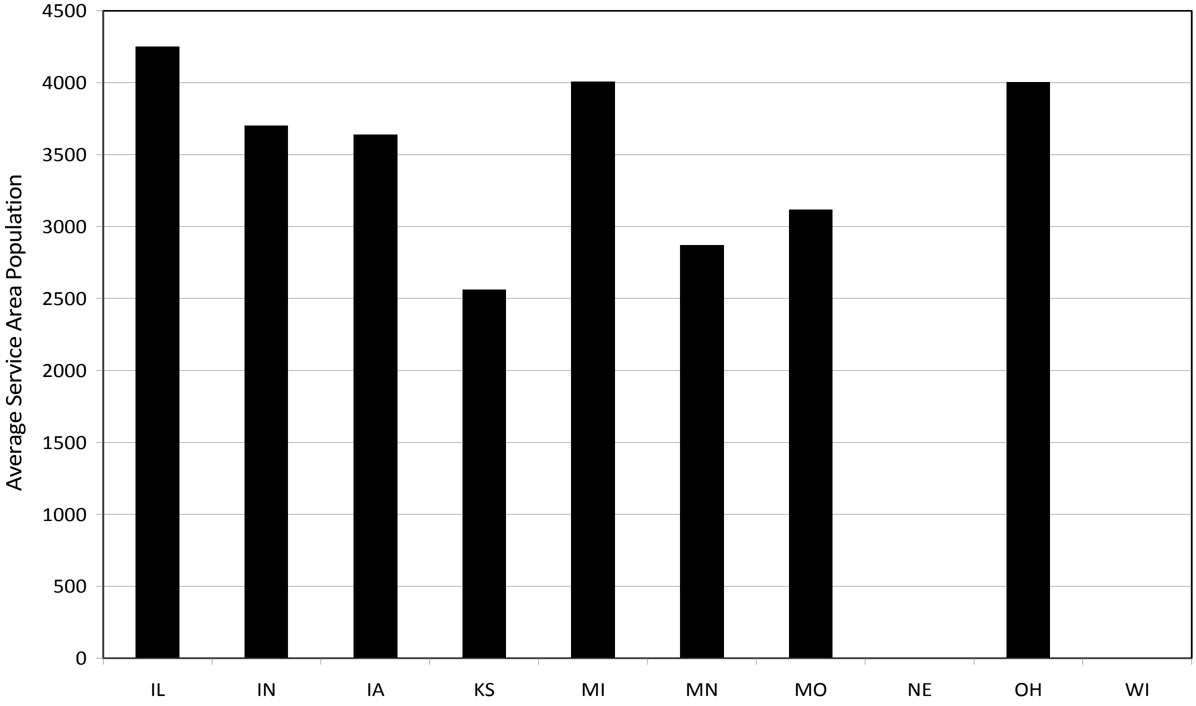

Figure 10. Average service population of small community water systems

Source Types

Numerous types of surface water sources supply these systems. Systems with access to natural lakes and rivers can often directly withdraw water from these bodies without needing to construct any type of reservoir to store water for use in dry periods. Some systems have constructed low channel dams, situated within the banks of the river, that create a pool from which pumping occurs but which also can store a small amount of water that provides additional supply during severe low flow spells. *Low channel dams* typically allow the stream's flow to pass over the dam in all but the lowest of flow conditions.

Other systems have constructed reservoirs to achieve a reliable water supply. *Impounding reservoirs* are typically earthen embankments damming a river or stream behind which water is stored in the river valley. These reservoirs typically store several inches of runoff from the stream's watershed, often enough water to meet community demands for one or more years. *Off-channel reservoirs* are storage reservoirs built some distance away from the stream that provides its main source of water, and from which water is pumped into the reservoir. Off-channel reservoirs are typically smaller than impounding reservoirs, and typically hold a sufficient amount of water to meet a community's water needs for several months up to two years. Telephone conversations with systems in Illinois and Ohio also indicated that some off-channel reservoirs have been constructed to store high-quality water for periods during which concentrations of nitrates or other pollutants in river water exceed the USEPA's Maximum Contaminant Levels (MCLs).

Communities also use *quarries* and *borrow pits* to collect and store water, although such systems are classified as off-channel reservoirs when they receive water pumped from nearby streams. Systems receiving a substantial percentage of their water from more than one of the source types described above are considered *combination* systems. Altogether, surface water systems in the Midwest can be classified using the nine categories listed in Table 5. Table 6 lists the total number of small community systems using each category of surface water source. Impounding reservoirs are the most common source for small communities, followed by river withdrawals and off-channel reservoirs.

Table 5. General Types of Surface Water Sources in the Midwest

Type	*Description*
Major River Withdrawal (MRW)	Intake situated on one of the three major rivers of the Midwest (the Mississippi, Missouri, and Ohio Rivers) with virtually no risk of a water supply drought.
Run of the River Withdrawal (RW)	Intake situated on an intrastate river or stream, which may or may not be at risk of a water supply drought.
Low channel dam withdrawal (LCD)	This category includes systems that have low channel dams.
Impounding Reservoir (IR)	Reservoir impounding a river valley.
Off-Channel Reservoir (OCR)	Reservoir located off the main channel of a river to which water is pumped from the river.
Quarry/Borrow Pit (QBP)	Former quarry, borrow pit, or other artificially excavated basin used to collect and store water without receiving any inflow from a diverted source.
Great Lakes (GL)	Intake situated on one of the five Great Lakes or a connecting channel between the Great Lakes.
Natural Lake (NL)	Intake situated on a natural lake other than one of the five Great Lakes.
Combination of Sources (C)	System pumping water from intakes on more than one of these types of sources on a regular basis.

Table 6. Number of Small Community Surface Water Systems by Type

		Community Population		
System Source Type	*Number*	*<= 1,000*	*1,001 - 3,300*	*3,301 - 10,000*
Major River Withdrawal	14	0	3	11
River Withdrawal	51	11	19	21
Low channel dam withdrawal	9	1	2	6
Impounding Reservoir	114	26	54	34
Off-Channel Reservoir	40	6	16	18
Quarry/Borrow Pit	9	3	5	1
Great Lakes	45	11	15	19
Natural Lake	8	2	2	4
Combination	30	1	10	18

Source Type by Geography

The distribution of surface water system source types throughout the MTAC region is indicative of regional differences in climate (drought duration) and local hydrogeology. Water supply droughts in Ohio are of relatively short duration when compared to the multi-year droughts of Kansas and Missouri. As a result, 25 community water systems in Ohio are able to depend exclusively on off-channel reservoir systems while only 11 systems rely upon impounding reservoirs. In contrast, 29 systems in Kansas use impounding reservoirs as their predominant source whereas not a single off-channel reservoir system is used as off-channel reservoirs are typically too small to store enough water for the multi-year droughts in Kansas. Figure 11 shows the distribution in the number of impounding versus off-channel reservoirs across the Midwest. Systems choose to build a storage infrastructure that best suits the duration of the most severe droughts.

Roughly half of the small-community river withdrawal systems in the Midwest are located in Kansas (Figure 12). However, many of the Kansas river withdrawal sites are located downstream of a large federal reservoir that releases water to maintain low flows, and would not provide an adequate supply to the community without these reservoir releases. Thus it could be argued that some of these river withdrawal systems, in essence, represent impounded reservoir sources of supply.

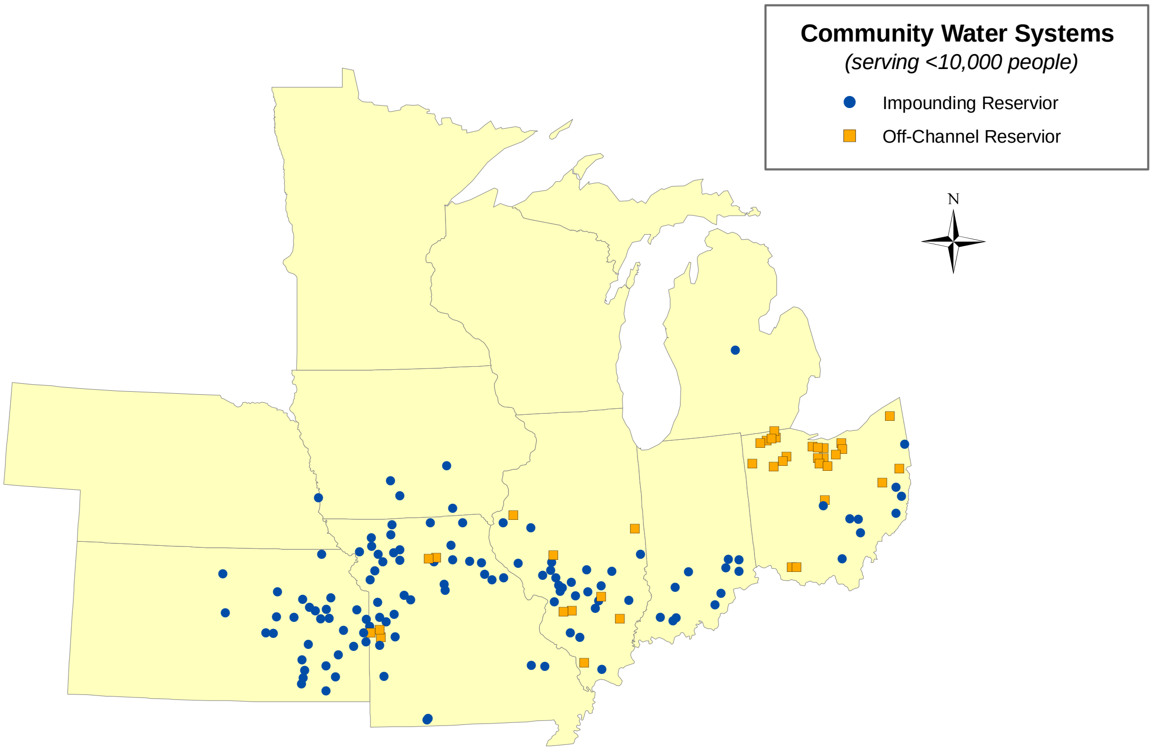

Figure 11. Impounding and off-channel reservoir systems in the Midwest

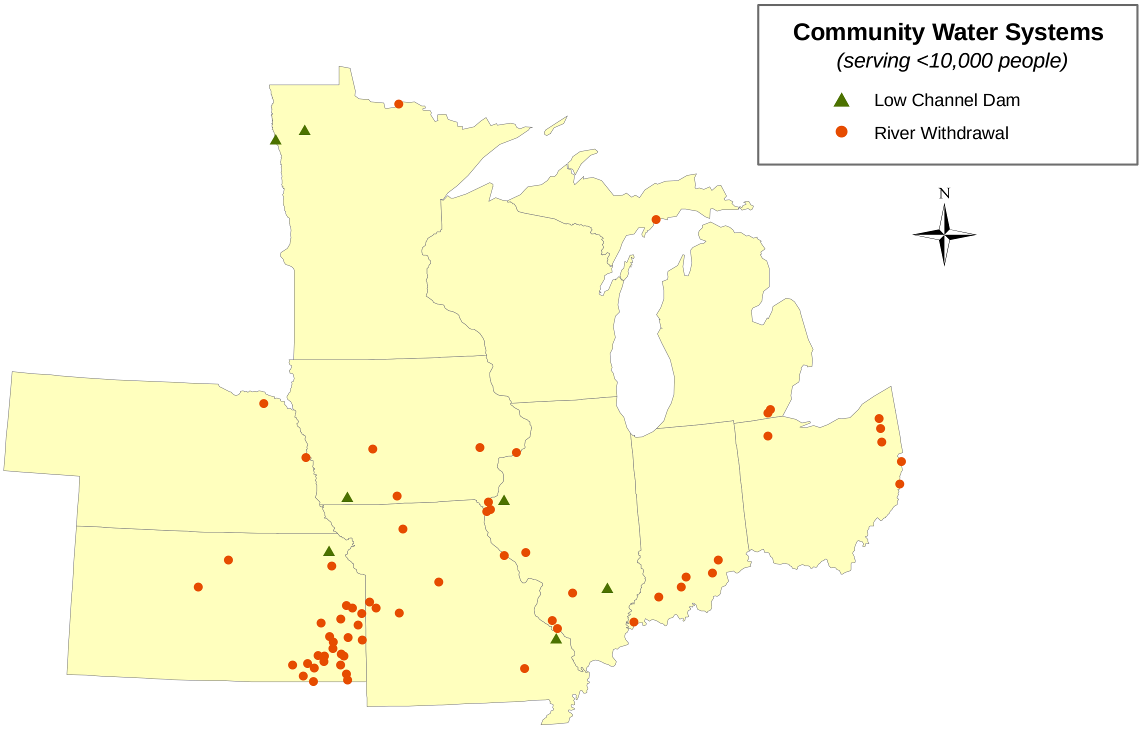

Figure 12. River withdrawal and low channel dam systems in the Midwest

These data also reveal almost a complete absence of reservoirs—both impounding and off-channel—in Minnesota, Wisconsin, and Michigan. In Minnesota, there are many readily available sources in natural lakes, abandoned mining pits, and rivers with high base flow percentages due to their frequent connection with lakes. In regions where these sources are not plentiful, groundwater resources are adequate. Many systems in Michigan are located in close proximity to the Great Lakes, and the state's relatively high precipitation and low evapotranspiration produces river flows capable of sustaining small communities through droughts without any need for storage.

