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Uncertainties and Data Needs in Evaluating the Adequacy of Community Surface Water Supply Systems in Illinois

by
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Prepared for the
Illinois Department of Natural Resources
Office of Water Resources

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Center for Watershed Science
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Abstract

This report examines uncertainties in data inputs used in estimating drought vulnerability and yield of community surface water systems in Illinois. Not only are uncertainties in individual data components characterized, but also comparative influence of those data components in the overall computation of yield. The two most influential data components identified through this analysis are: 1) existing reservoir capacity for community systems that use reservoir storage and 2) streamflow characteristics during drought, both for determining availability of flow for direct withdrawals from those streams as well as determining the cumulative amount of water that flows into or can be pumped to reservoirs. Additional uncertainties from climate data (precipitation and evaporation) are considerably less influential in yield estimation.

Data needs for estimating surface water system yields are identified not only by the uncertainties in and influences of various data components, but also are prioritized by cost and timeline for obtaining data and the expected likelihood that additional data noticeably could affect conclusions regarding drought vulnerability of individual systems. Considering these factors, obtaining bathymetric surveys for water supply reservoirs that do not already have such data represents the most effective way to improve yield estimates for Illinois surface water supplies as a whole. Many reservoirs in Illinois never have had sedimentation or bathymetric surveys. Results of this study show that available capacity estimates for these reservoirs are apt to be biased toward overestimation and have an estimated standard error of 28 percent. The amount of bias and error is greater for smaller reservoirs. Reservoirs with sedimentation surveys that are more than 35 years old may be subject to the same level of bias and uncertainty as unsurveyed reservoirs.

Streamflow data for water supply analyses remains a long-term data need. Most community supply reservoirs (impounding and off-channel) are in relatively small rural watersheds of less than 50 square miles. In most of these cases, there never has been a streamgage in the watershed, and estimates of drought inflow used for yield analyses typically are based on historical streamgage records from nearby watersheds that are assumed to have hydrologically similar flow regimes. Because the number of small watershed gages in the Illinois streamgaging network has been reduced substantially over the past three decades, very few gages in operation are appropriate for regional analysis of small watersheds. As a result, if a severe drought occurred today, there would be few continuous flow records to document the type of drought flow conditions necessary for application in future water supply analyses. Establishment of streamgages in small watersheds near existing water supply reservoirs is necessary to maintain, much less improve, levels of uncertainty in flow data for future water supply analyses and planning.

Contents

Introduction

Periodic evaluations of capacities and yields of surface water supply systems are necessary to ensure that such supplies have sufficient resources to provide water over the duration of a severe drought. McConkey-Broeren and Singh (1989) conducted the last comprehensive evaluation of the yields and adequacy of community surface water supplies in Illinois. That study, and all other previous evaluations of surface water supply yield by the Illinois State Water Survey (ISWS), produced a single predicted value of yield for each supply system without explicit examination of uncertainties in data used and their potential effects on yield estimates. In reality, it is understood that, depending on accuracy of data and methods used in the analysis, the true yield of each system could be greater or less than the predicted value. This report categorizes and examines uncertainties in data used in estimating yields of surface water supply systems in Illinois, and identifies data types that would reduce these uncertainties. Data uncertainties were assessed in this report by either quantitative or qualitative approaches, depending on data type and availability of previous quantitative studies.

This report is part of a larger project to reevaluate drought vulnerability and adequacy of Illinois' community surface water supplies. Existing information on community surface water supplies in Illinois is being documented, identifying specific data that will be used to determine yields of these supply systems and data uncertainties. Yield estimates for individual water supply systems and specific uncertainties in these estimates will be addressed in future reports.

Water supply adequacy examined in this study refers to sufficiency of available water quantity (raw water production) for a community during a severe drought. Data for three major types of supply sources were examined: 1) direct withdrawals from Illinois streams and rivers, 2) reservoirs that impound Illinois streams, and 3) off-channel reservoirs that store water withdrawn from streams. Of the 102 community water supply systems in Illinois that depend on surface water sources (Figure 1), 17 systems obtain their water from Lake Michigan and 13 systems obtain their water from the Mississippi and Ohio Rivers. There is no concern regarding adequacy of supply for these 30 systems, and, for this reason, uncertainties in their available data were not examined.

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Any opinions, findings, conclusion, or recommendations expressed in this report are those of the author, and do not necessarily reflect those of the Office of Water Resources or the Illinois State Water Survey.

Figure 1. Locations of community surface water supplies in Illinois

Components in Analyzing Surface Water Yield Uncertainty

To evaluate potential uncertainties in estimation of surface water supply yield, it is necessary to understand the types of data and methodology for estimating yield. Methods to estimate surface water supply yield are essentially extensions of water budget equations commonly used by hydrologists. A basic water budget equation for a surface water body is as follows:

$$AWt = CAP + Pt - Et + QINt - QOUTt + GWt \quad (1)$$

where the available water for a specific period of time, AW*t*, is computed as the total of the available capacity of the water body (CAP) and the following additions and subtractions to the volume of the water body over time *t*:

P*t* = Precipitation over the surface water body
E*t* = Evaporation over the surface water body
QIN*t* = Inflow into the surface water body
QOUT*t* = Water that flows out of the surface water body and is not available for withdrawal
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.

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

$$Yield = AWt / \Delta t \quad (2)$$

For water supplies, yield often is expressed in units of million gallons per day (mgd). For an individual drought, the safe or net yield is determined as the minimum value of $AWt/\Delta t$ considering all possible time periods. The value of Δt that produces the net yield for a surface water body is considered to be the critical drought duration.

Direct Withdrawals from Rivers and Streams

If the surface water supply is a direct withdrawal from a river or stream, available storage and surface area of the water body typically are considered to be zero, so that the available water is essentially equal to the available river flow; Δt is very small, and Equation 1 is reduced to:

$$AWt = QINt - QOUTt \quad (3)$$

In this case, QOUT*t* is the instream flow that continues downstream to maintain minimum flow levels in the stream (for the benefit of aquatic habitat or other instream flow uses) or a flow not feasibly captured by the withdrawal structure. If QOUT*t* = 0, then the yield of the direct withdrawal is theoretically equal to the instantaneous minimum flow in the stream; there are physical limits to pumping all flow in a river, however, unless there is also a low channel dam that creates pooled storage. Almost all direct withdrawals in Illinois for community surface water supplies are from large streams that have a streamflow gage either upstream or downstream. Thus, the gaging record and frequency estimates made from this record are typically the primary source of information for computing yield.

Impounding Reservoirs

Impounding reservoirs are created by a dam across the stream channel and its valley, completely obstructing flow in the stream and creating a reservoir that inundates the stream's valley and those of tributaries that flow into the reservoir. A water supply reservoir typically has no outflow during drought periods unless there is some provision to release water from the reservoir to maintain minimum low flows downstream of the dam. Thus, for most impounding water supply reservoirs in Illinois, Equation 1 is reduced to:

$$AWt = CAP + Pt - Et + QINt \qquad (4)$$

There is likely to be a small amount of water exchanged between reservoir storage and groundwater, but there are typically no data to estimate this exchange and GW*t* usually is assumed to be zero. Therefore this term was omitted from Equation 4. Thus, there are considered to be four primary data inputs for determining reservoir yield: 1) reservoir capacity, 2) precipitation over the reservoir during the course of the drought, 3) evaporation from the reservoir, and 4) stream inflow into the reservoir. Precipitation and evaporation during a drought period often are evaluated jointly, with the sum of these two variables termed as net evaporation. The deepest part of the reservoir may not be available for use because of access limitations or turbidity; in determining yields of Illinois reservoirs, McConkey-Broeren and Singh (1989) considered 90 percent of the reservoir capacity as usable.

Critical Drought Duration

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 drought 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 pertinent to estimation of yield. Recovery time for historical droughts in Illinois, in almost all cases, has been relatively short in comparison to the critical duration.

The critical duration can vary considerably between reservoirs, influenced by factors such as reservoir size, water use, watershed size, and hydrologic region, as well as temporal characteristics of individual droughts. In general, the critical duration for a reservoir increases as: 1) drought severity (recurrence interval) increases and 2) the ratio of reservoir capacity to the volume of average annual inflow increases. Because of differences in critical duration, it is possible for one reservoir to experience severe impacts from an intense but relatively short drought period, whereas a nearby reservoir (with a longer critical duration) remains relatively unaffected by the same drought conditions.