Survey of Selected Community Surface Water Systems

Semi-structured interviews typically lasting from 15 to 20 minutes were conducted with 60 system administrators, including superintendents, public works directors, and operators. The 60 interviewed water systems are listed in Table 7. Systems withdrawing water from large regional rivers (Mississippi, Missouri, and Ohio), any one of the Great Lakes, or their connecting channels (e.g., St. Clair River between Lake Huron and Lake Erie) in the MTAC region were not sampled in this study due to the extremely low probability that these sources' flows or levels would drop to a magnitude incapable of meeting the current and near-future drought demands of dependent systems. A minimum of 20 percent of all other types of surface water systems listed in Table 6 were sampled. A random number generator was used to rank systems into a priority list. Systems with which it was difficult to coordinate an interview were removed from the list

Table 7. List of the 60 Systems Interviewed and Source Information

System name	*State*	*Source type**	*Service area population*	*Restrictions (1988-2006)*	*Primary source(s)*
Alma	MI	C	9275	No	Groundwater, Pine River
Archie	MO	OCR	1000	Yes	South Grand River (OCR)
Baxter Springs	KS	RW	4707	No	Spring River
Blissfield	MI	RW	3200	No	Raisin River
Breckenridge	MO	IR	540	No	Holden Res.
Breese	IL	OCR	9500	No	Shoal Creek (2 OCRs)
Butler	MO	C	4200	No	Marais des Cygnes River diversion ditch (OCR)
Carbondale	KS	IR	2468	No	Strowbridge Res.
Chadron	NE	C	7134	No	Groundwater, Chadron Creek infiltration gallery
Chariton	IA	IR	4573	No	Lake Ellis, Lake Morris, Red Haw Lake
Chisholm	MN	QBP	4966	No	Fraser-Humphrey Pit
Cinnamon Lake	OH	C	1500	No	Cinnamon Lake
College of the Ozarks	MO	OCR	1500	No	Lake Taneycomo
Corning	IA	IR	5783	No	Lake Binder, Corning City Res., Lake Icaria
Douglas County RWD #3	KS	IR	2200	No	Clinton Res.
East Grand Forks	MN	LCD	8000	Yes	Red Lake River (LCD)
Eureka	KS	IR	8500	No	W-7 (Otis Creek) Res.
Eveleth	MN	NL	4175	No	Ely Lake
Fairfield	IL	OCR	6661	No	Little Wabash River (OCR)
Flora	IL	LCD	6100	No	Little Wabash River (LCD)
Franklin County RWD #6	KS	C	3000	No	Marais des Cygnes River, Melvern Lake, Pomona Lake
Garden City	MO	IR	1500	Yes	Old Lake, New Lake
Grenola	KS	LCD	221	Yes	Big Caney River (LCD)
Henry County PWSD #3	MO	IR	3000	No	Harry S. Truman Lake
Herington	KS	IR	3100	No	Herington Res.
Hillsboro	IL	IR	9000	No	Glenn Shoals Lake
Holiday Shores	IL	IR	3192	No	Holiday Lake
Humboldt	KS	RW	2100	No	Neosho River
International Falls	MN	RW	8054	No	Rainy River
Jackson	OH	IR	10000	No	Hammertown Lake, Jisco Lake
Jamesport	MO	IR	575	No	Jamesport Lake

Table 7. Concluded

System name	*State*	*Source type**	*Service area population*	*Restrictions (1988-2006)*	*Primary source(s)*
Kickapoo Tribe	KS	LCD	850	Yes	Delaware River (LCD)
Louisburg	KS	IR	3600	No	Louisburg City Lake
Marion	KS	IR	2510	No	Marion Res.
McClure	OH	RW	850	No	Maumee River
Milan	MO	C	7385	Yes	Elmwood Lake, Milan Lake, Big Locust Creek
Milford	IA	NL	3474	No	West Lake Okoboji
Monroeville	OH	OCR	1733	Yes	West Huron River (OCR)
Montezuma	IA	IR	2657	No	Diamond Lake
Mount Olive	IL	IR	2360	No	Old Mount Olive Res., New Mount Olive Res.
New Lexington	OH	IR	5126	Yes	New Lexington Res., Yeager Creek Res.
North Vernon	IN	C	10000	Yes	Brush Creek Res., Vernon Fork Muscatatuck (LCD)
Oakland City	IN	C	3000	No	Old Lake, New Lake, Patoka Lake
Oberlin	OH	RW	8600	Yes	W Br Black River
Osceola	IA	IR	6000	No	West Osceola Lake
Osgood	IN	OCR	2988	Yes	Laughery Creek (OCR)
Panora	IA	LCD	1175	No	Middle Raccoon River
Piedmont	MO	RW	2100	No	Black River
Plattsburg	MO	IR	8500	No	Smithville Lake
Santee Utilities, Inc.	IN	IR	1350	No	Lake Santee
Sebring	OH	C	8100	No	Mahoning River (LCD)
Severy	KS	IR	359	Yes	Severy City Lake
Shelbina	MO	IR	1640	Yes	Shelbina Lake
Springs Valley Regional WD (French Lick)	IN	C	3510	No	Lost River, Patoka Lake
Swanton	OH	OCR	3455	Yes	Swan Creek (OCR)
Vermont	IL	IR	814	No	Vermont Lake
Vienna	IL	IR	1600	Yes	Lake Bloomfield
Vienna Correctional Center	IL	IR	3700	No	Vienna Correctional Center Lake
Wauseon	OH	OCR	8000	Yes	Maumee River (2 OCR), Stuckey Ditch, Big Ditch Creek
Winslow	IN	LCD	931	No	Patoka River

Note: *****See Table 5 for explanation of source type abbreviations and replaced with ones with the next highest priority. Sixty out of 92 systems contacted (65 percent) participated in the telephone interviews. These systems are shown in Figure 13. Twenty-five contacted systems did not participate because an interview could not be arranged or they did not return messages, which were typically left with administrative assistants. Only seven systems (8 percent) directly declined to participate, usually citing time concerns or low drought risks as their reasons for refusal. Care was also made to ensure that the sample represented the geographic and service area population diversity of the community water systems in the MTAC region. Table 8 summarizes the number of systems in each state and type of surface water source.

Telephone interviews with each community system were used to gather information on the following aspects of drought among small community surface water systems in the Midwest:

- Availability of hydrologic data necessary to assess system yield
- Drought impacts (geographic and source type trends)
- Community-based drought planning
- Summer drought demand

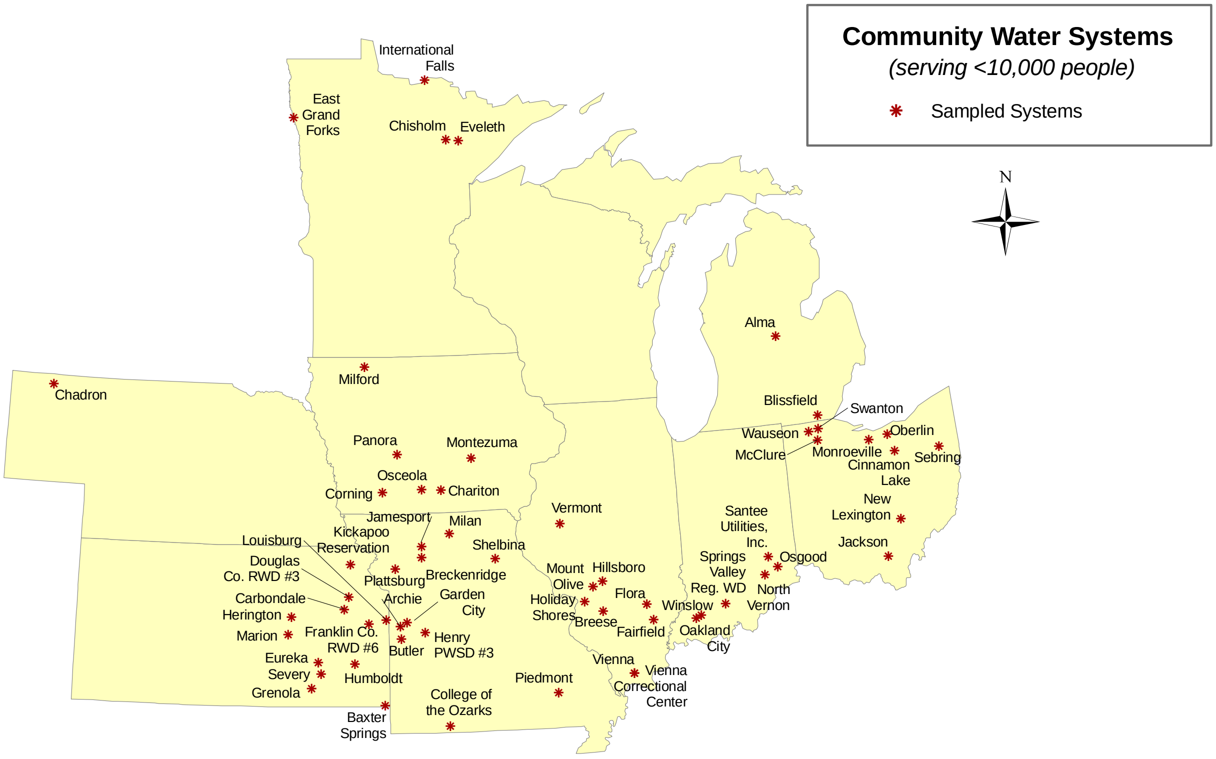

Figure 13. Location of the 60 communities that were interviewed for this study

Table 8. Summary of Source Types for Interviewed Systems

	RW	*LCD*	*OCR*	*IR*	*QBP*	*NL*	*C*	*Total*
IL		1	2	6				9
IN		1	1	1			3	6
IA		1		4		1		6
KS	2	2		5			3	12
MI	1						1	2
MN	1	1			1	1		4
MO	1		2	5			3	11
NE							1	1
OH	2		3	2			2	9
WI								0

Hydrologic Data Available for Yield Assessment

The first portion of the informal telephone interview consisted of an assessment of hydrologic data available to estimate the yield of a system's sources. Depending upon the source type, the information requested included the following: 1) reservoir surface area and capacity; 2) available stream records (use of USGS gages); 3) pumping rate (for off-channel reservoirs only); and 4) minimum flow requirements for river withdrawals, if they exist. The information gathered from telephone conversations were supplemented by data collected by other sources, such as reservoir data available from the National Inventory of Dams or streamgaging data available from the U.S. Geological Survey (USGS). In some cases, the telephone conversations provided an opportunity to verify data collected from these other sources. The following sections further describe the information obtained regarding reservoir size and available streamflow records.

Reservoir Data – Surface Area and Capacity

Reservoir surface area and capacity information was requested from all interviewees whose systems relied upon storage in impounding or off-channel reservoirs. Slightly less than half of contacted system operators/managers were able to provide capacity information. For most of the remaining cases, the capacity and surface area estimates were obtained from other sources such as the National Inventory of Dams. In all, information could be obtained for 45 of the 49 impounding reservoirs identified in the telephone interviews, representing 33 water systems (Table 9). In some cases, the capacity information obtained from alternative sources was found to be more recent estimates than that provided by the system operators during the interview.

Communities that have reservoirs as their primary supply typically have either one or two reservoirs. In most cases, the second (supplemental) reservoir is an older one that once served as the sole water source until the community's water use outgrew its yield. The typical water supply reservoir for a small community is located in a small watershed (less than 4 square miles)

Table 9. Impounding Reservoir Data for Interviewed Communities

System Name	*State*	*Source Name*	*Drainage area (sq mi)*	*Capacity (ac-ft)*	*Capacity (in)*
Chariton	IA	Lake Ellis	2.9	804	5.20
Chariton	IA	Lake Morris	7.1	1270	3.34
Chariton	IA	Red Haw Lake	1.6	1040	11.96
Corning	IA	Lake Icaria	28.0	7504	5.03
Corning	IA	Lake Binder	3.3	990	5.56
Corning	IA	Corning City Reservoir	0.8	220	5.16
Montezuma	IA	Diamond Lake	4.3	882	3.88
Osceola	IA	West Osceola Lake	8.6	4210	9.21
Panora	IA	Lake Panorama Assoc.	433.0	14900	0.65
Hillsboro	IL	Glenn Shoals Lake	80.0	9717	2.28
Hillsboro	IL	Lake Hillsboro	7.4	1018	2.57
Holiday Shores	IL	Holiday Lake	6.3	4605	13.64
Mount Olive	IL	Old Mount Olive Res.	5.2	282	1.01
Mount Olive	IL	New Mount Olive Res.	0.7	382	10.23
Vermont	IL	Vermont Lake	2.3	223	1.79
Vienna	IL	Lake Bloomfield	1.2	1473	23.81
Vienna Correctional Center	IL	Vienna Corr. Center Lake	1.3	1082	16.23
North Vernon	IN	Brush Creek Res.	14.3	1747	2.29
Oakland City	IN	New Lake	0.8	649	15.80
Oakland City	IN	Old Lake	0.1	66	10.31
Carbondale	KS	Strowbridge Reservoir	5.0	2700	10.13
Eureka	KS	Eureka City Lake	15.2	3125	3.85
Herington	KS	Herington Res.	24.8	5759	4.36
Severy	KS	Severy City Lake	1.3	70	1.03
Breckenridge	MO	Holden Res.	4.0	140	0.66
Butler	MO	Butler Lake	3.0	749	4.71
Garden City	MO	Garden City Old Lake	1.4	177	2.44
Garden City	MO	Garden City New Lake	2.5	441	3.31
Jamesport	MO	Jamesport Lake	1.4	163	2.17
Milan	MO	Elmwood Lake	6.1	2503	7.69
Milan	MO	Milan (Golf Course) Lake	1.1	555	9.82
Shelbina	MO	Shelbina Lake	58.0	406	0.13
Jackson	OH	Hammertown Lake	3.1	2481	14.81
Jackson	OH	Jisco Lake	1.7	725	8.04
New Lexington	OH	Yeager Creek Res.	1.2	529	8.27
New Lexington	OH	New Lexington Res.	0.8	451	10.84
Oberlin	OH	Wellington Res.	1.6	182	2.13
Sebring	OH	Westville Lake	8.5	609	1.34
<u>FEDERAL RESERVOIRS</u>					
Oakland City	IN	Patoka Lake	168	167290	18.67
Marion	KS	Marion Reservoir	200	80680	7.56
Franklin County RWD #6	KS	Pomona Lake	322	70600	4.11
Franklin County RWD #6	KS	Melvern Lake	349	154000	8.27
Douglas County RWD #3	KS	Clinton Reservoir	367	110400	5.64
Plattsburg	MO	Smithville Lake	213	144600	12.73
Henry County PWSD #3	MO	Harry S Truman	11500	1202700	1.96

and has a total capacity of less than 1000 acre-feet. The average size of a community reservoir is likely to be slightly smaller in the eastern portion of the MTAC region and slightly larger in the western portion. Eastern reservoirs are typically located in smaller watersheds and retain a larger amount of runoff, as measured in number of inches. Communities in the eastern portion of the region are also more likely to have more than one reservoir or alternative sources.

Seven of the reservoir systems that were interviewed obtain their water from a large federal reservoir that, in most cases, provides supplemental water to multiple communities. Six of the seven federal reservoirs are located in Kansas and Missouri. All of the federal reservoirs have watershed areas greater than 150 square miles.

Twelve of the interviewed communities had off-channel reservoirs (Table 10). The storage amount in these reservoirs ranged from 6 to 921 acre-feet. Most off-channel reservoirs have a depth of 8 to 13 feet.