Table 1 lists the critical drought duration for 61 selected reservoirs, as computed by McConkey-Broeren and Singh (1989) for droughts with an estimated recurrence interval of 50 years. A few of these reservoirs no longer are used for water supply. Most of these reservoirs have critical durations of either 16 to 20 months or 54 to 58 months. Thus, most of Illinois' water supply reservoirs must be designed to provide water to a community during a multi-year drought period. The typical 16- to 20-month drought is characterized by a hot, dry summer followed by abnormally dry winter and spring seasons. Drought periods lasting longer than 3 years are infrequent, with only two such severe droughts occurring in the past 100 years, during the 1930s and 1950s, the latter being the drought of record for many Illinois surface water supplies. Sustained drought periods such as these are not necessarily more intense than shorter drought periods; instead, persistence of the drought is the crucial factor in determining adequacy of the water supply system.

Off-channel Storage Reservoirs and Multiple-Source Combined Systems

An off-channel reservoir is a storage reservoir built away from the stream channel so as not to obstruct flow in the stream (other than perhaps a low-head weir or channel dam that may collect water in the channel). When there is available flow in the stream and the reservoir is not already full, water is pumped from the stream to be stored in the reservoir. The general purpose of the off-channel reservoir is to provide water for the community when direct withdrawal from the stream would be insufficient.

The water budget yield analysis for a simple off-channel storage reservoir system is similar to that for an impounding reservoir (Equation 4) except the value of QIN_t is calculated as the available water during the drought period that can be pumped practically from the river or stream that provides water to the reservoir. An examination of ISWS Bulletin 66 (Knapp, 1982), which describes factors for hydrologic design of side-channel reservoirs, illustrates that the value of QIN_t can be highly sensitive to the system's pumping capacity and other factors that influence the frequency that flow can be pumped from the stream. Although the water budget methodology used in Knapp (1982) cannot easily be divided into individual data components, it is expected that the influence of inflow in determining overall yield is comparatively greater for off-channel reservoirs than for impounding reservoirs.

There are relatively few simple off-channel reservoir systems in Illinois. Many off-channel storage systems are combined with other sources in that they also may contain sizeable storage behind a channel dam at the river intake or have an impounding reservoir component. Multiple-source systems that require additional water budget elements tend to have unique data characteristics that cannot be addressed easily in a general uncertainty analysis such as that for this report.

Table 1. Critical Drought Duration of a 50-Year Drought for Illinois Water Supply Reservoirs

	Months				
Reservoir	*8-14*	*16-20*	*24-32*	*42-50*	*54-58*
Altamont Reservoir					X
Alto Pass Reservoir		X			
Ashley Reservoir		X			
Lake Bloomington		X			
Lake Camelot		X			
Canton Lake			X		
Carbondale Reservoir			X		
Lake Carlinville		X			
Carthage Lake		X			
Cedar Lake (Carbondale)					X
Lake Centralia			X		
Coulterville Reservoir		X			
Lake Decatur	X				
Dongola Reservoir	X				
East Fork Lake (Olney)					X
Lake of Egypt					X
Eldorado Reservoir		X			
Eureka Lake		X			
Evergreen Lake		X			
Gillespie New Lake					X
Gillespie Old Lake					X
Glenn Shoals Lake		X			
Governor Bond Lake (Greenville)					X
Greenfield Lake					X
Highland Silver Lake				X	
Lake Hillsboro					X
Lake Holiday (Holiday Shores)					X
Jacksonville Lake				X	
Lake Kinkaid					X
Kinmundy Reservoir					X
Little Cedar Lake (Alto Pass)		X			
Lake Lou Yaeger		X			
Marion City Lake		X			
Lake Mattoon		X			
Mauvaise Terre Lake	X				
Mt. Olive New Lake	X				
Mt. Olive Old Lake					X
Nashville Reservoir		X			
Lake Nellie (St. Elmo)		X			
Otter Lake					X
Palmyra-Modesto Lake					X
Pana Lake					X
Lake Paradise (Mattoon)		X			
Paris Twin Lakes		X			
Pinckneyville Reservoir				X	
Lake Pittsfield			X		
Raccoon Lake		X			
Salem Reservoir		X			
Sangchris Lake					X

Table 1. (concluded)

	Months				
Reservoir	*8-14*	*16-20*	*24-32*	*42-50*	*54-58*
Lake Sara (Effingham)					X
Spring Lake (Macomb)		X			
Lake Springfield		X			
Staunton Lake				X	
Lake Taylorville		X			
Vandalia Lake		X			
Lake Vermilion (Danville)	X				
Vermont Reservoir		X			
Vienna City Reservoir			X		
Virginia Reservoir					X
Washington County Lake		X			
Waverly Reservoir					X

Uncertainty of Individual Data Components in Yield Analyses

Uncertainties in each of the four primary data inputs in determining surface water yields were considered: 1) drought streamflows, either as low flows at the site of a water supply withdrawal or as cumulative inflows into a reservoir over the course of a drought, 2) reservoir capacities, 3) precipitation over a reservoir during the course of the drought, and 4) evaporation from a reservoir.

Estimating Streamflow during Droughts

There are three general types of uncertainty related to estimating low flows and drought flows for analyzing water supply availability: 1) accuracy of low flow records at streamgages, 2) ability to estimate flow characteristics of severe droughts at gaging sites when the available gaging record does not include a severe drought period, and 3) use of regional data to estimate drought flow conditions at ungaged sites. For most communities that have direct withdrawals from streams (for example, Aurora, Carlyle, Elgin, Kankakee, Peoria, Pontiac, and Wilmington), streamgages in the vicinity can be used to estimate flow conditions. In these cases, accuracy of the daily flow record is the most pertinent source of uncertainty. On the other hand, for most impounding reservoirs in Illinois, there is no available streamgage record upstream of the reservoir, and use of regional data for estimating drought flows, including use of regression equations, is the primary source of uncertainty.

Accuracy of Low Flow Estimates at Gaging Locations

Flow measurements at streamgages normally are classified as good if they are within 5 percent of the actual flow amount, and, in themselves, are usually not considered a significant source of error in the estimation of daily streamflows. Flow measurements at U.S. Geological Survey (USGS) gages typically are scheduled at 6- to 8-week intervals, and the relationship between the river stage and the flow amount can vary or shift between measurements depending on flow conditions and character of the stream channel. The shifting of the stage-discharge relationship (rating curve) typically is caused by either accumulation of debris in the channel and floodplain or by scour and deposition of stream bed materials. For estimating flows occurring in the period between two field measurements, it often is assumed that there is a gradual change in the rating shift over time; there is usually no information to determine when shift changes actually occur, or whether that shift is gradual or related to isolated flow events, however.

For large stable streams, such as the Fox and Kankakee Rivers, the shift between measurements tends to be small (often less than 0.05 feet). During most conditions, measured flows on such rivers are typically less than 5 percent different than the standard rating curve, although shifts can cause more than a 10 percent difference in estimates during the lowest flows. In contrast, for other rivers — such as the Little Wabash and Vermilion Rivers — a shift in the rating curve of ±0.2 feet between measurements is not unusual. Smaller streams often may have an even greater amount of shift in the rating curve. During the lowest flow conditions, this shift potentially can create more than a 50 percent error in the flow estimate on these streams. It is recommended that additional field measurements during drought conditions noticeably could improve data used to determine the availability of streamflow for water supplies. It is recognized that frequency of site visits to streamgages is a primary factor affecting gage operation costs; thus, it is probably not cost effective to augment frequency of discharge measurements except during the lowest flow conditions. Additional field measurements would be of greatest value when flows approach and/or fall below 10-year low flows.

Estimating Drought Frequency from Gaging Records

Several factors affect computation of drought and low flow frequencies at individual gage locations, including: 1) length of the streamflow record, 2) variability of low flows within the record (often represented by the standard deviation of the low flow series), 3) type of probability distribution or other analytical procedure used to characterize and predict frequency of drought flows, and 4) local modifications to a stream's low flows such as the presence of a reservoir or wastewater treatment facilities. Quantification and complete characterization of such uncertainties for specific sites would require detailed analyses beyond the scope of this investigation. Previous low flow analyses conducted by the ISWS instead have focused on uncertainty and error of regional flow equations used to estimate low flows at ungaged sites, as discussed in the next section. Uncertainties in regional flow equations represent composite errors of the above factors as well as errors related to equation development, and are believed to represent a practical upper limit to errors at gaged locations.

Estimating Drought Flows from Regional Data

With few exceptions, streams that flow into most of Illinois' water supply reservoirs do not have hydrologic records from which to directly estimate inflows during drought. It is therefore necessary to estimate drought inflows into the reservoir using streamflow data from other gages believed to share similar hydrologic characteristics.

Previous studies developed by the ISWS for estimating reservoir yields — Bulletin 51 (Stall, 1964) and Bulletin 67 (Terstriep et al., 1982) — defined hydrologic regions in Illinois and incorporated drought flow characteristics for each long-term gaging record within that region into design tables and graphs. The report user was instructed to select a gage record best representing the reservoir site being studied; but relatively few guidelines were available to determine the best gaging record to use, and results of yield analyses could vary substantially depending on the record chosen. These earlier studies also lacked information regarding potential analytical errors.

For many hydrologic regions in Illinois, the ISWS has developed regression equations capable of estimating drought flows at ungaged locations. These regression equations are used in the Illinois Streamflow Assessment Model (www.sws.uiuc.edu/data/ilsam/), which provides streamflow frequency estimates for streams throughout much of Illinois (currently available for the Fox, Kankakee, Kaskaskia, La Moine, Little Wabash, Mackinaw, Rock, Sangamon, Spoon, and Vermilion-Illinois River watersheds). These regression equations are available for low flow and drought durations lasting from as little as one day up to 54 months. Longer duration drought flows were developed specifically for use in estimating reservoir yields. Drought flow equations also range from mild droughts (10-year recurrence interval) to severe droughts (50-year recurrence interval). The error estimate for each equation was analyzed to determine expected uncertainties in reservoir inflow estimates for various types of watersheds. Table 2 shows the range of expected uncertainty associated with each equation. Flows presented in Table 2 for selected drought durations lasting from 9 months to 54 months roughly cover the potential range of critical drought durations for water supply reservoirs in Illinois.

As shown in Table 2, there is greater uncertainty in estimating magnitude and frequency of flow amounts over shorter drought periods than longer drought periods. Flow conditions during infrequent 50-year droughts are also more difficult to predict than those for more frequent 10-year droughts. Table 2 shows a range of uncertainty values for each drought duration and recurrence interval. In general, the smallest uncertainty values in each given range are associated with larger streams that have relatively high baseflow amounts. In contrast, the largest uncertainties are associated with smaller streams that have relatively low drought flows and, in most cases, can be expected to go dry during substantial portions of a drought period.

Estimating Reservoir Capacity

Reservoir capacities can be measured by either a sedimentation or bathymetric survey. Both involve measuring lake depth. The sedimentation survey, however, is a more extensive process that involves measuring sediment thickness that has accumulated in the reservoir over time, and, in some cases, sediment density and particle-size distribution. The ISWS has conducted more than 150 lake sedimentation surveys throughout Illinois in the past 60 years to establish both the reservoir capacity and to determine rates of capacity lost as a result of sediment deposition. Reservoir capacities measured by sedimentation surveys of this type typically are considered to have an error of about 10 percent (Morris and Fan, 1998). Using data from these surveys, the ISWS has developed methods to estimate changes in reservoir capacity based on computed sediment accumulation (Singh and Durgunoglu, 1990). In addition to its own surveys, the ISWS also has records of a smaller number of reservoir capacity surveys conducted by other entities and estimated capacities of unmeasured reservoirs.

Most water supply reservoirs in Illinois never have had sedimentation or bathymetric surveys; thus, a great concern is the uncertainty in capacity estimates for these unmeasured reservoirs. ISWS files contain unsurveyed estimates of reservoir capacity coming a variety of sources, including U.S. Army Corps of Engineers' National Inventory of Dams or NID (http://crunch.tec.army.mil/nidpublic/webpages/nid.cfm) and Dam Safety Inspection Reports

Table 2. Uncertainties (percent) in Estimating Drought Flows at Ungaged Sites

	Recurrence interval		
Drought 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

Sources of data: Knapp and Myers (2001); Knapp and Russell (2004).

completed around 1980, reservoir design documents, Illinois Environmental Protection Agency water supply fact sheets, Illinois Department of Natural Resources (IDNR) fisheries data on lake depth, personal communications with municipalities, and pre-1960 ISWS file reports of individual systems. To evaluate uncertainty in these various unsurveyed estimates, individual estimates were compared when possible with results of a subsequent sedimentation or bathymetric survey of the reservoir. Table 3 lists such comparisons between surveyed and estimated (unsurveyed) capacity values for 33 reservoirs. Survey measurements were matched with estimates representing the same time period in the reservoir's life in an attempt to eliminate

Table 3. Comparison of Surveyed Reservoir Capacity and Unsurveyed Estimates

Reservoir	*Measured capacity (ac-ft)*	*Source and year of survey*	*Capacity estimate (ac-ft)*	*Source of unsurveyed estimate*	*Error (%)*
Alto Pass	128 [a]	ISWS 1976	168	NID [b]	+31.25
Ashley	174 [a]	ISWS 1985	200	1980 DSIR [c]	+14.94
Borah	1555 [a]	ISWS 1960	2060	NID [b]	+32.48
Canton Lake	3513 [a]	ISWS 1960	4540	NID [b]	+29.23
Carlinville	2350 [a]	ISWS 1986	2110	NID [b]	-10.21
Carthage	406 [a]	ISWS 1949	399	ISWS 1934 file report	- 1.72
Charleston	2129 [a]	ISWS 1960	2639	ISWS 1954 file report	+23.95
Dawson	1619 [a]	ISWS 1986	1620	Design estimate	+ 0.06
Dongola	558	ISWS 1981	550	NID [b]	- 1.43
Gillespie New	1694	USGS 1997	2190	Singh & Durgunoglu (1990)	+29.28
Glenn Shoals	9717	Local 2006	11606	Singh & Durgunoglu (1990)	+19.44
Governor Bond	9159	Local 1996	9291	Singh & Durgunoglu (1990)	+ 1.44
Highland Silver	7340 [a]	ISWS 1981	10400	U.S.Soil Conservation Service	+41.69
Le-Aqua-Na	579 [a]	ISWS 1981	557	Design estimate	- 3.80
Lou Yaeger	15837 [a]	ISWS 1977	15523	U.S.Soil Conservation Service	- 2.89
Mattoon	13160 [a]	ISWS 1980	11820	Design estimate	-10.21
Mauvaisse Terre	1505 [a]	ISWS 1952	1811	ISWS 1934 file report	+20.33
Mt. Olive New	465 [a]	ISWS 1938	457	NID [b]	- 1.72
Mt. Olive Old	452 [a]	ISWS 1981	614	ISWS 1923 file report	+35.84
Nashville	320 [a]	ISWS 1954	400	NID [b]	+25.00
Oakland	115	ISWS 1973	143	NID [b]	+24.35
Otter Lake	15043	ISWS 1998	16077	Singh & Durgunoglu (1990)	+ 6.87
Paradise	1407	ISWS 1979	1758	1978 DSIR [c]	+24.95
Pinckneyville	2020	ISWS 1990	2766	Singh & Durgunoglu (1990)	+36.93
Pittsfield	3580 [a]	ISWS 1974	4809	Design estimate	+34.33
Raccoon	5650 [a]	ISWS 1959	5852	ISWS 1954 file report	+ 4.28
Sorento	54	IDNR 2000	92	Singh & Durgunoglu (1990)	+71.19
Spring	2880	ISWS 1968	3363	NID [b]	+16.77
Staunton	1248 [a]	ISWS 1954	1172	ISWS 1935 file report	- 6.09
Taylorville	9406 [a]	ISWS 1977	10400	ISWS 1965 file report	+10.50
Vermont	366 [a]	ISWS 1980	359	Design estimate	- 1.91
Waverly	308 [a]	ISWS 1952	476	1980 DSIR [c]	+54.55
White Hall	459 [a]	ISWS 1952	556	NID [b]	+21.13

Notes:
a = Estimates of original reservoir capacity were used for this comparison.
b = National Inventory of Dams (http://crunch.tec.army.mil/nidpublic/webpages/nid.cfm).
c = Dam Safety Inspection Reports published by the U.S. Army Corps of Engineers, Chicago District.

the influence of sedimentation from the capacity estimate. When an unsurveyed capacity estimate appeared to represent the original capacity of the reservoir, as is the case with many NID estimates, it was compared to the original capacity value produced by the sedimentation survey.