Streamflow Data

The USGS has operated gages along the streams or on the lakes from which 28 of the 60 sampled communities withdraw their water. However, some of these gaging records are not sufficiently long enough to contain a major drought needed to evaluate adequacy of the supply. Only 19 of these systems have flow records for at least one of their water supply sources spanning at least 30 years and/or including records from the 1950s, the drought of record for many locations in the Midwest. The great majority of these gages are located on larger streams and rivers with drainage areas greater than 300 square miles that provide water for direct withdrawals, low channel dam withdrawals, or inflows for large federal reservoirs. Drought flow

Table 10. Off-Channel Reservoir Data for Interviewed Communities

System name	*State*	*Source name*	*Reservoir type*	*Capacity (ac-ft)*
Archie	MO	Off-Channel Res. (Old)	OCR	6
Archie	MO	Off-Channel Res. (New)	OCR	117
Breese	IL	Off-Channel Res. #1	OCR	94
Breese	IL	Off-Channel Res. #2	OCR	94
Butler	MO	Butler Lake	IR-OCR	749
Cinnamon Lake	OH	Off-Channel Res.	OCR	15
College of the Ozarks	MO	Lake Honor	OCR	15
Fairfield	IL	Off-Channel Res.	OCR	276
Franklin County RWD #6	KS	Settling Basin	OCR	11
Monroeville	OH	Off-Channel Res.	OCR	230
Swanton	OH	Swanton Res.	OCR	307
Vienna	IL	Off-Channel Res.	OCR	117
Wauseon	OH	Big Res.	OCR	921
Wauseon	OH	Little Res.	OCR	230

records are available for nine of the 13 sampled direct and low channel dam withdrawal systems. In contrast, drought flow records are available for only two of the 23 impounding reservoir systems, which are typically on smaller watersheds. Of the 13 combination source systems, six have at least one source with a long gaging record; however, as with the other systems, these sources tend to be large rivers.

Drought Impacts – Restrictions Imposed in Recent Droughts (from 1988 to 2006)

The easiest method by which to determine that a community has been affected by drought is the issuance of water use restrictions. Although a community's decision to issue restrictions can be influenced by its *perception* of the risk and willingness to conserve water, the use of a community's decision to restrict uses can, nonetheless, serve as a general indicator of a community's preparation for drought.

In this study, communities that instituted some level of water restrictions at least once in the past 20 years were considered to have been affected by a water supply drought. The 20-year period allows for the impacts of the 1988 regional drought to be assessed, a drought that provoked the worst impacts in many of the communities sampled. Restrictions resulting from limited plant capacity were not considered impacted systems. Systems that had successfully augmented their supply sources after a drought during this period were also noted. In all, 18 of the 60 systems sampled needed to institute restrictions at least once during the 1988–2007 sampling period. Eight of these impacted systems augmented their supply sources as a response to these drought hardships and have not since needed to institute new restrictions.

Figure 14 shows by state the number of systems that implemented restrictions within the past 20 years. Ohio had the greatest percentage of systems that had instituted drought restrictions during the sample period, as five out of nine systems sampled in Ohio needed to institute water use restrictions at least once during 1988–2007. In Missouri, four out of 11 systems instituted restrictions during this period, while one-third of the systems sampled in Illinois (three of nine) and Indiana (two of six) implemented them as well.

The likelihood that a system imposed water use restrictions is influenced by the type of surface water source used for supply. Figure 15 shows the number of systems that implemented water use restrictions as sorted by source type. The following observations are noted:

- Half of the interviewed systems with low channel dams had needed to institute restrictions. In contrast, none of the eight systems using river intakes without low channel dams implemented them. The systems without dams typically withdraw water from intakes with a large contributing area while systems that have constructed low channel dams have done so in part as an adaptive measure against low flow hazards.
- Systems with off-channel reservoirs were more than twice as likely to impose restrictions compared to systems with impounding reservoirs.
- No quarries and natural lake systems imposed restrictions or reported significant drawdowns during drought. This suggests that these systems may in general be less susceptible to droughts; however, this is not a conclusive finding given the small sample size of these systems.

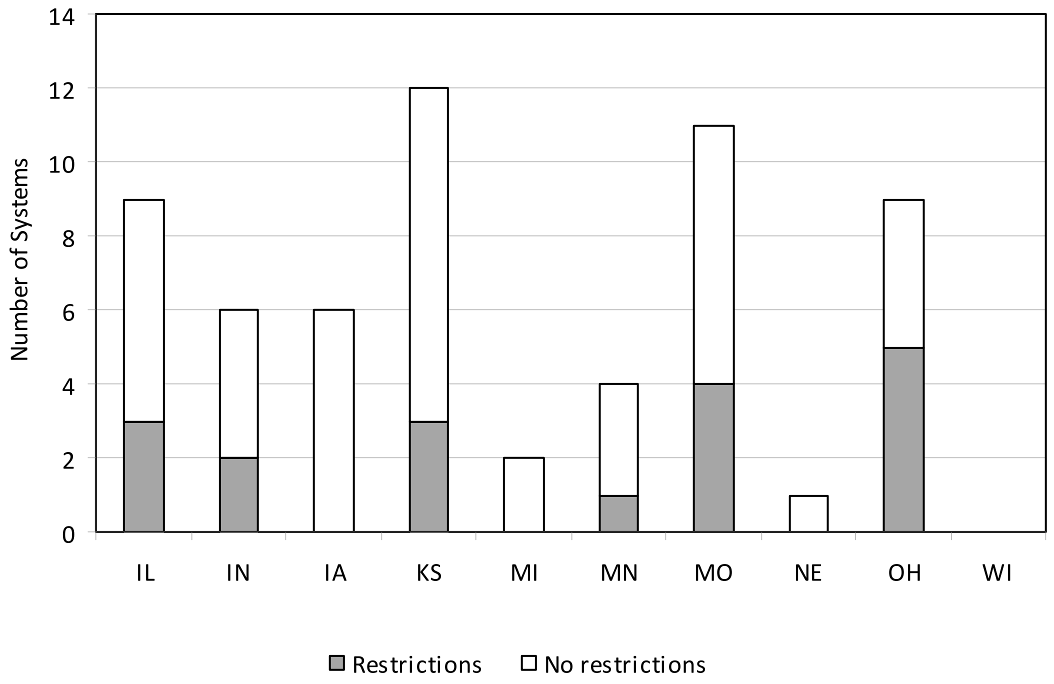

Figure 14. Number of systems that have imposed water use restrictions in the past 20 years

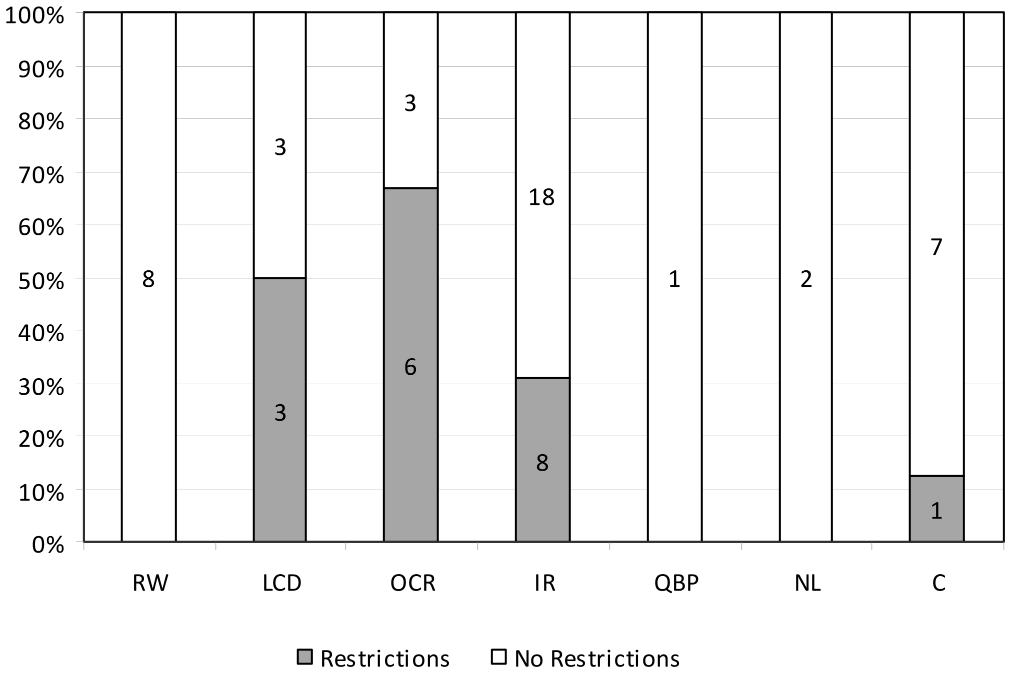

Figure 15. Number of systems that have imposed water use restrictions in the past 20 years, as classified by surface water source type

- Systems with multiple types of sources also appear to be less vulnerable to drought. Among the five systems reliant exclusively upon surface water sources, only one had to institute restrictions. None of the three systems that supplement their surface water production with groundwater or purchase water from external purveyors needed to impose restrictions.

Community-Based Drought Response Planning

A state requirement for community water systems to have their own drought response or conservation plan is usually the primary impetus that prompts small community water systems to develop such plans. All 11 non-tribally administered systems in Kansas had state-mandated drought response plans. Minnesota requires community water systems to develop plans, but Pirie et al. (2004) observed that enforcement of these requirements was weak, and only two out of four Minnesota communities contacted reported having such plans. While other MTAC states have developed state drought plans, they have not required their community water systems to develop operational drought response procedures. Community procedures typically do not include emergency operation plans that identify emergency sources for droughts and other natural and human-induced disasters. Only a few systems had drought response plans that included specified restriction actions to be undertaken when defined hydrologic triggers were reached. New Lexington, Ohio, for example, conceived their own plan after needing to institute restrictions in 1988 and 1992.

Increased Demand during Summers and Droughts

Most communities experience an increase in summer water use during the stages of a drought prior to the implementation of restrictions. The amount by which a system's use may increase is primarily dependent upon the extent of its outdoor water use and seasonal economic activity. Survey respondents were questioned about their system's typical summer demands and the additional increases that may occur during particularly hot and dry summers. In some cases, respondents gave a range of summer water use (June, July, August), but did not specify the additional amount of water that might be used during a summer drought. In these cases, the upper bound of the reported summer water use range was considered to be the summer drought demand.

Estimates of summer water use during a drought were collected for 40 of the 60 systems interviewed. The median system had a summer drought demand that was 37.1 percent greater than their annual average daily demand. However, these results indicated a wide range of drought summer use variability. Winslow, Indiana, a system serving 931 people that withdraws its supply from an intake on the Patoka River, did not report any additional increases in demand during drought summers. In fact, they reported that summer use is typically 3 percent lower than winter use. On the other hand, Milford, Iowa, located on Lake Okoboji, routinely registers a summer increase of more than 100 percent due to the region's tourism industry.

Overall, seasonal water use data revealed that the ratio of summer drought use to average annual demand and the ratio of summer drought use to typical summer demand is greater in the west (Kansas, Missouri) and lower in the east (Indiana, Ohio). The data also indicate that smaller communities have a more variable drought demand increase during the summer (Figure 16). Larger communities may be more likely to have an industrial-commercial water use sector that is less susceptible to seasonal changes. However, many small systems also reported low drought summer use increases and there was not a strong correlation between service area population and drought summer use increases.

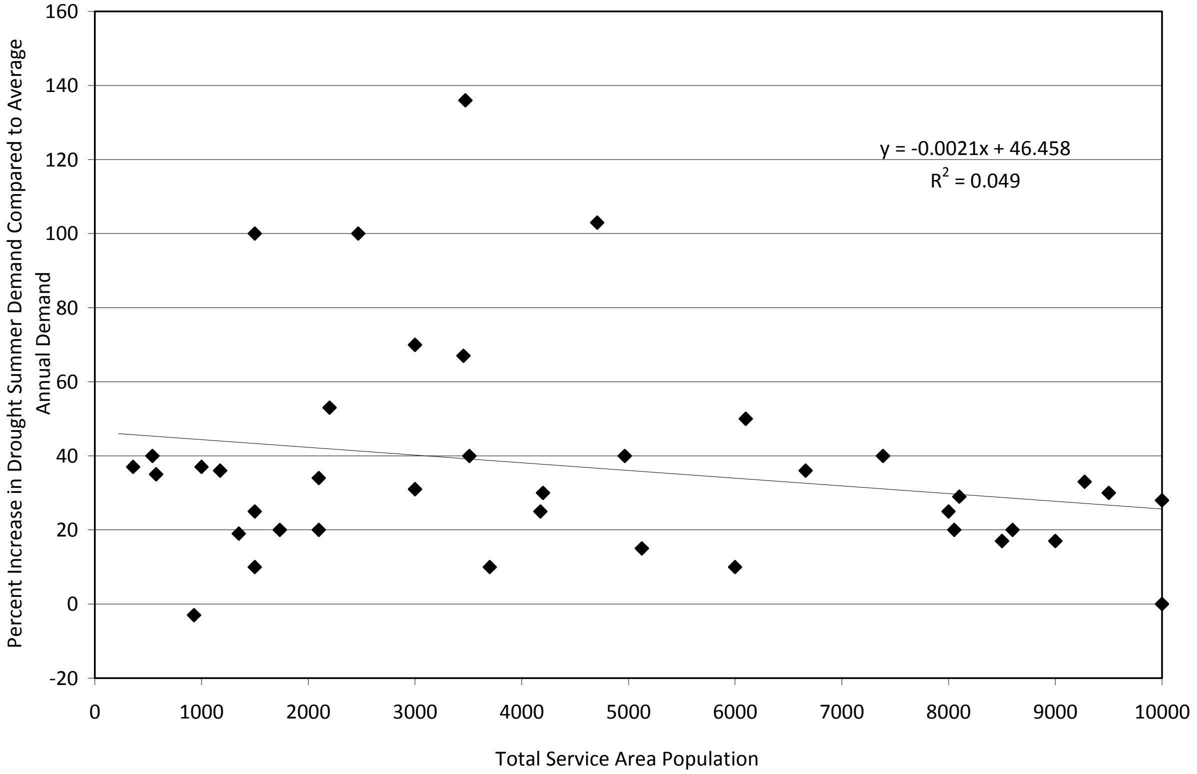

Figure 16. Relationship between service area population and the percentage increase in summer use above average annual use

Data and Methods for Assessing Water Supply Availability

The type of hydrologic data and information needed to assess the availability of surface water supplies depends upon the type of surface water resource. Most types of surface water systems depend on a certain amount of surface storage. For these systems, there are three basic categories of information needed to assess water availability: 1) amount of water in storage; 2) inflow of water into storage; and 3) storage increases from precipitation and decreases from evaporation. Of these, determining the storage capacity and inflow are the most critical and potentially problematic steps in reliable assessment of water supply adequacy. Depending on data availability, estimation of inflows may range from straightforward to highly uncertain, and such evaluations are typically undertaken by experienced hydrologists. In this section potential pitfalls are identified and reasonable approaches for preparing rough approximations of system yield are described where possible.