Estimated values of reservoir capacity (fourth column of Table 3) come from various sources, as illustrated by the following examples. For Lake Charleston, a 1954 ISWS file report estimated the original lake capacity as 2639 acre-feet; but a 1960 sedimentation survey more accurately computed the original capacity as 2129 acre-feet (second column of Table 3). For the Gillespie New Reservoir, values of sedimentation loss in Singh and Durgunoglu (1990) were used to estimate the 1997 lake capacity as 2190 acre-feet; in contrast, the 1997 USGS bathymetric survey measured lake capacity as 1694 acre-feet. The percentage error given in Table 3 is computed by subtracting the surveyed value from the unsurveyed estimate and then dividing the difference by the surveyed value.

An additional 13 cases were examined in which reservoir capacity measured by a sedimentation or bathymetric survey was compared to projected capacity using a prior survey. In each of these cases, projected capacities developed by Singh and Durgunoglu (1990) were used. This comparison can be used to understand uncertainties in capacity estimates for reservoirs with previous sedimentation or bathymetric surveys. These 13 comparisons are shown in Table 4.

Table 5 shows the computed error when comparing measured surveys to either independent estimates of capacity or projected capacity using previous survey data. Where a previous sedimentation survey provides the basis for the "estimated" value, a distinction is made

Table 4. Comparison of Surveyed Reservoir Capacity and Projected Capacities from Previous Surveys

Reservoir	*Measured Capacity (ac-ft)*	*Source and year of survey*	*Projected capacity (ac-ft)*	*Source and year of survey used for projection**	*Error (%)*
Carlinville	1650	ISWS 1986	1310	ISWS 1959	-20.61
Gillespie Old	434	USGS 1997	570	ISWS 1954	+31.34
Highland Silver	5832	ISWS 1999	5504	ISWS 1984	- 5.62
Jacksonville	5830	ISWS 1986	6099	ISWS 1952	+ 4.61
Lake Mattoon	11588	ISWS 2001	10430	ISWS 1980	- 9.99
New Mt. Olive	292	IDNR 2000	214	ISWS 1981	-26.65
Old Mt. Olive	325	IDNR 2000	368	ISWS 1981	+13.27
Pana	3080	IDNR 2000	3130	ISWS 1977	+ 1.62
Paradise	1252	ISWS 2001	1233	ISWS 1979	- 1.52
Pittsfield	2679	ISWS 1992	2547	ISWS 1985	- 4.93
Spring Lake	1715	ISWS 1996	2453	ISWS 1968	+43.03
Staunton	960	IDNR 2000	975	ISWS 1981	+ 1.56
Vermilion	7971	ISWS 1998	7518	ISWS 1976	- 5.68

Note: * Cumulative loss of capacity from the previous survey was estimated by Singh and Durgunoglu (1990).

Table 5. Uncertainty in Estimating Reservoir Capacity Classified by Source of Estimate

Source	*Number of cases*	*Range of error (%)*	*Bias (%)*	*Standard error (%)*
Sedimentation survey since 1970	9	-26.65 to +13.27	- 4.22	10.96
Sedimentation survey before 1970	4	-20.61 to +43.03	+14.59	28.63
No sedimentation survey, original capacity estimates	33	-17.42 to +71.19	+15.12	24.20

between projected capacities using older sedimentation surveys and more recent surveys. Bias, a measure of the tendency to either overestimate or underestimate capacity, is computed as the average difference in the percentage error. The standard error is the square root of the mean squared error. As shown in Table 5, if a sedimentation survey has been conducted in the previous 35 years (since 1970), estimates of current capacity (based on capacity lost to projected sediment accumulation) appear to be relatively unbiased (-4 percent) with a standard error of about 11 percent. Note that the standard error of 11 percent is about the same as the measurement error associated with a typical sedimentation survey (10 percent). Thus, having a recent survey and its calculation of the sedimentation rate is expected to provide accurate information of reservoir storage for many years.

If a sedimentation survey is more than 35 years old, current reservoir capacity (with loss of capacity from sedimentation) is likely to be overestimated by an average of 15 percent with a standard error of about 29 percent. Retired ISWS scientist, William Bogner has conducted numerous sedimentation surveys and confirms that methods used in early ISWS surveys likely may have overestimated water volume in lake inlets and tributary arms, thereby affecting the total capacity estimate (William Bogner, personal communication, June 7, 2007).

If there never has been a sedimentation or bathymetric survey for a reservoir, the available sample suggests that estimates of current capacity are likely to overestimate true capacity by 15 percent, with a standard error of about 24 percent. The amount of overestimation (positive bias) is dependent on reservoir size. As shown in Table 6, if reservoir capacity is less than 5000 acre-feet, the expected average overestimate is about 20 percent. If reservoir capacity is greater than 5000 acre-feet, the average overestimate is about 8 percent. The standard error also is shown to be less for larger reservoirs. Unsurveyed estimates of the reservoir's original

Table 6. Average Bias and Estimation Error for Cases Based on Original Capacity Estimates

Reservoir capacity (ac-ft)	*Number of cases*	*Average bias (%)*	*Standard error (%)*
0 – 1000	13	+20.59	31.03
1000 – 5000	11	+19.33	24.73
> 5000	9	+ 7.68	16.36

capacity typically are based on topographic maps of the land surface that eventually becomes lake bottom. Much of the expected error in the reservoir capacity estimate may be linked to resolution errors in topographic maps, and it is reasonable to expect that the relative effect of these errors diminishes for larger reservoirs. It also is noted that, of the various unsurveyed sources of capacity estimates, the NID estimates have a noticeably higher standard error (28.53 percent) and overestimation bias (22.81 percent).

Estimating Precipitation over a Water Body

Precipitation over a reservoir during a drought period is usually estimated from a nearby precipitation gage. The average measurement error of precipitation gages in Illinois is roughly 8-10 percent, and usually this is biased toward undercatching precipitation due to wind and other factors (Groisman and Legates, 1994). There is additional error when the precipitation gage is not near the lake. With an average density of one gage per 250 square miles, roughly similar to the National Weather Service cooperative network in Illinois, Winter (1981) estimated error in seasonal average rainfall of about 5 percent. While there can be additional uncertainties related to observer error and gage exposure, these errors are of unknown magnitude and treated as random errors (Jim Angel, Illinois State Climatologist, personal communication, April 25, 2007). With all factors combined, the error in estimating average precipitation over an extended drought is likely to be in the range of 10 percent.

Estimating Evaporation over a Water Body

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 Illinois tend to have short or incomplete data, however, and there can be a considerable variability in pan evaporation measurements between sites. For Illinois, the annual ratio between lake evaporation and measured pan evaporation is expected to range between 0.72 and 0.76 (Farnsworth et al., 1982) but varies considerably by season. Winter (1981) indicated that the pan coefficient in itself can be a significant source of uncertainty in the estimate of lake evaporation, with up to a 50 percent error for monthly estimates. For seasonal and annual evaporation estimates, the range of error arbitrarily is assumed to be half of the monthly amount listed by Winter (1981), i.e., 25 percent.

Because of incomplete pan data, empirical equations using available climate data often are used to estimate lake evaporation. Previous reservoir yield studies by the ISWS (Stall, 1964; Terstriep et al., 1982) used an empirical procedure developed by Kohler et al. (1959) and adjusted by Roberts and Stall (1967), and using data on wind speed, solar radiation, dew-point temperature, and air temperature. Winter et al. (1995) examined the use of 11 empirical equations for estimating lake evaporation, comparing them to evaporation estimated from an energy budget method based on detailed data. The standard error of monthly evaporation estimates ranged from as little as 10 percent to nearly 30 percent. The most accurate equations required on-site climate data and water temperature data to represent the change in heat stored in the lake. Heat storage is affected by lake depth, and other local factors, such as wind exposure and vegetative cover, can produce noticeable variation in the evaporation between two lakes having similar climatic conditions. Equations that did not use water temperature but rather a regional climate station for data inputs (types expected for most general applications) typically produced standard errors of 20-25 percent. Several equations examined by Winter et al. (1995) also showed substantial bias.

The most preferred methods of estimating evaporation for a specific lake, using detailed energy budget or water budget approaches, are rarely applied. Those methods are very data intensive, and there are relatively few U.S. lakes for which necessary data are available. These methods, however, are the only ones capable of estimating lake evaporation consistently within 10 percent error (Winter et al., 2003).

Table 7 compares estimates of average lake evaporation for Springfield and Urbana using three independent sources: 1) pan evaporation data collected at both locations, 2) evaporation computed from Roberts and Stall (1967), and 3) mapped estimates from the national evaporation atlas by Farnsworth et al. (1982). These lake evaporation estimates are generalized and do not apply to specific lakes at either location. Evaporation is presented only for the May-October period when pan evaporation data are usually available. May-October evaporation is considered to represent approximately 75 percent of the annual total evaporation. To estimate lake evaporation, seasonal pan evaporation data were adjusted using a generalized pan coefficient of 0.72, as recommended for central Illinois by Farnsworth et al. (1982).

For all three estimates, the evaporation at Springfield was higher than at Urbana. Farnsworth et al. (1982) and Roberts and Stall (1967), respectively, estimated Springfield evaporation as 2.2 and 3.5 inches higher than that at Urbana. Adjusted pan evaporation at Springfield was 8.1 inches (or 35 percent) higher than that at Urbana. This illustrates the high variability associated with pan evaporation data, as it is unlikely that climatic differences between locations would account for such a large change.

An often neglected source of uncertainty related to evaporation estimates is the measurement of lake surface area and the reduction of surface area as the lake level drops during drought periods. The surface area at full pool 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, although empirical reduction factors often are used; 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.

Estimation of drought evaporation frequency using short climate records potentially would produce an additional layer of uncertainty related to climate variability, for which there is no available error analysis. Such impacts of climate variability are not addressed in this study. It is assumed that estimators of drought evaporation and precipitation will use climate records that are sufficiently long to be consistent with streamflow frequency estimates, including severe drought periods such as those in the 1930s or 1950s.

Table 7. Estimates of Average Lake Evaporation for May-October, Urbana and Springfield

	Average May-October evaporation (inches)	
Source of data	*Springfield*	*Urbana*
Pan evaporation data	31.1	23.0
Roberts and Stall (1967)	27.9	24.4
Farnsworth et al. (1982)	30.0	27.8

Because of variations in data and equations used to estimate evaporation, no single available value of uncertainty can be applied to evaporation estimates. For purposes of this study, uncertainty in lake evaporation estimates during a drought is considered to be roughly 25 percent when regional climate data are used for the estimation. Estimates of net evaporation over the course of the drought (evaporation minus precipitation), often used in reservoir yield analyses, are expected to have about the same level of uncertainty.

Comparative Weight of Data Types in Reservoir Yield Analyses

Computations developed in the study by McConkey-Broeren and Singh (1989) were used to characterize the comparative weight of three major data inputs into reservoir yield analyses: reservoir storage, net evaporation, and stream inflow. Table 8 compares the net yield of selected reservoirs with the yield provided by storage alone and by inflow alone. Also shown is the net evaporation, which is included in the computation of the yield provided by storage. [Note that the summation of the estimated yield from storage, and the net evaporation is equal to the reservoir capacity divided by the critical duration.] All values of yield and net evaporation are provided in units of million gallons per day (mgd). The last column, the portion of the yield provided by storage alone, is computed as the yield from storage divided by the net yield of the reservoir. For example, the yield from storage at Altamont Reservoir represents 54.6 percent of the total yield; the remaining portion of the net yield (45.4 percent) is provided by inflow over the 54-month critical duration of the drought. Net evaporation accounts for 0.026 mgd, 10 percent of the net yield (0.26 mgd).

There is a considerable variation throughout these reservoirs in the portion of yield provided by storage. One primary factor that influences this amount is the critical duration of the drought. Figure 2 illustrates that the portion of yield provided by storage decreases as critical drought duration increases. For the most common range of critical drought duration, from 16 to 20 months, the average portion of yield provided by storage is 73 percent. For the second most common range of critical drought durations, from 54 to 58 months, the average portion of yield provided by storage is 50 percent.

Conceptually, it makes sense that the comparative yield provided by stream inflow would increase with longer drought periods. During shorter intense drought periods, there can be very little flow in many Illinois streams. During a severe 18-month drought (50-year recurrence interval), surface runoff in many regions of central and southern Illinois may be equivalent to less than an inch of rainfall. Because longer droughts do not have this same sustained level of dryness, average inflows are considerably higher.

Values in Table 8 indicate that the net evaporation is less than 15 percent of the net yield of the reservoir for about two-thirds of the reservoirs listed. The percentage of the net evaporation is related to the critical duration of the drought, with the evaporation representing an average of 19 percent of the yield for 16- to 20-month droughts and 11 percent for 54- to 58-month droughts. Average values are skewed by the few reservoirs whose net evaporation is greater than 25 percent (Mauvaise Terre Lake, Vandalia Lake, and New Mt. Olive Lake). The Mauvaise Terre and New Mt. Olive Lakes are comparatively shallow lakes from which expected evaporation would consume a greater amount of the yield.

Table 8. Comparative Weight of Storage Capacity, Drought Inflow, and Net Evaporation on Yield Estimates

Reservoir	*Capacity in 1990* (acre-ft)*	*Net yield* (mgd)*	*Critical duration* (months)*	*Net evaporation* (mgd)*	*Capacity/ duration (mgd)*	*Yield from storage only (mgd)*	*Yield from inflow (mgd)*	*Portion of yield from storage alone (%)*
Altamont Reservoir	940	0.260	54	0.026	0.168	0.142	0.118	54.6
Alto Pass Reservoir	80	0.060	18	0.006	0.043	0.037	0.023	61.0
Ashley Reservoir	118	0.090	16	0.018	0.071	0.053	0.037	58.7
Lake Bloomington	7411	4.870	20	0.530	3.573	3.040	1.830	62.4
Lake Camelot	442	0.210	20	0.041	0.213	0.173	0.037	82.3
Canton Lake	2924	1.460	30	0.170	0.940	0.770	0.690	52.7
Carbondale Reservoir	862	0.550	30	0.066	0.277	0.211	0.339	38.4
Carthage Lake	395	0.270	16	0.047	0.238	0.190	0.080	70.4
Cedar Lake	27652	7.150	56	0.312	4.761	4.449	2.701	62.2
Lake Centralia	2709	1.420	32	0.127	0.816	0.690	0.730	48.6
Coulterville Reservoir	163	0.090	16	0.023	0.098	0.075	0.015	83.4
Lake Decatur	17859	28.580	8	4.310	21.523	17.213	11.367	60.2
Dongola Reservoir	478	0.590	10	0.060	0.461	0.401	0.189	67.9
East Fork Lake (Olney)	12359	2.850	56	0.367	2.128	1.761	1.089	61.8
Lake of Egypt	39319	12.840	56	0.420	7.150	6.730	6.110	52.4
Eldorado Reservoir	572	0.310	18	0.068	0.307	0.239	0.071	77.0
Eureka Lake	279	0.160	20	0.024	0.135	0.110	0.050	68.9
Evergreen Lake	11705	5.930	20	0.620	5.640	5.020	0.910	84.7
Gillespie (two lakes combined)	2128	0.800	58	0.080	0.470	0.390	0.410	48.8
Governor Bond Lake (Greenville)	9413	2.920	58	0.240	1.565	1.330	1.590	45.5
Greenfield Reservoir	376	0.090	56	0.021	0.065	0.044	0.046	49.2
Highland Silver Lake	5947	3.530	42	0.285	1.365	1.080	2.450	30.6
Lake Hillsboro	951	0.270	58	0.039	0.158	0.119	0.151	44.0
Lake Holiday (Holiday Shores)	4495	0.910	56	0.152	0.774	0.622	0.288	68.3
Lake Jacksonville	5763	1.090	50	0.190	1.111	0.922	0.168	84.6
Kinkaid Lake	77388	24.560	58	0.300	12.864	12.560	12.000	51.1
Kinmundy Old Reservoir	337	0.140	56	0.006	0.058	0.052	0.088	37.1
Little Cedar Lake	477	0.480	18	0.047	0.255	0.209	0.271	43.5