Storage, precipitation, and evaporation are not considered when evaluating run-of-river withdrawals, where only the streamflow amount is needed to assess availability. Those interested in run-of-the-river withdrawals may choose to jump directly to its designated section (page 62). For many quarry and borrow pit systems, the flow of water into storage comes primarily from groundwater sources, which are not evaluated in this study.

Water Budget Calculations

Water budget calculations are needed to evaluate water supply sources that depend on storage filled by streamflow. There are four basic types of systems included in this broad category:

- Withdrawals at a Low Channel Dam
- Impounding Reservoirs
- Off-Channel Reservoirs
- Natural Lakes

A typical water budget equation for storage in a surface water body is as follows:

$$AW(t) = CAP + P(t) - E(t) + QIN(t) + QDIV(t) - QOUT(t) + GW(t) \qquad (1)$$

where the available water for a specified period of time, AW(t), is computed as the sum of the available capacity of the reservoir (CAP) and the following additions and subtractions to the stored water over time, t:

P(t)	Precipitation over the surface water body
E(t)	Evaporation over the surface water body
QIN(t)	Water that flows into the surface water body from an upstream watershed
QDIV(t)	Water that is artificially diverted (pumped) into the body of water, such as stream water that is pumped into off-channel storage

QOUT(t)	Water that flows out of the surface water body.
GW(t)	Net exchange of water between the surface water body and groundwater, either through seepage from the surface water body, release of bank storage into the surface water body, or other exchanges.

In application of the water budget equation, several terms are often considered to be zero or negligible. For example, for impounding reservoirs and low channel dams, the water budget is typically computed only for the periods after the water level falls below the crest of the spillway or low channel dam, thus QOUT is considered to be zero. Similarly, off-channel reservoirs usually have no outflow.

Groundwater movement to and from the reservoir [GW(t)] is typically the most difficult part of the water budget calculation to assess. All reservoirs lose water through seepage, as the impounded water slowly moves through the dam and its foundation; seep water is often found at the base of earthen dams. Dam seepage is typically less during droughts and other periods of reservoir drawdown (Hudson and Hazen, 1964); the amount of seepage depends on underlying soil properties and the type of compaction and fill material used in dam construction. There will be an additional exchange of water between the reservoir and groundwater adjacent to the reservoir. As the reservoir fills with water, some of the surface water will seep into the groundwater, creating bank storage. When the reservoir water level falls, such as during a drought, bank storage often flows back to the reservoir, counteracting dam seepage losses and in some situations causing a net positive groundwater exchange into the reservoir. The gain or loss from bank storage will depend upon local hydrogeology, but data are rarely available to directly quantify the surface-groundwater interaction. Calculations from selected Illinois water supply reservoirs suggest situations where there is a net positive groundwater flow into the reservoir during drought periods; but in general, reservoir yield calculations in Illinois have ordinarily assumed that GW(t) is negligible (Broeren and Singh, 1989). In contrast, studies of Missouri reservoirs have identified net losses of water from reservoir seepage, and seepage rates have been used in determining reservoir water supply yields (http://www.dnr.mo.gov/env/wrc/drought/RESOPreports.htm). Thus, it appears there may be regional differences in GW(t) within the Midwest. Although no further study on seepage rates was performed, it is suggested that net groundwater losses may be more likely to occur in the western portions of the Midwest compared to the eastern states where high groundwater tables may provide a more sustained release of bank storage to reservoirs during times of drawdown. The computation of GW(t) should always be included in water budget calculations whenever there is evidence of high seepage losses from a reservoir.

Equation 1 can be used as a starting point for developing the equations used to compute the net yield for any type of surface water source. However, the significant terms in this equation may change depending on the types of surface water sources.

Listed below are the variables that would typically be taken into account for each source type:

Source types	*Typical water balance*
Impounding Reservoir; Low Channel Dam	$AW(t) = Cap + QIN(t) + P(t) – E(t) + GW(t)$
Impounding Reservoir with Diverted Inflow	$AW(t) = Cap + QIN(t) + QDIV(t) + P(t) – E(t) + GW(t)$
Off-Channel Reservoir	$AW(t) = Cap + QIN(t) + QDIV(t) + P(t) – E(t) + GW(t)$
Natural Lake	$AW(t) = Cap + QIN(t) – QOUT(t) + P(t) – E(t) + GW(t)$

Computation of Yield

The yield of the surface water body for the period, t, is equal to the available water, AW(t), divided by the duration of the drought t, or Δt:

$$\text{Yield} = AW(t)/ \Delta t$$

Thus, the yield is considered to be the steady amount of water withdrawn over the course of the drought without depleting the supply. For instance, if the available water for a small impounding reservoir system was calculated to be 600 acre-feet during a 60-month drought, its yield would be 10 acre-feet per month or 0.33 acre-feet per day, equivalent to 106,000 gallons per day, a supply that is adequate for most systems that do not have any major water-consuming industries and serve a population of fewer than 1000 people.

For an individual drought, the net yield (also called the safe or firm yield) is determined as the minimum value of $AW(t)/\Delta t$ considering all possible time periods. The value of Δt that produces the net yield for a surface water body is the critical duration. As described earlier, the critical duration is the period between when the reservoir first starts falling below full pool in the early stage of the drought and when the reservoir reaches its lowest level prior to recovery.

To determine the relative adequacy of a supply, this net yield is compared to the quantity of water that needs to be withdrawn to meet demands during this same period. It is important to distinguish between the quantity of water withdrawn and the amount of water customers actually use since unaccounted-for water can comprise a significant proportion of consumption in small community water systems, many of which have antiquated distribution systems prone to leakage. If estimated withdrawals needed during this period exceed the drought yield, the system’s supply sources are likely inadequate for the drought for which they are planning. However, the uncertainty in the results of this yield analysis should be taken into account. Both the uncertainty of hydrologic input data and the assumptions implicit in the water budget model used to generate these estimates contribute uncertainty to the drought yield estimates.

Sequential versus Non-Sequential Analysis

The water budget equation is often applied to a specific time period, for example to a historical drought, where the hydrologic and climatic data used in the equation all represent a specific historical sequence. However, the water budget can also be used to represent synthetic drought conditions that have no historical sequence, such as the 20-year or 50-year drought event. In these cases, termed non-sequential analysis, the streamflow, precipitation, and evaporation components of the equation are typically estimated using statistical analysis of hydrologic and climatic records.

Data Resources for Water Budget Analysis

Measurements and Estimates of Storage Capacity

Reservoir capacity is usually one of the largest and easiest components in the water budget to accurately measure. When possible, values of reservoir capacity should be provided from a documented bathymetric or sedimentation survey; however, most water supply reservoirs have never had such a survey. Many times, a water supply manager will have an estimate of their reservoir capacity, but not know the source of that estimate. If that manager does not have an estimated capacity, chances are that such a value may be obtained from the online database of the National Inventory of Dams (http://crunch.tec.army.mil/nidpublic/webpages/nid.cfm), maintained by the U.S. Army Corps of Engineers. It should be noted, however, that many of the storage estimates in this database are for the maximum flood pools of reservoirs, not the normal pools at spillway level.

The Missouri Department of Natural Resources has funded the U.S. Geological Survey to conduct bathymetric surveys of many small water supply reservoirs in Missouri. Bathymetric survey information for more than 40 Missouri water supply reservoirs can be obtained from the MoDNR Web site: http://www.dnr.mo.gov/env/wrc/drought/RESOPreports.htm. The Kansas Biological Survey has an ongoing initiative, ASTRA: Applied Science and Technology for Reservoir Assessment (http://www.kars.ku.edu/astra/), to measure the bathymetry and characterize sediments for Kansas reservoirs, including most of the reservoirs used for water supply. The Illinois State Water Survey also has conducted measurements for a number of water supply reservoirs in Illinois.

Unless there has been a detailed bathymetric or sedimentation survey of the reservoir, the capacity estimate can be considerably inaccurate. Knapp (2007) found that the standard error in estimated (unmeasured) capacities of an Illinois water supply reservoir was over 24 percent (Table 11). For small reservoirs, with a capacity of less than 1000 acre-feet, the standard error was roughly 31 percent. This means that estimation errors for small reservoirs could be even greater than 31 percent for nearly one out of every three reservoirs. Moreover, Knapp (2007) found that estimated capacities were biased towards overestimation, tending to be larger than measured capacities by roughly 20 percent.

Sedimentation Surveys

Reservoir capacities can be measured by either a bathymetric or sedimentation survey. Both involve measuring lake depth. The sedimentation survey, however, is a more extensive process that involves the physical measurement of the sediment thickness that has accumulated in the reservoir; typically many measurements are taken along established transects across the lake. Reservoir capacities measured by sedimentation surveys using established transects across

Table 11. Average Bias and Error in Estimates of Reservoir Capacity, Illinois Impounding Reservoirs

Original reservoir capacity (acre-feet)	*Average bias (%)*	*Standard error (%)*
0 – 1000	+20.59	31.03
1000 – 5000	+19.33	24.73
> 5000	+ 7.68	16.36

From Knapp (2007)

the reservoir typically are considered to have an error of about 10 percent (Morris and Fan, 1998). Measurement accuracy can be improved if a detailed bathymetric survey, discussed below, is conducted in conjunction with a sediment survey.

The benefits to having a sedimentation survey, as opposed to a depth survey alone, is that the historical rate of lake sedimentation can be calculated, which can then be used to predict future reductions in reservoir capacity resulting from sedimentation. Unless a survey was conducted recently, the capacity of the reservoir should always be adjusted to reflect the losses caused by sedimentation. The use of established transects with the sedimentation survey also provides the ability to reproduce the survey several years later maintaining direct comparison between measured locations. Successive sedimentation surveys would be necessary if a community wanted to assess the effectiveness of erosion control and sediment reduction measures in the reservoir's watershed.

Bathymetric Surveys and Depth Measurements

Detailed bathymetric surveys have the potential to be somewhat more accurate than sedimentation surveys with transects, primarily because the entire surface of the lake bottom, not just selected transects, can be mapped. With recent advances in acoustic depth-sounding and global positioning system (GPS) technologies, bathymetric (depth) surveys can, in concept, be conducted relatively quickly and inexpensively as compared to traditional sedimentation surveys. However, the difference in costs between the two methods may not necessarily be that great if effort is put into maintaining an accurate survey. Accuracy of the bathymetric survey can depend upon several factors, including: 1) the completeness and density to which depth soundings cover the lake; 2) stability of the instrument as influenced by waves and tilting of the boat; and 3) amount of ground-truth data (manual water depth measurement) collected to calibrate depth soundings. For use in determining water supply yield, bathymetric and sedimentation surveys should ideally produce a stage-storage relationship of each lake that can be used to analyze remaining capacity as the water level is drawn down during a drought. Many engineering consulting firms and state and federal agencies now have the instrumentation and computer software for conducting bathymetric surveys.

In evaluating water budgets for impounding reservoirs in Illinois, Knapp (2007) estimated that for short-duration droughts (less than 30 months), an average of 70 percent of their yield came from stored water in the reservoir. For longer drought durations (30 months or longer), an average of 50 percent of the yield could be attributed to the reservoir storage. With reservoir storage being such a sizable component of the yield estimate and depth surveys being the easiest and least expensive option for improving yield estimates, *the first thing a community should consider when assessing their water supply yield is improving their reservoir capacity estimate(s).*

Larger off-channel reservoirs should have depth measurements obtained in the same method as an impounding reservoir. But it may be reasonable in some cases, with a smaller, cut-and-fill off-channel storage reservoir having comparatively uniform dimensions, to calculate capacity using water depth measurements from a number of sample locations over the reservoir surface. Where available, land surveys of the reservoir bottom prior to being filled can provide better detailed information.

For low channel dams, a quick estimate of the storage behind the dam can be made by multiplying the length of the pool created by the dam, the average width of the river from the dam to the upper end of the pool, and the average depth of the pool. The average depth would be calculated from channel cross-section measurements at several spots along the length of the pool. A more accurate estimate can be provided with the same data using a prismatic volume calculation.

Measurements and Estimates of Streamflow

The USGS currently operates 1400 streamgages within the 10-state MTAC region, and historical records are available for thousands of other discontinued USGS gages. In contrast, there are nearly 1 million miles of rivers and streams in the MTAC region. Moreover, comparatively few of the USGS gages are located on streams with small watershed areas that are the typical locations of small community surface water withdrawals and reservoirs. For all these reasons, there likely will not be a USGS gage located near a water supply source, in which case it is necessary to estimate streamflows from gaging records located some distance from the withdrawal or reservoir, rather than to use direct stream measurements.

The estimated inflow into a water body can be developed from one of the three basic sources:

1) Streamflow records from a gaging station located on the same stream as the withdrawal or upstream of the reservoir
2) "Surrogate" streamflow records, adopted for use for the site of interest, but measured from separate streams within a region considered to have similar hydrologic properties
3) Statistical flow summaries or "processed data" from hydrologic transfer methods, such as the analysis of flow frequency, or that use data from multiple streamflow records to either extend short records or develop a "regional" estimate that is applied to a specific stream location. Flow estimates in this last category are ordinarily developed by a trained hydrologist.

Streamflow Records from an Upstream Gaging Station

The most ideal streamflow data for analyzing the water budget are from a long-term streamgage located immediately upstream of the water supply source and where there has been no direct or apparent modification to the flow by human intervention. This ideal data condition usually does not exist, and the period of the flow record, location of the gage, and extent of flow modification are all important factors that collectively should be evaluated to determine the usefulness of the gaging record, as discussed below.

Period of the Flow Record. Whether a flow record is “long-term” is usually defined by the application need, but for analyzing drought conditions, a long-term record is one that would contain a sufficient number of major and moderate droughts to provide the ability to estimate the magnitude and frequency of drought flows. However, regardless of length of record, the existence of a dominant drought within the flow record is the most important characteristic defining the usefulness of the flow record. A short flow record containing the known drought-of-record for that region is considerably more useful than a 30-year record that did not contain any major drought periods.

Location of the Gage. The most useful gage is one located as near as possible to the source of withdrawal. With impounding reservoirs, it may be necessary to locate a streamgage a considerable distance upstream. In such cases, the flow record needs to be adjusted to account for the additional runoff and accretion of baseflow into the stream that happens between the gage and the location of the reservoir. For most cases, the flow in the stream may be considered to be proportional to its drainage area. Thus the inflow at the reservoir, QIN, is estimated as the flow at the gage times the ratio in drainage areas (DA) between the two locations:

$$QIN(t) = Qgage(t) \times DA\ reservoir / DA\ gage \quad \text{..........} \quad (2)$$

Equation 2 is normally considered applicable when the drainage area at the gage is less than 50 percent different from the drainage area at the reservoir, assuming the hydrogeologic character of the stream is not noticeably changed. Under most circumstances, however, the amount of baseflow accreted to streams increases with drainage area. For this reason, if the gaging station is far up the watershed, for example representing only 10 percent of the contributing watershed area to the reservoir, use of a surrogate gage or other inflow estimate should be considered for estimating drought flows.

Extent of Human Modification. To what extent are the watershed conditions from historical flow records representative of the present-day watershed conditions? An effort should be made to verify that there have been no obvious man-made alterations to the river flow since the major drought for which there are records, such as may be caused by construction of a large reservoir or sizable effluent discharges, withdrawals, or diversions. When there are substantial alterations to the flow amount, hydrologists may tend to disregard the streamflow record for periods prior to that alteration. For example, if a reservoir were constructed in 1970, low flow frequencies for the stream might be computed only for the portion of the flow record since 1970. However, when analyzing supply adequacy, this approach may throw out or disregard the portion of the record containing the most severe droughts–with the most important information regarding water availability–because these droughts may have occurred prior to the construction of the reservoir. In such cases, an effort should be made, when possible, to adjust the streamflows from the earlier severe droughts to reflect the expected impact of these alterations on the drought flows. If, over the course of the hydrologic record there has been a large reservoir, diversion, or effluent discharge introduced upstream of the streamgage, the stream’s flow conditions may be permanently altered since the historical drought period of interest; in which case, the earlier flow record needs to be adjusted or neglected. If modifications to the flow amount (e.g., the increase in an effluent discharge amount) can be quantified, it is highly recommended that steps be taken to adjust the earlier drought flow records to reflect the influence of present-day changes. Flow records of major droughts are too valuable to be discarded unless there is no reasonable way to adjust them.

Surrogate Gaging Records

Since gaging records are often not available on a given stream, the use of surrogate streamflow records from another stream is a common method of predicting flow characteristics. The most ideal use of surrogate gages occurs when the watershed of the gaged stream has the same general climate conditions, land use, hydrogeologic character, and drainage area size as the watershed to which the data will be applied. The proximity of the surrogate gage's watershed is often considered to be a good indicator of similar climate, land use, and hydrogeology, although proximity does not always ensure that these characteristics are similar. Drainage area size is one factor that is often neglected by practitioners in choosing surrogate gages, as it may be difficult to find nearby gages on small watersheds. However, large watersheds do not have similar flow patterns to small watersheds. Regardless of proximity and other similarities, it is generally not a good idea to use data from a larger watershed (such as a 500 square-mile watershed), to represent streamflow conditions in a small watershed (such as 6 square miles).

In choosing surrogate gages, attention should be paid to the period of the flow record and the extent of human modification to the watershed upstream of the gage, to the same degree as described previously regarding the use of streamflow records from an upstream gaging station. In particular, if multiple surrogate gages are available with records covering separate drought periods, estimates of water availability and yield may be substantially different depending on which drought period is covered by the surrogate gage.

There is always uncertainty when using surrogate data because the comparative similarity between the surrogate gage location and the stream of interest is never fully known. If more than one gaging record is available for use as a surrogate gage, then it is recommended that alternative estimates of water availability and yield be estimated using different surrogate gage choices. In general, it would be expected that surrogate gages from comparatively larger watersheds would provide comparatively higher estimates of yield. The variation in the alternative yield estimates would provide the user with a rough indication of uncertainty in the estimates. This should be compared to the potential errors associated with regional regression equations developed using multiple gages (described in the next section); regional equation errors would generally be expected to provide a lower limit of the uncertainty associated with the use of surrogate gages.

Regional Regression Equations

In selected regions of the Midwest, regional regression equations may have been developed to estimate low flows and monthly drought flows for ungaged stream locations. In Illinois, for example, such equations have been developed for major watersheds covering more than half the state (http://gismaps.sws.uiuc.edu/ilsam/). A regression equation is a predictive equation that is developed using multiple past observations. In this case, historical streamflow observations from a large number of gages within a region are used to develop an equation that predicts the magnitude and frequency (recurrence) of a particular low flow condition. For example, the equation may predict the lowest one-day flow that might occur on average once in

25 years, or another equation may predict the total amount of flow that might be expected over the worst 24 months of a severe 50-year drought. The flow amounts predicted by the equations typically depend on selected characteristics of the stream's watershed, which may include such factors as the watershed size, average slope of the land, soil characteristics, climatic variables, etc. The equation is typically considered applicable for any stream location in the region that has similar hydrologic properties to the range of properties displayed by gages used in preparing the equations. Most selected regions are considered to have homogeneous hydrologic properties such that the predictive equation can apply to any stream location in the region.

A hydrologic region is assumed to display homogeneous characteristics, but in reality, every stream in the region will display natural variability and bias that is in varying degrees different from the regional average. Thus each gaging record used in the development of the regional regression equations displays unique characteristics that both: 1) help to explain the physical relationships between watershed properties and low flow quantity and 2) collectively add variability and range to the equation. It can be expected that the true flow characteristics for an individual stream will vary from the equation's prediction. This uncertainty, expressed as a standard error of estimate, should be documented for every regional equation. Table 12 shows a typical range in the standard error for Illinois drought flows as estimated by Knapp (2007). For example, regional equations in Illinois for estimating the average flow over an 18-month 25-year drought may be expected to have a standard error of 25–35 percent. In general, the lower value of the range is the expected uncertainty in flows for large watersheds and the higher value in uncertainty is for small watersheds. Equation uncertainty also can vary from region to region; the values in Table 12 may not apply specifically to other states but provide examples of the general level of uncertainties that can be expected.

Table 12 shows that regional equation error for small watersheds and short drought durations can be considerable; for example, the standard error for a 9-month 50-year drought can be as great as 60 percent for small watersheds. Although this appears to be a considerable level of uncertainty, it is important to realize that the 9-month 50-year drought flow for small watersheds in Illinois usually is a very small amount, often representing less than 0.1 inch of runoff. A 60 percent deviation from this amount could be created easily by one moderate storm event. The percentage error in estimating shorter flows such as the one-day minimum flows can be even greater, particularly low flow events approaching zero flow.

Table 12. Standard Errors of Estimate (Percent) When Using Regional Regression Equations to Estimate Average Flow Conditions Over Selected Drought Flow Durations: Example from Illinois

	Recurrence interval		
Drought flow duration	*10 years*	*25 years*	*50 years*
9 months	25-35	25-45	35-60
18 months	15-25	25-35	30-45
30 months	10-15	15-25	20-30
54 months	10-15	12-15	15-20

From Knapp (2007)

The amount of uncertainty associated with regional regression equations is expected to be less than that associated with the use of surrogate gage records. The equations represent the regional average expected conditions, whereas the individual surrogate gage values may be biased and vary considerably from the regional expected average. One drawback to the use of regional equations is that it can be used only for non-sequential analysis. The use of surrogate gages would be necessary when a daily flow record is needed, such as would be useful for analyzing the water budget of off-channel reservoirs. Regional equations are also typically used to estimate flows in selected drought quantiles, such as the 25-year or 50-year drought, instead of specific historical droughts.

Which Streamflow Data Sources are the Best to Use?

Calculation of appropriate streamflow estimates is usually the most critical aspect of preparing a water supply budget assessment, and the aspect that may need experienced judgment if clear cut data are not available. Potential uncertainties in the use of surrogate data should always be considered and the guiding principle should be to select data that minimize those uncertainties. With this in mind, some general principles can be followed, several of which have been discussed earlier. The assumptions in these guidelines are that the user wants to evaluate water supply adequacy during a drought of record or other severe drought.

- *Use the selected flow records in Table 3 as a guide to determine if a flow record from your region is likely to contain a major drought.*
- *If the drought of record has substantially lower flows than other historical droughts, you should want to use flow data only from streamgages that were monitoring during that drought of record, even if the available data are from a gage located farther away.*
- *If flows from other major droughts are similar in magnitude to the drought of record, then you may have a broader choice of available data and may focus on the gage that has the most similar watershed to the location of interest.*
- *A short-term record (without a major drought) from the same stream is better than a long-term record from a different stream only when examining direct withdrawal from the stream, not when analyzing reservoir storage that requires longer-duration flow estimates. Not having a major drought on record can result in a sizable underestimation of drought vulnerability. This assumes that the short-term record does not include the drought of record; otherwise the short-term record would be more valuable because of proximity to the location of interest.*
- *Regional regression equations, if available, are generally considered to have higher value for non-sequential analyses than surrogate gages. However, it may be useful to compare results from both data types*.
- *If there are two or more reasonable choices for a surrogate gage, try using each of them in the water budget calculations. However, it is very important to choose a surrogate gage from a watershed that has a similar drainage area. Smaller watersheds usually produce less water supply yield than larger watersheds.*
- *Simulated low flows from watershed models in most cases are not sufficiently accurate for evaluating inflows and yields during a drought.*
- *Accurate measurements of stream discharge at a water supply intake, collected at various times during a period of severe drought, are useful for analyzing flows when continuous gaging records are not available.*

Because of the nature of estimating streamflow conditions when direct measurements are not available, there can be considerable uncertainty in calculating available water and yield, even when performed by an experienced hydrologist. The most useful yield estimates are those that also can provide a range of uncertainty in their estimate, or can present a range of alternative estimates such as that provided by calculating yield using different surrogate gages.

Measurement and Estimates of Precipitation and Evaporation

Precipitation over a reservoir during a drought period is usually estimated from the nearest precipitation gage. For a typical sequential water budget, the precipitation records should be matched with the period during which streamflow is the lowest, which may not coincide with the period of minimum precipitation. For instance, if a community water system's drought of critical duration (54 months) lasted from September 1952 through February 1957, then the precipitation that occurred during this same 54-month period must be computed. The Midwest Regional Climate Center (mrcc.sws.uiuc.edu) maintains an archive of daily and monthly precipitation data for many stations throughout the Midwest.

Evaporation from an open body of water is very difficult to measure directly. Thus, the amount of lake evaporation usually is represented using one of several estimation techniques. The simplest method uses measured evaporation from a standard Class A pan and makes adjustments to account for systematic differences between pan evaporation and lake evaporation. Most pan evaporation records in the eastern portion of the Midwest have short or incomplete data, however, and for all regions there can be a considerable variability in pan evaporation measurements among sites. Measured pan evaporation overestimates lake evaporation and must be multiplied by a coefficient to estimate lake evaporation. The annual ratio between lake evaporation and measured pan evaporation in the Midwest is expected to range between 0.70 and 0.77 (Farnsworth et al., 1982), but varies considerably by season. Winter (1981) indicated that the variation in the pan coefficient in itself can be a significant source of uncertainty in the estimate of lake evaporation; however, seasonal estimates are expected to be within 25 percent of the "true" evaporation amount (Winter, 1981). Pan evaporation data are not as readily available as many other types of climate data. Water supply managers may want to contact the office of their State Climatologist for such data. Each state may have only a handful of stations providing pan evaporation estimates for any individual drought period.

For Illinois and Ohio, respectively, Terstriep et al. (1982) and Koltun (2001) have developed net evaporation estimates for specific drought durations and recurrence intervals. In both studies, lake evaporation is estimated with empirical equations using climate measurements such as wind speed, relative humidity, temperature, and solar radiation. Use of climate-based equations provides more consistent evaporation estimates than the use of pan evaporation data, but is more difficult to apply for the average practitioner. In the application of the net evaporation estimates by Terstriep et al. (1982) and Koltun (2001) for estimating reservoir yield, the period of maximum net evaporation is typically assumed to coincide with the period of minimum streamflow, although this is a "conservative" assumption that is apt to overestimate net evaporation for a particular drought scenario.

Additional sources of lake evaporation information are the average lake evaporation estimates in the United States Evaporation Atlas (Farnsworth et al., 1982) and average pan evaporation data in Farnsworth and Thompson (1982). Evaporation estimates suggest that over an extended drought period, such as for evaluating reservoirs with long critical durations, lake evaporation may be expected to be 10 percent above average in the eastern half of the Midwest, but as much as 20 percent above average in the western half. Estimates of potential evapotranspiration, such as those developed by the Midwestern Regional Climate Center (mrcc.sws.uiuc.edu) using airport climate data, have also been used as surrogate values for lake evaporation. Whereas potential evapotranspiration is believed to overestimate lake evaporation by perhaps 10 percent, it provides consistent values for most locations. Again, it may be useful to contact a State Climatologist for assistance in obtaining such data.

Knapp (2007) estimates that, during a severe drought, Illinois reservoirs on average may be expected to lose roughly 15 percent of their total storage to net evaporation. An assessment of water budgets for a sample of Kansas reservoirs indicates that they could lose an average of 30 percent of their total storage to net evaporation during a severe drought, with some reservoirs losing up to 50 percent.

Available Hydrologic Design Methods and State Reports

Guidance documents typically are available from state agencies regarding general factors and requirements that must be addressed in evaluating surface water supply systems, as illustrated by the following guidance from the Kansas Department of Health and Environment (1995): “where water is drawn from a flowing stream, river or spring, … flow records should confirm its availability to meet the maximum daily demand for the design period during a 50 year drought with all prior water rights considered.” Outside of such general statements, to the authors’ knowledge only three states (Illinois, Missouri, and Ohio) provide specific technical methods and/or data from which to compute yields and adequacy of supplies.

Illinois State Water Survey Bulletins 66 and 67 (Knapp, 1982; Terstriep et al., 1982) provide hydrologic methods to estimate yields of off-channel and impounding reservoirs, respectively, which can be applied both to estimate yields of existing reservoirs in Illinois and to evaluate potential reservoirs. A similar hydrologic analysis, patterned after the method used in Illinois, was developed by the USGS for use in Ohio (Koltun, 2001). In all these studies, a non-sequential water budget analysis is used to estimate the gross yield for selected values of reservoir capacity using flow frequency analysis of historical USGS stream records. Since the methods are typically applied to ungaged sites, the results for individual gage records have been reduced to a set of graphs and tables that can be applied to other sites with varying watershed and reservoir sizes. Further details regarding the use of these documents are included in the following sections on *Impounding Reservoirs* and *Off-Channel Reservoirs*.