Table 8. (concluded)

Reservoir	*Capacity in 1990* (acre-ft)*	*Net yield* (mgd)*	*Critical duration* (months)*	*Net evaporation* (mgd)*	*Capacity/ duration (mgd)*	*Yield from storage only (mgd)*	*Yield from inflow (mgd)*	*Portion of yield from storage alone (%)*
Lake Lou Yaeger	12142	5.700	18	1.193	6.504	5.311	0.389	93.2
Marion Reservoir	1395	0.940	18	0.166	0.747	0.581	0.359	61.8
Mauvaise Terre Lake	495	0.300	12	0.154	0.398	0.244	0.056	81.3
Mt. Olive New Reservoir	250	0.150	14	0.053	0.172	0.119	0.031	79.3
Mt. Olive Old Reservoir	375	0.090	56	0.013	0.065	0.052	0.038	57.2
Nashville Reservoir	381	0.210	20	0.033	0.184	0.151	0.059	71.8
Lake Nellie (St. Elmo)	773	0.330	20	0.057	0.373	0.316	0.014	95.6
Otter Lake	16188	2.650	58	0.270	2.691	2.420	0.230	91.3
Palmyra-Modesto Lake	496.6	0.110	58	0.013	0.083	0.070	0.040	63.6
Pana Lake	3207	1.330	56	0.080	0.552	0.470	0.860	35.3
Lake Paradise	1319	0.790	18	0.163	0.707	0.544	0.246	68.9
Paris Twin Lakes	1483	0.930	18	0.230	0.794	0.570	0.360	61.3
Pinckneyville Reservoir	2766.3	1.400	44	0.075	0.606	0.532	0.868	38.0
Lake Pittsfield	2606	1.390	24	0.126	1.156	1.030	0.360	74.1
Raccoon Lake	4543	3.340	16	0.582	2.738	2.156	1.184	64.5
Salem Reservoir	494	0.340	16	0.063	0.297	0.235	0.105	69.1
Lake Sangchris	34382	11.440	54	1.162	6.139	4.977	6.463	43.5
Lake Sara	13453	3.360	56	0.288	2.316	2.028	1.332	60.4
Spring Lake (Macomb)	2542	1.710	16	0.287	1.532	1.245	0.465	72.8
Lake Springfield	51387	26.560	20	3.500	24.770	21.270	5.290	80.1
Staunton Reservoir	1008	0.350	42	0.042	0.231	0.190	0.160	54.2
Lake Taylorville	6829	5.190	18	1.140	3.658	2.510	2.680	48.4
Vandalia Lake	6320	1.460	20	0.570	3.047	2.480	0.230	91.5
Vermont Lake	190	0.140	16	0.030	0.114	0.084	0.056	60.2
Vienna Reservoir	1539	0.580	32	0.025	0.464	0.439	0.141	75.6
Virginia Reservoir	163	0.130	56	0.008	0.028	0.021	0.109	15.8
Washington County Lake	2764	1.580	20	0.204	1.332	1.128	0.452	71.4
Waverly City Lake	758	0.270	56	0.053	0.131	0.077	0.193	28.6

Note: *Reservoir capacity, net evaporation, critical duration, and yield estimates taken from ISWS files prepared in the study by McConkey-Broeren and Singh (1989).

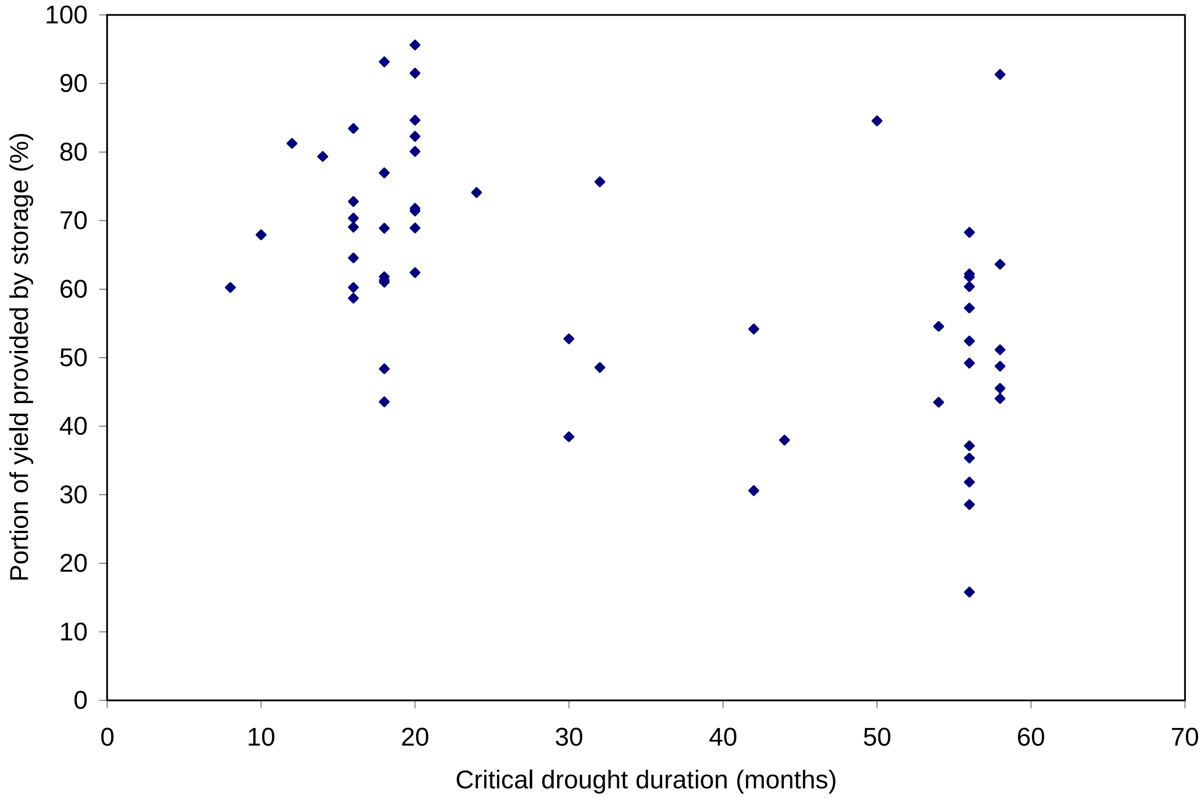

Figure 2. Relationship between drought critical duration and the percentage of yield provided by storage

Summary of Uncertainties in Reservoir Yield Analyses

Table 9 summarizes the overall influence of reservoir capacity, inflow, and net evaporation in estimating reservoir yield. The comparative weight is the average portion of the yield estimate attributed to each data type. Net evaporation is listed separately, but it is also a component within the portion of yield attributed to reservoir capacity.

The uncertainty listed for reservoir capacity assumes no previous sedimentation or bathymetric survey of the reservoir. The range of uncertainty is dependent on reservoir size, with small reservoirs (less than 1000 acre-feet of capacity) having the greatest average uncertainty (31 percent) and larger reservoirs (greater than 5000 acre-feet) having the smallest average uncertainty (16 percent). The uncertainty listed for inflow depends on factors such as hydrologic region and watershed characteristics, with larger watersheds generally having a smaller uncertainty.

The uncertainty of the estimate for each data type is multiplied by the comparative weight to estimate the overall "influence" of the data type in estimating reservoir yield. On average, regardless of critical drought duration, reservoir capacity has the greatest overall influence in estimating net yield. For the 16- to 20-month drought duration, even though the percentage uncertainty in estimating reservoir inflow is greater than that in estimating reservoir capacity, reservoir capacity accounts for more of the net yield and thus has more influence in the overall computation of yield.