The Missouri Department of Natural Resources (MoDNR) Public Drinking Water Program prepared the *Design Guide for Community Water Systems*, which recommends using a water budget reservoir operations model to determine the capacity of reservoirs, as well as performing a drought study using the 1950s drought of record. MoDNR has also applied these methods to estimate drought-of-record yields for numerous water supply reservoirs throughout Missouri (http://www.dnr.mo.gov/env/wrc/drought/RESOPreports.htm). The Illinois State

Water Survey has also prepared 50-year drought yield and adequacy estimates for community surface water supplies throughout Illinois (Broeren and Singh, 1989). For both the Missouri and Illinois studies, results indicated that more than one-third of the analyzed surface water systems would be either inadequate or marginally adequate (unable to provide for moderate growth in the community's water use) if a severe 50-year drought or drought of record was to occur.

General Guidance for Evaluating Specific System Types

Run-of-the-River Withdrawals

Run-of-the-river withdrawals are considered to be any withdrawals where there are no dams impeding the flow of the river, or where low channel dams have an insignificant effect on the rate of river flow even during the lowest flow conditions. The availability of the supply at any time during a drought condition is determined by the difference between: 1) the flow in the river and 2) the amount of that flow, if any, that is required to pass the point of withdrawal for downstream users and/or instream flow needs. Direct withdrawal systems are typically the simplest to analyze because there is no water storage calculation; however, analysis of this system type is also the most dependent on long-term flow data from a nearby gage. Of all system types, this is also the one where the expected water availability should have a large margin of safety. In contrast to storage systems, there is little time to either adjust water use or find supplemental supplies prior to the period of water shortage. Low channel dams are often built on rivers in locations where the low flow availability may be marginal with respect to the community's water needs.

Determining the Minimum Drought Flow in the River

For these types of withdrawals, the existence of a long-term streamflow record for the river at or near the point of withdrawal is essential for assessing the availability of the supply during drought. It is not merely sufficient that the record be long-term, but that the record contains a major drought period that is representative of one of the worst droughts on record. If a gaging record is not present on the stream of interest, an assessment of the drought vulnerability of the system must rely on past performance of the system during major droughts. If there is no gage record upstream or downstream of the withdrawal, it is not recommended that minimum flow records from a nearby stream be used for this assessment, as local hydrogeologic conditions may cause considerable differences in the minimum flow amounts between two streams. The use of surrogate gage records from other streams is too uncertain when trying to predict the drought vulnerability of stream withdrawals.

Generally, yields from a direct withdrawal source can be estimated using the average daily flow rate. This duration accounts for the approximate one day's worth of treated water storage that systems have available. If the record one-day minimum flow is lower than the expected peak daily demand, the flow is relatively inadequate for the system's demand. From an examination of the minimum flows in Table 3 it is noted that the flows from the drought of record may be noticeably lower than flows in other major droughts. Thus, if possible, flow records should be examined from what is believed to be the region's drought of record.

Most run-of-the-river withdrawals are located on larger streams on which it is likely that the U.S. Geological Survey has operated a gaging station. For example, all of the run-of-the-river withdrawal systems contacted during this study have a nearby streamgage from which minimum low flow values could be extracted (although in some cases the system operators were unaware of the gage). If the withdrawal is located some distance upstream or downstream of the gage, the gaging record is typically considered acceptable for analysis if the drainage area at the gaging station is within 50 percent of the drainage area value at the point of withdrawal. An accepted rule of thumb, presented earlier, is that the low flow rates at the gage and point of withdrawal are considered to be proportional to the drainage areas at the two locations. This assumes that there are no known hydrogeologic conditions or man-made alterations that would alter the expected low flow relationship between the gage location and point of withdrawal.

As discussed earlier in *Measurements and Estimates of Streamflow*, an effort should be made to verify that there have been no obvious human alterations to the river's flow or changes in water use since the major drought for which there are records. Where flow alterations exist, the streamflows from the earlier severe droughts should be adjusted when possible to reflect the expected impact of these alterations on the drought flows. However, such adjustments are not always possible.

Determining Protected Instream Flows or Considerations for Downstream Users

Water supply operators should verify that there are no required protected flows for their stream location that would limit their withdrawal of water. Several Midwestern states have instream flow requirements that would apply to new public water supply withdrawals, but typically do not apply to "grandfathered" withdrawals that existed prior to the establishment of instream flow requirements. This study does not attempt to investigate or summarize these legal requirements.

Withdrawals at Low Channel Dams

Low channel dams are typically located on smaller rivers and streams where a small dam is needed to provide a pool in the stream where a submersible pump can be situated. In some of these cases streams may flow sufficiently at all times so that there is always flow over the dam, in which case the system should be assessed as a run-of-the-river withdrawal without consideration of the water stored behind the dam. But in other cases, storage behind the dam may be needed to provide water for periods within a major drought when the streamflow alone is insufficient to meet the withdrawal needs of the community. During the period when the streamflow rate is insufficient to meet the withdrawal demands, flow over the low channel dam will cease and pumping will draw from the water stored behind the dam.

As with run-of-the-river withdrawals, an assessment of the drought vulnerability of low channel dam withdrawals requires flow data at or near the point of withdrawal. However, because low channel dam systems are typically located on smaller streams, such records are less likely to be available. If flow records are not available, an analysis of drought vulnerability is dependent on past performance of the supply. Has the flow over the channel dam ceased in previous drought periods? If so, for how long? If the community water use has not changed substantially over the years, these answers might be determined using local accounts and anecdotal evidence from previous major droughts. Again, efforts should be taken to identify evidence available from what is believed to be the drought of record and other major droughts for the region.

For the period when the streamflow is insufficient to meet the water withdrawal demand, the adequacy of supply during pool drawdown must be evaluated through a water budget analysis similar to that used for impounding reservoirs, discussed in the next section. The storage capacity of the pool behind the dam should be measured if it is not known, not only for assessing system yield, but also for the purpose of drought response management. As with an impounding reservoir, there is a possibility that the storage behind the channel dam may have been diminished over time as a result of sedimentation.

Case Study: Flora, Illinois

Although Flora switched water supply sources in 2008 and no longer withdraws from the Little Wabash River, it provides an excellent example of the type of assessment that is needed for low channel dam systems. Prior to 1955, Flora obtained its water by direct withdrawal from the Little Wabash River. For a few weeks in October 1953, the river was barely sufficient to supply the city's water use of 0.6 million gallons per day (mgd) (1.0 cfs). Then, for at least 17 days in September 1954, the river flow was unable to fully supply the city, and additional water had to be obtained by pumping water from various pools located along the river. The channel dam was constructed later that year, and at that time the dam was reported to have a storage capacity of 50 million gallons.

Since 1915 the USGS has monitored flow in the Little Wabash River near Clay City, located 27 miles downstream of the Flora dam. The river's drainage area at the dam is 760 square miles, or roughly 33 percent less than the 1131 square-mile drainage area at the USGS gage. From 1965 to 1982 the USGS also had a flow gage at Louisville (745 square miles), located only 4 miles upstream of the Flora dam, but this flow record does not include any significant drought periods. The flow at the Flora dam during a drought can be approximated by reducing the observed flow at the Clay City gage by 33 percent; however, prior to this computation, the amount of flow at Clay City should be adjusted, adding the amount of flow taken out of the river by the Flora withdrawal (1.0 cfs). For example, if the observed flow at the Clay City gage was 0.3 cfs, the unaltered flow (minus the 1.0 cfs Flora withdrawal) might have been expected to be roughly 1.3 cfs. This can then be reduced by 33 percent to estimate the unaltered flow (0.9 cfs) upstream of the Flora withdrawal.

With these flow estimates, the critical missing piece of information in a water budget analysis is the amount of storage available behind the Flora dam. There has never been a measurement of the storage behind the low channel dam. Even if the original capacity of 50 million gallons was accurate, sediment deposition over the past 50 years may have decreased the storage amount. If the storage amount had decreased to as low as 10 million gallons, the storage may not have been sufficient to supply Flora if conditions similar to the 1954 low flows had recurred. Larger amounts of storage might have provided the potential for modest growth in the city's water use (which had increased to 0.7 mgd in 2005). In summary, if the city had continued using the river for its water supply, it would have been advisable for it to conduct a depth survey of the low channel dam to determine its yield during a severe drought.

Impounding Reservoirs

Impounding reservoirs are bodies of water that are created when a dam is constructed across a stream channel and its valley, completely obstructing downstream flow. This impoundment inundates the valley immediately upstream from the reservoir, including those portions of tributary valleys that flow into this reach of the river. Water supply reservoirs usually store enough water to provide a community with water through long drought periods during which there is little or no inflow into the reservoir, with drought periods lasting anywhere from six to nine months (typically in the eastern Midwest) to five to six years (in the western Midwest). The most important step a community needs to take in evaluating their drought vulnerability is to obtain a current and accurate estimate of the capacity of the reservoir, if one isn't already available.

When evaluating the capacity of the reservoir (CAP) to the expected cumulative inflow during a drought, both amounts can be expressed as an equivalent *inches of runoff* from the watershed. To convert reservoir capacity (acre-feet) to total inches of runoff, it is necessary to know the drainage area (DA) of the reservoir's watershed in acres:

$$\text{Equivalent inches of runoff} = 12 * \text{CAP} / \text{DA}$$

Most water supply reservoirs in the Midwest store between 1.5 and 10 inches of runoff. If the reservoir storage represents a relatively low amount of runoff, it is possible that the reservoir may be capable of refilling after only a relatively short drought period, perhaps less than one year. In contrast, if the reservoir storage represents a relatively high amount of runoff, it could potentially take several years of drawdown before the reservoir was able to fill during a major drought—assuming that the reservoir was being used to its fullest capability.

As described earlier in *Geographic Differences in Hydrologic Impacts*, the flow values in Table 3 may be used to provide a rough indication of the refill capacity of a reservoir and the expected critical drought duration for specific regions of the Midwest. Understanding the critical drought duration of a reservoir system is not only important in estimating its yield, but also has a profound effect on the types of drought response and demand management plans a community may choose to pursue. For example, if a community has a critical duration of nine months or less, there will be a relatively short amount of time available for drought response once the occurrence of drought has been recognized.

In the application of reservoir yield analysis, the water supply drought is considered to start when the reservoir first begins to fall below full pool; thus the reservoir is considered to be at full capacity at the onset of the drought period. The *critical duration* (or critical drawdown period) over which the yield is computed is the duration between drought onset and when the reservoir reaches its lowest level. The public often perceives that a drought continues beyond its critical duration as the reservoir level begins to recover, but recovery time is not directly related to the estimation of yield.

The amount of precipitation that falls directly into a reservoir and the amount of water that evaporates from its surface during a drought period often are evaluated jointly, with the difference of these two variables (evaporation minus precipitation) termed as net evaporation. Both precipitation and evaporation amounts depend upon the reservoir's surface area, which decreases as the reservoir is drawn down. The net evaporation will be overestimated if the surface area of the lake at full pool is used for water budget calculations. Although the change in surface area with drawdown can be provided with a bathymetric survey of the lake, usually an empirical reduction factor is used instead; for example, Stall (1964) estimated average lake surface area over the course of a drought as roughly 65 percent of the surface area at full pool.

The surface area at full pool also can be measured from USGS topographic maps or aerial photographs. Use of aerial photographs typically is preferred because they provide greater detail and are often more current, the latter quality being important as sedimentation may reduce surface area of a lake over time. Bathymetric surveys have the potential to accurately provide the change in surface area with drawdown. Not all water stored in a reservoir can be affordably withdrawn and treated. Portable pumps may be needed if the water level falls below the deepest intake. The deepest part of the reservoir may not be available for use because of access limitations or water quality issues. In determining yields of Illinois reservoirs, Broeren and Singh (1989) considered 90 percent of the reservoir capacity as usable.

Finally, a QDIV(t) term (diverted flow) can be included if supplemental sources, such a groundwater or pumping from a nearby river, provide additional water to the reservoir. Its amount should reflect operational policies that determine when secondary sources are accessed. If the water is artificially pumped into the reservoir, limits of the pumping system must be taken into account. These limitations are further described in methods used for computing the yields of off-channel reservoirs in the section below.

For existing Illinois and Missouri community water supply reservoirs, estimates of drought yield and supply adequacy may have already have been performed by the Illinois State Water Survey or Missouri Department of Natural Resources. Thus water system managers may want to contact these agencies before beginning their own assessment of drought vulnerability. Hydrologic design manuals also exist for use in locations in Illinois (Terstriep et al., 1982) and Ohio (Koltun, 2001), which include precalculated components so that users do not need to conduct full water budget analyses. In these manuals the primary choices made by users are the selection of surrogate gages to be used in the yield evaluations. In states where design manuals or existing yield estimates are not available, a drought-of-record water budget approach similar to that used in the Missouri Reservoir Operation Study (RESOP) is recommended.

Case Study: Hammertown Lake, Ohio

Hammertown Lake is the primary water supply for Jackson, Ohio. The lake is reported to have a watershed area of 3.14 square miles, a surface area of 165 acres, and a capacity of 2,481 acre-feet, which is equivalent to a watershed runoff volume of 14.8 inches. Long-term USGS stream gages on Ohio Brush Creek and Wakatomika Creek, listed in Tables 2 and 3, are located 45 miles southeast and 70 miles northeast of the lake, respectively. As shown in Table 3, the 1950s drought is the drought of record for both Ohio Brush Creek and Wakatomika Creek. Based on the runoff values for these two gages (Table 3), it is estimated that the critical drought duration (refill duration index) for Hammertown Lake would be roughly 30 months.

A first step in preparing a water budget analysis of the lake is to identify potential surrogate gages to use in estimating inflows. A search for historical USGS streamflow records from the general vicinity of Hammertown Lake identified the following gaging records:

USGS gage	*Location description*	*Drainage area (sq mi)*	*Period of record*
03201902	Raccoon Creek near Bolins Mills	100.	1984-2008
03201929	Zinns Run near Radcliff	3.41	1988-1991
03201947	Strongs Run near Ewington	15.8	1988-1991
03201980	Little Raccoon Creek near Ewington	205.	1984-2008
03235500	Tar Hollow Creek at Tar Hollow State Park	1.35	1947-1979
03236500	Little Salt Creek near Jackson	76.1	1925-1932
03236000	Salt Creek near Londonderry	286.	1939-1950

Note: Lists of USGS gages for specific counties can be obtained by going to the USGS Surface Water Data Web site (http://waterdata.usgs.gov/usa/nwis/sw) and designating the geographic area (state) of interest before selecting "daily data."

Following the guidelines presented in *Data Resources for Water Budget Analysis,* the preferred surrogate gage records should have a watershed size similar to that of Hammertown Lake and should have a gaging period that contains the expected drought of record. Based on these criteria, the Tar Hollow Creek gaging record is the best choice for a surrogate gage. The Zinns Run gaging record might have provided a second desirable surrogate gage because the 1988 drought also was one of the worst on record in this portion of Ohio; however, its short period of record does not fully cover the duration of the 1988 drought. Because no other nearby gaging records include the 1950s drought of record, the gaging record from Ohio Brush Creek is used as a second gage for comparing water budget results.

Net evaporation estimates for a 50-year drought at Columbus, Ohio were taken from Koltun (2001) and used for the 1950s drought-of-record water budget analysis. The effective surface area of the lake during the drought was computed to be 65 percent of the surface area at full pool. The amount of available storage (CAP) in the lake was assumed to be 90 percent of the full capacity. Equation 1 was used to compute available water for various drought durations ranging from 18 to 60 months. The QDIV, QOUT, and GW components of Equation 1 were assumed to be equal to zero. When the streamflow amounts from the 1950s flow record at Tar Hollow Creek were used for QIN, the reservoir was estimated to have a critical duration of 42 months and a yield of 1.13 mgd. In comparison, when the streamflow amounts from the 1950s flow record at Ohio Brush Creek were used for QIN, the reservoir was estimated to have a critical duration of 32 months and a yield of 1.57 mgd. It is believed that the differences in critical duration and yield can be explained by differences in the watershed sizes between Tar Hollow Creek (1.35 square miles) and Ohio Brush Creek (387 square miles). Smaller watersheds tend to have comparatively less flow during drought periods; thus, using the flow record from a larger watershed may inappropriately inflate the yield estimate. Because the size of the Hammertown Lake watershed is only 3.41 square miles, the yield computed using the Tar Hollow Creek record, 1.13 mgd, is considered to be the more appropriate estimate.

Case Study: Carbondale, KS

Carbondale is a town of 1468 people located in eastern Kansas' Osage County. Customers from two rural districts with an estimated population of 10,000 people receive about 10 percent of their water from Carbondale, effectively raising the service area population (SAP) to 2468 people. Strowbridge Reservoir (a.k.a. Carbondale Lake), the system's lone supply source, receives runoff from a 5 square-mile contributing watershed primarily covered with agricultural land. No major streams flow into the reservoir and its inflow is not gaged at any location. No other major purveyors have water rights to the lake.

A sedimentation survey of Stowbridge Reservoir was completed in 2006 as part of the Kansas Biological Survey's ASTRA initiative (http://www.kars.ku.edu/astra/), producing a capacity estimate of 2700 acre-feet. This capacity is equivalent to 10.1 inches of runoff over the watershed. The reservoir is located less than 15 miles from the USGS gage on Salt Creek near Lyndon, for which drought flow values are included in Table 3. From these values, it is clear that the critical drought duration (refill duration index) of the reservoir would likely be 60 months or longer. The Salt Creek record was chosen as the best surrogate gage for this location. Unfortunately, the streamgage's drainage area is more than 20 times larger than the reservoir's, but there are no other long-term gages in the state that have a drainage area less than 100 square miles and span the duration of the 1952–1957 drought. An initial water budget analysis, conducted with a drought duration of 60 months and assuming that 90 percent of the reservoir's storage was available for water supply (2430 acre-feet), produced a yield estimate of 0.29 mgd. When other drought durations were considered, not limited to the durations presented in Table 3, it was found that the critical duration was instead 58 months, producing a yield estimate of 0.23 mgd. It is clear from this example that a comparatively small change in duration can, in some cases, make a noticeable difference in the yield estimate.

In calculating its yield, the water budget for Stowbridge Reservoir can be broken down into three basic components: 1) the starting (full) capacity of the lake; 2) the watershed inflow over the 58-month period; and 3) the net evaporation (total evaporation minus precipitation) over the 58 months. If the available reservoir capacity (2430 acre-feet) was analyzed separately, it would be equivalent to a yield of 0.45 mgd over 58 months. Similarly, the watershed inflow and net evaporation amount to yields of +0.05 mgd and –0.27 mgd. Thus, the net evaporation consumes over half of the available water from the reservoir and its inflow. It is also clear that the amount of inflow over 58 months adds only a small portion to the overall water budget of the lake.

Off-Channel Reservoirs

In the case of off-channel storage reservoirs, analysis of the diverted flow amount (QDIV) must jointly consider the availability of water in the initial source of supply (stream) and the portion of that water that the pumping system is capable of delivering. The water budget approach distinguishes the inflow that naturally enters the body of water from its upstream contributing area (QIN) from inflow that is artificially diverted into it (QDIV). Many off-channel reservoir systems do not receive runoff from a contributing area, in which case QIN = 0. However, inflow must be considered when impounding reservoirs on small watersheds are also used to store water pumped from a larger river.

QDIV represents the volume of water that is pumped from an intake on a nearby river that does not flow into the reservoir. Thus, the design of a pumping system affects the amount of water available for sustaining reservoir levels during droughts. The number of pumps, their maximum pumping rates, and their ability to pump water at lower than maximum rates all affect the amount of water that can be withdrawn from the stream and added to the reservoir. Fixed-speed pumping systems can only pump water at near their maximum capacity (for example, at 1000 gallons per minute [gpm]) while variable-speed pumping systems have motors that can pump at a defined continuous range of discharges (Knapp, 1982). Hence, a source with a fixed-speed pump cannot withdraw water when streamflow drops below its pumping rate, while a system with variable-speed pumps has some flexibility to continue withdrawing water at lower rates. In many cases, systems will choose to use several fixed-speed pumps that have varying pumping rates.

To determine the amount of diverted water that can be pumped from a river into an off-channel reservoir, it is necessary to examine the drought flow record of the river on a daily basis to determine whether the available pumps could be used on that day. Thus, the water budget requires a sequential analysis as opposed to the non-sequential analysis typically used for impounding reservoirs (which accounts for cumulative inflow regardless of sequence).

The importance of this consideration can be illustrated using daily streamflow from the 1953–1954 drought of record for the Skillet Fork at Wayne City, Illinois. For a 208-day period from July 23, 1953 to February 15, 1954, the average flow at the streamgage was 0.62 cubic feet per second (cfs). If the flows during this period were assumed to be constant, as is often the case when using non-sequential analyses, then no water could have been pumped into the city’s off-channel reservoir since that flow rate is insufficient for the system’s 500-gpm (1.12 cfs) fixed-rate pump. However, there were 19 days during this period when the flow exceeded 1.12 cfs, during which the pump could be used and a substantial amount of water could be added to the off-channel reservoir. The flow during these 19 days accounted for 61 percent of the cumulative flow during the entire 208-day period. Storm runoff interspersed between low flow periods can, in many cases, significantly increase storage in off-channel reservoir during droughts. A non-sequential analysis cannot account for this intra-drought pumping, thereby showing the importance of using daily sequential flows in the water budget assessment.

Although off-channel reservoirs are ordinarily designed to provide a supply of water during droughts when the stream lacks sufficient flow, in many cases the reservoirs also may be used when the quality of the stream water is poor, for example, when the concentration of nitrate, arsenic, atrazine, or some other constituent is above the U.S. Environmental Protection Agency’s maximum contaminant level, or when turbidity or algae cause taste and odor problems. The use of the off-channel storage for water-quality management may leave the reservoir partially empty at the start of the drought period. In these cases, it may be necessary to separate the reservoir storage into a water quality control component and a drought supply component, and size the reservoir so that it has sufficient storage to provide water during successive periods of quality management and drought.

Off-channel reservoirs are often located next to smaller-sized streams and rivers, which are less likely to have streamflow records when compared to direct withdrawal systems on larger rivers. If a flow record at the stream source is not available, then use of a surrogate gage record from a similar stream may be the only way to predict the number of days that an off-channel reservoir does not receive diverted water. However, a community might prepare other records, taken during dry years, which would be valuable in a future assessment of water availability when used in conjunction with surrogate flow records. Daily pumping logs can describe when the river was unable to provide diversion water either because of a quantity or quality consideration. An account of the days that a river or stream ceases to flow can also be useful. It is not necessary for the stream to have a dry bed to denote zero flow, only that there is a nearby bar or riffle crossing the entire width of the stream over which there is no observed flow. If the stream has a low channel dam, records could denote the days when the stream ceased to flow over the dam, either on its own or as induced by withdrawals.

Case Study: Wayne City, Illinois

A prior paragraph in this section described the low flow condition at Wayne City during the 1953–1954 drought of record. Although the capacity of Wayne City's off-channel reservoir (OCR) has not been measured, it is estimated to be 164 acre-feet, equivalent to a 178-day supply at the average use of 0.3 mgd. Additional storage (17 acre-feet) exists in the pool behind the low channel dam on the Skillet Fork, the location of the stream withdrawal. A bathymetric survey of the OCR and the channel dam pool would be needed for a more accurate assessment. The estimated days of storage does not consider: 1) the likelihood that water use is above normal during drought and 2) the impact of net evaporation on the reservoir level. During a severe six-month dry period, the total net evaporation from the OCR can be more than 24 inches.

The quality and treatment of the water from the Skillet Fork is a concern, as can be the case with many off-channel systems. Water from the Skillet Fork is not usually pumped from the stream during months in the late spring (typically May and June) when atrazine levels are typically high. The OCR may be drawn down as much as 6 feet during this time, using over 40 percent of the available storage. Following this period of water quality management, it is possible that there is little opportunity to refill the OCR before streamflow becomes very low in July, as has occurred in several major droughts, including the 1953–1954 drought of record.

A sequential water budget scenario, using the present Wayne City system but climatic and hydrologic conditions from the 1953–1954 drought, was prepared using: 1) daily flow records from the Skillet Fork; 2) precipitation from the Wayne City gage; and 3) lake evaporation assumed equal to potential evapotranspiration, as estimated by the Midwestern Regional Climate Center using climate data from Evansville, Indiana, located 50 miles to the southeast. Seasonal water use using was estimated to be approximately 0.4 mgd during the June–August period, 0.25 mgd from November through April, and 0.3 mgd in the remaining months. It is assumed that the OCR would be full at the beginning of May, and that water would not be pumped from the Skillet Fork during the May–June period of low stream quality. After July 1, it is assumed that all low flows in the Skillet Fork would be captured by the channel dam and transferred to the OCR. The channel dam pool level would be drawn down to prevent overflow except when the streamflows exceed the pumping capacity. The analysis indicates that, even with an aggressive strategy to capture all low flows, the OCR would go dry by December 1953.

In late 2008, one of the rural water districts that purchased water from the Wayne City system switched its supplier and now purchases water from a larger regional water supply system. Although this switch was apparently prompted by economic considerations, the move reduced the drought vulnerability for both the rural water district and Wayne City. As a result of the more than 40 percent reduction in its average water use, the Wayne City system is now expected to be fully capable of providing an undiminished supply of water through a record drought condition similar to the 1953-1954 drought.

Natural Lakes and Quarries

There are no easily applied methods for estimating yields of natural lakes or quarries. Water levels in these surface water bodies may be maintained by either surface inflow or groundwater seepage. If there is a significant groundwater contribution, it may be difficult to quantify, which may make use of a water budget approach impractical. If the origin of a lake is natural, but an outlet structure has been created that causes lake outflow to cease during dry years, then the lake may be evaluated in the same manner as an impounding reservoir. On the other hand, if there is natural surface drainage from these water bodies, it may not cease during drought periods. Even if measurements of QOUT were available, an accurate assessment of drought vulnerability might be provided only if there were also measurements of lake level changes during historical drought periods.

Multiple Source Systems

The methods presented previously can be used to estimate the drought yields of individual water supply sources. However, many systems depend upon more than one source for their water supply. When evaluating the combined yields of several sources, it is necessary to make sure that the yields are all computed using the same time frame or drought duration. For example, if one impounding reservoir has a critical duration of 18 months and another reservoir has a critical duration of 54 months, the total yield of the two reservoirs is not the simple addition of their yields. It would be necessary to compute the yields of each reservoir using the same drought duration and then adding the results; in this way it is possible that the critical duration of the combined two-reservoir system could be 18 months, 54 months, or some duration in between. The following guidelines are given for evaluating yields of various source combinations.

<u>The treatment plant receives water from multiple sources that are not interconnected</u>. The drought yields of each source should be computed separately using a common drought duration and added together. The selected drought duration is the one that minimizes total yield.

<u>Two reservoirs share a common contributing watershed area</u>. Many community water systems have more than one impounding reservoir connected “in series,” in a manner such that the outflow from one reservoir provides a portion of the inflow for the second reservoir. In some cases, water from the lower reservoir may be pumped to the upper reservoir, where the treatment plant intake is located. The yields of the reservoirs may be calculated separately using a

common value of drought duration, but with this approach the estimated inflow to the lower reservoir should assume that there is no contribution from the upper reservoir, excluding both the contributing watershed area and possible outflows from the upper reservoir.

Surface water production is supplemented by groundwater pumpage or water purchased from nearby purveyors. If supplemental water is provided on a full-time basis, the average daily supplemented amount can be added to the yield of the surface water source to estimate total system yield. However, if groundwater is pumped or water is purchased only after a reservoir level reaches a low threshold, only the portion of time that supplemental water is provided should be added in the calculation. Any physical limitations on groundwater withdrawals or contractual limitations for purchased water should be considered as well.

Combinations of the previous four configurations. First, the yield from any sources in a series should be computed. Then, yields from each set of sources with separate connections to the treatment plant should be computed. After the total yield from all of the surface water sources from which the system produces water is computed, then water from wells and external purveyors can be added to the total.

Case Study: Wauseon, OH

This case presents an example in which the use of multiple water sources in a partnership with nearby communities was used to solve both water supply and water quality problems. The community of Wauseon in northwestern Ohio, with a service area population of 8000 people, had repeatedly faced water shortages during droughts, including the 1988 event that caused water supply hardships throughout the Midwest. The system pumped runoff from two small watersheds with drainage areas of 3.8 square miles and 3.7 square miles into two off-channel reservoirs with respective storage capacities of 300 million gallons and 75 million gallons.