Table 9. Weights and Uncertainties in Data Types for Estimating Reservoir Yield

16- to 20-Month Critical Drought Periods

Data type	*Average value of comparative weight in yield estimate (%)*	*Uncertainty (%)*	*Influence (weight times uncertainty)*
Reservoir capacity	73	16-31	0.117-0.226
Inflow	27	30-45	0.081-0.122
Net evaporation	19	25	0.048

54- to 58-Month Critical Drought Periods

Data type	*Average value of comparative weight in yield estimate (%)*	*Uncertainty (%)*	*Influence (weight times Uncertainty)*
Reservoir capacity	50	16-31	0.080-0.155
Inflow	50	15-20	0.075-0.100
Net evaporation	11	25	0.028

The influence metric is also an indicator of potential improvement or change that could occur in the yield estimate were the true value of each data type known. Thus, knowing the true capacity of a “small” reservoir by conducting a bathymetric survey would change the estimate of net yield by an average of 22.6 percent for reservoirs with a critical duration of 16 to 20 months. As indicated earlier in this report, estimates of reservoir capacity tend to be biased toward overestimation. In most cases, a bathymetric survey would reduce estimated yield of the reservoir. Note that influence metrics are an average value for all reservoirs examined; the potential change in yield of specific reservoirs could vary considerably from average values. When examined individually, however, reservoir capacity produced the highest influence factor in 48 of the 56 reservoirs examined in Table 8. Only in eight instances (Carbondale Reservoir, Highland Silver Lake, Kinmundy Old Reservoir, Little Cedar Lake, Pana Lake, Pinckneyville Reservoir, Lake Taylorville, and Waverly City Reservoir) did stream inflow produce the highest influence metric.

In most cases, net evaporation has a comparatively smaller influence in the estimate of the net yield; in no instance did it produce the highest influence factor in determining reservoir yield. Even if net evaporation could be estimated with zero uncertainty, on average, it would not change the overall estimate of net yield for most systems by more than 5 percent.

Data Needs in Water Supply Yield Analyses

Three general factors were used in identifying data needs for surface water supply yield analyses: 1) relative influence of data types in determining yield, 2) expected likelihood that the supply source would be inadequate or marginally adequate to meet water needs in a severe drought, such that additional data noticeably could affect conclusions regarding drought vulnerability, and 3) cost and timeline for obtaining data.

Improved Reservoir Capacity Data

In most cases, obtaining bathymetric surveys for water supply reservoirs that do not already have such data represents the most effective way to improve yield estimates for these reservoirs. With recent advances in acoustic depth-sounding and global positioning system (GPS) technologies, bathymetric surveys can be conducted relatively quickly and inexpensively compared to traditional sedimentation surveys. 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. Accuracy of the bathymetric survey can depend upon several factors, including: 1) completeness 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. There is a need for studies that compare use of bathymetric and sedimentation surveys for determining lake capacity. For water supply purposes, surveys should 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.

Although bathymetric surveys may be useful for assessment of current yields, a survey of sedimentation depth and composition is necessary to provide the rate of sedimentation for future yields as well as other sediment information for lake management and quality assessment. Usefulness of sedimentation surveys is illustrated by the following examples. If a bathymetric survey indicated less lake capacity than previously was estimated, there would be no way to know whether the original capacity was underestimated or the sedimentation rate was much higher than anticipated. There is the potential that successive sedimentation surveys may be able to demonstrate the effectiveness of erosion control and sediment reduction measures.

As indicated earlier, if there never has been a sedimentation survey for a reservoir, the available estimate of capacity may be too high. For smaller reservoirs of capacity less than 1000 acre-feet, the overestimate may be greater than 19 percent (Table 6). Water systems whose primary supply is a small reservoir that never has had capacity measured may be considered potentially vulnerable during drought conditions because of intrinsic uncertainty in the estimated capacity. These include the following water supply systems in Illinois: Altamont, Ashland, Greenfield, LaHarpe, and Palmyra-Modesto. Bathymetric surveys of these small lakes are necessary for reliable yield estimates and should be considered the highest priority in any data collection effort. Sedimentation surveys would provide additional information for projecting future capacities of these reservoirs. Other small reservoir systems with high sedimentation rates and no sedimentation surveys in more than 25 years also should be considered a high priority for capacity measurements, including ones for Carthage Lake, Coulterville Reservoir, Little Cedar Lake (Alto Pass's primary supply), Vermont Reservoir, and Waverly City Lake. For these systems in particular, a sedimentation survey may be useful to estimate changes in sedimentation rate from previous surveys.

Capacities of many off-channel reservoirs also never have been measured. Obtaining capacity measurements for such reservoirs at Blandinsville, Breese, Fairfield, Farina, New Berlin, and Wayne City should be considered a high priority unless detailed engineering drawings for these reservoirs are available.

Several other unmeasured reservoirs appear to have considerable surplus capacity based on current levels of water use and are not currently considered vulnerable to severe drought. These include Lake Holiday, Kinmundy New Reservoir, Vandalia Lake, and Vienna City Reservoir. It is recommended that yield analyses for reservoirs with unmeasured capacity such as these should use a reduced capacity estimate to account for the overestimation bias described in Table 6.

Several communities that use small reservoirs or off-channel storage (Alto Pass, Ashland, and New Berlin) indicated that they may be considering a change in their primary source of supply. If these communities or others pursue alternative sources, recommended capacity measurements for their respective lakes may no longer be a high priority.

Streamflow Data

In estimating drought vulnerability and adequacy of surface water supplies, the value of streamflow data is greatest when long-term gaging records are available to establish frequency and magnitude of flow characteristics during severe droughts. Thus, except for the unlikely circumstance that a severe drought occurs during the first few years that a gage is in operation, procurement of streamflow data for water supply analyses is a long-term monitoring effort. Whereas streamflow data typically have the second-highest influence of data used in analyses of reservoir yield and are critical for this purpose, the timeline for procuring data probably would not reduce the level of uncertainty for the present investigation of surface water supply yields in Illinois.

Streams with Direct Withdrawals and Off-Channel Storage

Table 10 lists 24 Illinois communities whose primary source of supply is a river/stream intake: these communities either directly use water from these streams or send it to off-channel storage. For larger rivers and streams, there is, in most cases, a USGS gaging station either upstream or downstream of the supply intake, such that the difference in drainage areas between the gage and the intake is less than 25 percent. In these cases, the streamgaging record typically can be used to estimate flow at the point of withdrawal for either operational needs or historical analysis of flow adequacy. For the communities of Charleston (Embarras River) and Fairfield (Little Wabash River), the difference in drainage areas between the gage and the intake is considerably greater, which may limit the accuracy of an analysis to estimate daily flows at the intake. For both cases, establishment of nearby streamgages would provide a much more reliable

Table 10. Illinois Communities with River/Stream Withdrawal or Off-Channel Storage as a Primary Water Source

River/stream	*Community supply system*	*Drainage area (sq mi)*	*Nearest USGS gage location*	*Drainage area (sq mi)*
East Fork Kaskaskia	Farina	3	Sandoval	113
Embarras River	Charleston	786	Ste. Marie	1516
Fox River	Aurora	1704	Montgomery	1732
	Elgin	1464	Algonquin	1403
Illinois River	Peoria	14165	Kingston Mines	15818
Kankakee River	Kankakee	4592	Wilmington	5150
	Wilmington	5150	Wilmington	5150
Kaskaskia River	Carlyle	2719	Carlyle	2719
	Evansville	5668	Venedy Station	4331
	Kaskaskia WD	5128	Venedy Station	4331
	SLM Commission	4466	Venedy Station	4331
	Sparta	5453	Venedy Station	4331
	Vandalia	1940	Vandalia	1940
Little Indian Creek	Ashland	6	N/A	N/A
LaHarpe Creek	Blandinsville	13	N/A	N/A
Little Wabash River	Effingham	223	Effingham	247
	Fairfield	1801	Clay City	1131
	Flora	748	Clay City	1131
Salt Fork Vermilion	Oakwood	489	St. Joseph	134
Shoal Creek	Breese	733	Breese	733
Skillet Fork	Wayne City	464	Wayne City	464
Spring Creek	New Berlin	31	Springfield	107
Vermilion River	Pontiac	579	Pontiac	579
	Streator	1068	Leonore	1252

Note: N/A = no available gage.

estimate of the amount of flow that could be withdrawn for water supply. For the cases on smaller streams, there are either no gages (Ashland and Blandinsville) or the gaging station is far enough from the intake to offer no direct information on streamflows at the intake (Farina and New Berlin). Estimating the frequency at which flows can be pumped from the stream and related limitations requires streamgage records for these small streams.