After the 1988 drought, the possibility of purchasing water from the nearby village of Archbold’s Tiffin River source was discussed. However, negotiations sputtered out because Archbold stated that Wauseon’s service would be shut off if the Tiffin River could not supply enough water for Archbold during a drought. Another drought afflicted Wauseon in 1998–1999. The mayor of Wauseon issued a voluntary conservation advisory during fall 1998, which stayed in place until spring rains alleviated the shortage the following year. Arcadis Engineering, Inc., a consulting firm that regularly contracts with Wauseon’s water system, proposed a solution that would increase Wauseon’s water supply without causing it to be dependent upon another system. The city of Napoleon, located along the northern bank of the Maumee River seven miles south of Wauseon, had a reliable source of water from the Maumee River. However, this water often has high nitrate and turbidity levels. Previous attempts to build a reservoir that could store water with lower nitrate and turbidity levels for periods when these concentrations are high had failed since Napoleon would need to buy land, build a reservoir, and pump the water several miles back to its downtown treatment plant. Arcadis Engineering, Inc. saw a potential cooperative solution that would save money for both communities. A water line running from Napoleon’s Maumee River intake to Wauseon’s two reservoirs could be used to (1) boost reservoir levels during periods when the Stuckey and Big Ditches were providing insufficient inflow into the reservoir and (2) gravity feed Napoleon water when nitrate and turbidity levels in the Maumee River were too high.

This mutually beneficial solution attracted the interest of both communities, and they signed a contract for the project in 1999. Napoleon financed $2.4 million while Wauseon agreed to furnish $4.6 million or the remaining costs. Napoleon’s contribution included the $1.4 million value of a 1 mgd supply to Wauseon for 25 years. Intakes on the Maumee River and in Wauseon’s reservoirs were also renovated to facilitate this service, and the new 24-inch water main came into operation in November 2001. In 2002, many communities in northwestern Ohio had water supply problems during a summer drought. However, Wauseon, now with a dependable supply from the Maumee River, was unaffected. The following winter, many towns obtaining their water from the Maumee River were subject to high nitrate advisories. However, Napoleon could obtain stored water with lower nitrate concentrations from Wauseon’s reservoir. Other community water systems relying upon inflows from small watersheds that are located near relatively large rivers could apply this basic model.

The Role of Demand Management in Evaluating Drought Vulnerability

An assessment of the drought vulnerability of water supply systems would not be complete without also addressing the potential for using demand management to reduce drought vulnerability. Demand management can be applied in two ways, as a response to drought conditions and as a longer-term water conservation program that reduces the overall water use of a community during all years.

Most drought response plans focus on restricting outdoor water uses, such as lawn watering. These restrictions may work well in reducing water use during summer months, but have relatively little effect on water use in the Midwest from October through April. For example, mandatory outdoor water restrictions implemented throughout northern Georgia in late 2007 were successful in reducing May–August 2008 water use by more than 20 percent compared to 2007 values, whereas total water use in the winter and early spring declined by roughly 6 percent (Georgia Department of Natural Resources, 2008). The reductions in winter may have come as a result of other voluntary conservation measures not related to outdoor water use.

The timing of hydrologic droughts in the Midwest often limits the effectiveness of outdoor water use restrictions during the first year of a drought. Many hydrologic drought periods, particularly those in the eastern Midwest, start in early summer, and the impact of the drought on water supplies such as reservoirs is often not recognized until late summer or fall after a hot and dry summer has already produced high water use and excessive drawdown in reservoir levels. In these cases, heightened awareness of the drought conditions and subsequent drought response measures often occurs too late to cause a substantive reduction in seasonal water use. Outdoor restrictions may be particularly ineffective for systems having a critical duration of 12 months or less, in which the reservoir would be expected to return to full pool by the next summer season.

Examples of several intensive water conservation programs suggest that some communities may be able to reduce their overall water use by up to 20 percent. Such a reduction was accomplished in Portland, CT, described in the case study at the end of this chapter. On a much larger scale, Chicago, IL was able to reduce their water use over 10 years (1995–2005) by nearly 20 percent, from 1.1 to 0.9 billion gallons per day. This reduction included broad implementation of water-saving devices, better metering to identify water losses, improvements in infrastructure, and enforcement of allocation restrictions to satellite users. Whether a small community can accomplish similar long-term reductions depends on many factors, including age of the community and whether previous efforts have already resulted in some level of conservation. If much of the housing in the community is new, infrastructure improvements and retrofitting of water-saving devices may offer little potential for conservation. Unaccounted losses in water distribution are typically greater for older systems, but small communities may have limited revenue to afford the infrastructure remedies needed to address these losses.

In addition to the technological changes, such as installing more water-efficient fixtures in homes, conservation can be accomplished by encouraging behavioral changes in citizens and businesses. But in many ways, technological changes are more easily accomplished. Bringing about behavioral changes in the populace usually requires an acceptance that such changes are the only solution to a water crisis. Citizens may be willing to sacrifice outdoor water use during periods of drought and potential shortage, but not so willing on a full-time basis.

The impact of conservation on a community's drought vulnerability may also depend on how the community responds to the reduction in water use. Successful long-term conservation programs can make municipal officials believe that their community has a water supply surplus that can be used to accommodate new industries or residential developments. However, if these conservation savings are allocated to new customers, the system may become more vulnerable to droughts because there are fewer new conservation measures that can be used to reduce demand during a drought.

Demand management can reduce a system's vulnerability to a drought, but should never be viewed as a replacement when an additional or augmented source of supply is needed. If current water use exceeds the estimated system yield, then supply augmentation is most likely needed even if conservation measures are also implemented. In contrast, if the system yield (taking into account uncertainties in yield estimation) exceeds the current water use, a successful conservation program may be an appropriate response to delay or avoid the need to develop additional supply sources. However, the authors know of no way to predict exactly how much water a community can save by implementing a long-term conservation program. Thus it is recommended that the community should act and not make decisions based on the promise of potential water use reduction that may not come to pass.

A wide variety of publications and resources related to water conservation are available, from which two useful internet resources are listed. An American Water Works Association Web site (www.waterwiser.org) provides a clearinghouse of information related to water use efficiency. Similarly, an Illinois State Water Survey Web site provides links to water conservation Web sites for various states across the nation (http://www.isws.illinois.edu/wsp/watermgmtoptns.asp).

Case Study: Portland, CT

Although Portland, Connecticut is not located in the Midwest, some of the experiences from this case study are applicable for older community systems in the region containing fixtures whose water consumption exceeds NEPA (National Energy Policy Act) water use standards. In 1990, the State of Connecticut mandated all community water systems containing more than 1000 service connections to disperse water-conservation kits to all customers. The town of Portland, with a system serving just 8300 residents, did not have the financial resources to deliver these kits to their customers. With just four employees, the system could not afford to hire a conservation specialist nor assign these duties to existing staff members, who were already quite occupied with other aspects of the system's operations. The town-tech program, a unique high school program in which students receive instruction from both Portland High School and local businesses and agencies, provided an alternative means of garnering conservation assistance. In 1991–1992, students delivered conservation kits to customers throughout the utility's service area. Seminars were held prior to the distribution of these kits to educate students about water conservation in general and prepare them for questions that customers may have. Then students went door-to-door delivering kits with the following devices to customers:

1) Low flow showerheads
2) Faucet aerators
3) Toilet displacement bag or dam
4) Dye tablets for toilet leak detection
5) Conservation booklet

This innovative program reduced the community's water use by nearly 20 percent. These savings made it unnecessary for Portland, then reliant upon just one 0.5 mgd well, to continue applying for a permit to divert water from the Connecticut River that they had sought prior to this program. The decision to grant a major role to high school students also kept program costs at a minimum. Yet small water systems also must consider the revenue losses that may occur from implementing conservation programs. The community saved nearly 20 percent in water, but lost 20 percent of its revenue.

Summary and General Recommendations

This study concentrates on the drought vulnerability of small community water supply systems in the Midwest that obtain their water from surface water bodies, such as rivers, streams, natural lakes, and man-made reservoirs. The vast majority of small surface water supplies in the Midwest are located in a relatively narrow band crossing the states of Kansas, Missouri, Iowa, Illinois, Indiana, and Ohio. Much of this report's discussion on drought characteristics focuses on this "southern tier" of Midwestern states. The report does not address communities that obtain their water from the Great Lakes or major rivers where the availability of supply during severe droughts is not in question. The most common small community surface water system obtains its supply from one or two small impounding reservoirs; however, a sizable number of communities obtain their water instead from river withdrawals or from the off-channel storage of water withdrawn from streams and rivers.

Sixty of the 320 small community surface water systems in the Midwest were interviewed for this study. These interviews were used to gather information that could potentially be used to determine the drought vulnerability of their system, including information on the capacities of reservoirs, availability of hydrologic data, recent experiences with drought impacts and related water use restrictions, differences in seasonal water use, and community drought plans. Fewer than half of the interviewed systems that have a reservoir could provide information on their reservoir's capacity. Capacity estimates that were provided were typically neither recent nor based on actual measurements. Few communities were aware of available hydrologic data such as streamflow measurements.

The need for a community to institute voluntary or mandatory water use restrictions was used as a common measure of that community's drought vulnerability. Eighteen of the 60 interviewed communities needed to institute restrictions at least once during the past 20 years. Eight of those systems have since augmented their supplies. Communities most likely to need restrictions were those with off-channel reservoir or low channel dam water supplies. Off-channel reservoir and low channel dam systems also are the least likely to have sufficient data for evaluating adequacy of supply; thus, in general, these system types may be considered to have the highest potential vulnerability to drought conditions.

This report provides information on historical hydrologic droughts in the Midwest, including data on comparative drought streamflows for 27 selected long-term gaging records in the southern tier of Midwestern states where most surface water supplies are located. For longer drought durations (18 months or longer), the 1950s drought is clearly the worst on record for most selected locations. Flow conditions during the drought of record may be considerably lower than other historical droughts. Thus for determining the vulnerability of a system to severe drought, it is very important for that gage's period of record to include either the 1950s or other drought periods comparable in effect to the identified drought of record.

For most states, there is no pre-defined drought threshold that communities are required to surpass in developing their water supply sources. For very small communities, it may not be economically feasible to develop alternative water supplies capable of meeting water use during a drought of record if supplies are adequate during moderate droughts. But for communities where there are no existing alternative supply options, especially for larger communities, it would seem essential that existing resources are capable of meeting water needs during a very severe drought. The past half century has shown that climate is variable; so, even if it has been many decades since the occurrence of some of the worst droughts on record, the likelihood exists that such droughts can occur again and attention should be given toward planning for that eventuality.

Need for Physical and Hydrologic Data for Determining Yield and Drought Vulnerability

To evaluate their vulnerability to severe drought, communities that depend on reservoir supplies need to obtain accurate measurements of the capacities of their reservoirs, if they have not recently been conducted. For Kansas and Missouri reservoir systems, bathymetric (depth) surveys may have already been made through initiatives by the Kansas Biological Survey and Missouri Department of Natural Resources. The Illinois State Water Survey also has conducted measurements for a number of water supply reservoirs in Illinois. A first step for communities with impounding and off-channel reservoirs can be to identify the agencies or consultants that are capable of conducting a bathymetric survey of their reservoir. Capacity estimates not developed from a detailed survey of this type may be substantially inaccurate and particularly may be biased towards overestimating the capacity for small reservoirs. Capacity estimates also should account for the loss of capacity over time as the result of sedimentation.

The lack of applicable streamflow information is often the biggest source of uncertainty when trying to evaluate drought vulnerability, and it is not a gap in data that is easily filled. To be useful in water supply analysis, it is essential that a flow record cover the duration of a major water supply drought. If a new stream gage were to be installed to provide information for water supply analysis, it may take decades for a severe drought event to occur at that stream gage. The evaluation of direct river withdrawals are most dependent upon long-term data collected at or near the point of withdrawal, and, fortunately, most locations with direct river withdrawals are situated reasonably close to a USGS gage. However, gaging data for locations on smaller streams, where water may be withdrawn to supply for off-channel storage, are typically not available.

Surrogate gaging records or regional regression equations of drought flows are often used to estimate inflows into reservoirs during extended droughts. Because short-duration (daily) low flows can differ from stream to stream as a result of variations in local hydrogeology, the use of surrogate gages becomes relatively less accurate for use in estimating the availability of flow for withdrawals from streams and rivers. As a result, the use of surrogate gage records is usually inadequate when evaluating the yields of systems that withdraw directly from streams and rivers. Surrogate gaging records can be used to roughly estimate the collective amount of water that can diverted to off-channel reservoirs, but may not always be representative of conditions at the withdrawal site. For this reason, the availability of other types of data from off-channel reservoirs, such as daily pumping logs and reservoir levels during dry periods, can be extremely useful for refining yield estimates produced from surrogate gage records; communities with off-channel reservoirs are urged to keep records of pumping and reservoir levels in a form that can be useful for future evaluation.

Even if adequate hydrologic information is not available from which to determine the yield of a water supply system, managers should attempt to understand the type of drought period that is likely to test the adequacy of the available supply. The critical drought duration is a measure of the length of time during which low streamflows are incapable of providing a community's water needs, requiring that the community rely upon stored water from either a reservoir or low channel dam. For impounding reservoirs, flow data provided in this report combined with an approximate value of reservoir capacity can be used to estimate the critical duration associated with the most severe drought periods. For most off-channel reservoirs and small impounding reservoirs in Ohio, the critical duration will be less than a year, and the reservoir may fully recover before the following summer. In contrast, impounding reservoir systems in Kansas will likely need to draw down their supplies for five years or more.

The selected streamflow data listed in Tables 2 and 3 also provide a historical perspective on major droughts for various locations throughout the Midwest. If the sources and water use for a community system have not changed substantially in recent decades, local records of the behavior of the system in severe drought periods can provide valuable information regarding drought vulnerability and adequacy of supply, even if hydrologic data are not available for a more thorough analysis. Again, particular attention should be paid to the historical drought of record and its associated reductions in water availability. If a system has needed to implement restrictions during recent moderate droughts, its vulnerability during a drought of record should be a concern. On the other hand, adequacy of supply during a recent moderate drought does not necessarily indicate that the system would be adequate during a severe drought.

If hydrologic data and basic physical data such as storage capacity are lacking, it will be difficult for either system managers or experienced professionals to estimate a community system's yield and potential drought impacts, particularly for off-channel reservoir and low channel dam systems that are more likely to be vulnerable to drought. There are several types of data, in addition to the measurement of storage in reservoirs and behind low channel dams, that a community could begin collecting that may be useful for future assessments. Daily records can be kept of: 1) stream withdrawals, including a description of pumping amount and the number of days when water was not withdrawn because water quality was poor or stream levels were too low; 2) drawdown levels for reservoirs and low channel dams in the pools; and 3) precipitation. The first two sets of data could provide information on the relative availability of water, which could then be compared to more complete hydrologic data from regional streams for predicting local conditions during severe drought. Without proactive efforts to keep records of these types, for many communities the only alternative is to wait and see what the next drought brings.

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