Regional Data for Impounding Reservoirs

Most community supply reservoirs (impounding and off-channel) are located in relatively small rural watersheds of less than 50 square miles. In most of these cases, there never has been a streamgage in the watershed and estimates of drought inflow in reservoir yield analyses typically are based on streamgage records from nearby watersheds assumed to have hydrologically similar flow regimes. In 1971, 30 streamgages in Illinois were in rural watersheds with drainage areas less than 50 square miles; today there are only 8 such gages, listed in Table 11, with no gage in the Illinois River basin, which covers more than half the state. Because of the limited number of small watershed gages in the current streamgaging network, development of drought flow equations necessary to estimate reservoir yield may not be feasible for many regions of Illinois using the current network. Whereas older discontinued records are helpful for defining flow quantity during the worst hydrologic droughts, such as those in 1950s, if a severe drought occurred today there would be insufficient documentation of flow conditions of the type necessary for future supply analyses. Without data on current droughts, usefulness of historical streamflow data on small streams will continue to decline over time. The need for streamflow information on small watersheds has been discussed in previous studies (Knapp and Markus, 2003) and is a concern not only for water supply analyses, but for many other small stream issues, including stream and watershed restoration and water quality load assessment.

The need for streamflow data on small watersheds for use in water supply analyses is greatest in regions with a high density of impounding reservoirs and those locations listed in Table 10 with no gages near an intake for off-channel storage reservoirs. The greatest density of reservoirs, as shown in Figure 1, lies southwest and west of Springfield in the vicinity of Macoupin County. Other clusters of reservoir systems are near Jackson, McDonough, Marion, Morgan-Sangamon, and Perry-Washington Counties. A gage near each cluster region, on watershed sizes similar to those of the supply reservoirs in the region, is necessary if there are to be sufficient data to analyze water supplies for the region in the future.

Efforts should be made, when possible, to locate gages directly upstream of a supply reservoir or other locations where data potentially can provide operational uses or other direct benefits in addition to providing regional flow data for nearby communities. Consideration could be given to siting streamgages upstream of some reservoirs with stream inflow as the greatest influence factor (Carbondale Reservoir, Highland Silver Lake, Kinmundy Old Reservoir, Little Cedar Lake, Pana Lake, Pinckneyville Reservoir, Lake Taylorville, and Waverly City Reservoir) or upstream of stream intakes for off-channel reservoir systems with no streamflow data (Ashland and Blandinsville).

Table 11. Active USGS Streamgages in Rural Watersheds with Drainage Areas Less than 50 Square Miles

USGS gage #	*Stream and location*	*Drainage area (sq mi)*	*Period of record*
03384450	Lusk Creek near Eddyville	42.9	1967-2005
05414820	Sinsinawa River near Menominee	39.6	1967-2005
05438283	Piscasaw Creek near Walworth, WI	9.6	1992-2005
05512500	Bay Creek at Pittsfield	39.4	1939-2005
05588000	Indian Creek at Wanda	36.7	1940-2005
05591550	Whitley Creek near Allenville	34.6	1980-2005
05592575	Hickory Creek near Brownstown	44.2	1988-2005
05597500	Crab Orchard Creek near Marion	31.7	1951-2005

Continuous streamgage records are the backbone for regional hydrologic studies and provide the potential for multiple uses of data. But because water supply applications are concerned primarily with the need for low flow conditions, it is possible that alternative monitoring schemes also could be devised specifically for low flow analyses. A practical limitation of low flow monitoring schemes is availability of field personnel, given the infrequency of low flow conditions.

Evaporation Data

Collection of detailed, on-site climate and water temperature data for lake evaporation analyses would better define the amount of evaporation lost for the monitored lake, perhaps reducing evaporation estimation error to around 10 percent. Because of the influence of local factors on evaporation, however, it is unlikely that results from one lake substantially would reduce uncertainties in estimating evaporation in surrounding reservoirs. If data were collected for a number of lakes, subsequent analyses probably could determine the best empirical equation for use in regional climatological evaporation estimates for Illinois lakes. Even once this was accomplished, however, application of the climatological estimates still may be subject to a 20-25 percent variability without accounting for individual lake factors such as heat storage and exposure to winds. Net evaporation has a comparatively smaller influence in the estimate of net yield, so results of such studies would improve the overall estimate of net yield for most reservoirs by less than 5 percent. Monitoring of on-site climate data for evaporation analysis therefore is not considered a high-priority data need.

In circumstances where there is expected to be relatively little inflow into the reservoir during a drought, such as for a very small watershed or for an off-channel reservoir where pumping to and from the reservoir is recorded, lake evaporation can be computed through a water budget analysis of the lake using records of lake levels, local precipitation, and water use. In such cases, the combination of lake evaporation and the net groundwater flow loss would be computed as the by-product of other variables in the water budget. For this type of analysis to be successful, continuous or daily records of lake level and precipitation would be necessary.

Summary

This report examines uncertainties in the primary data inputs used to estimate yields of Illinois community surface water sources. The four primary data categories considered are: 1) drought streamflow, either as low flows at the site of supply withdrawal or as the cumulative inflow into a reservoir over the course of a drought, 2) capacities of water supply reservoirs, 3) precipitation over reservoir during the course of the drought, and 4) evaporation from a reservoir. Uncertainties in precipitation estimates are comparatively small (generally estimated to have a 10 percent error), and the summation of precipitation and evaporation are often analyzed together as net evaporation, with uncertainties in evaporation estimates being predominant. For evaporation estimates, there are few available quantitative data studies and, by necessity, uncertainty has been characterized with rough qualitative estimates of the expected data error (such as 25 percent). Even such rough estimates are useful in determining overall uncertainty of yield estimates and related data needs, however.

A metric was created that compares the relative influence of the various data categories on the uncertainty in estimating yields of impounding reservoirs. It indicates that uncertainty in the reservoir capacity is the single greatest factor influencing accuracy of the yield estimate for impounding reservoir systems. Obtaining bathymetric surveys for reservoirs that do not already have such data represents the most expedient and cost-effective way to improve yield estimates for these reservoirs.

If there never has been a sedimentation or bathymetric survey of the reservoir, the available capacity estimate likely is not only uncertain (standard error of 24 percent) but also too high (overestimation bias of 15 percent). Amounts of bias and error in the estimate of reservoir capacity are expected to be noticeably greater for smaller reservoirs with capacities less than 1000 acre-feet, and somewhat less for larger reservoirs with capacities greater than 5000 acre-feet.

If the reservoir had an older sedimentation survey, prior to 1970, the amount of bias and error in the current estimate of reservoir capacity may not be substantially different than had the reservoir never been surveyed. On the other hand, if there has been a sedimentation survey within the last 30-35 years (i.e., measured information on the sedimentation rate), then the current estimate of reservoir capacity may be, on average, within 11 percent of that measured by a new survey.

Uncertainties in streamflow data are the greatest source of error in estimating yields for direct stream withdrawals, off-channel storage reservoirs, and certain impounding reservoirs. Fortunately, almost all direct stream withdrawals and roughly half of the intakes for off-channel reservoirs are located on streams and rivers near a gaging station that can be used to estimate availability of streamflow. For the remaining off-channel reservoir systems, the lack of streamflow data is likely a considerable source of uncertainty for determining yield and adequacy of that water system; given the available data, however, this investigation was unable to quantify the expected uncertainty for such off-channel reservoir systems.

Even when reservoir capacity is the most influential source of uncertainty in yield analyses, estimates of drought inflow into the reservoir remain an additional dominant input in the water budget assessment of the yield. Drought inflows for most reservoirs never have been measured and are instead estimated by regional analysis of streamgage records. While there have been methodological improvements in estimating streamflows at ungaged locations, such as provided by regional studies used in developing the Illinois Streamflow Assessment Model, there has been a general erosion in the underlying data used to develop these estimates. If a severe drought occurred today there would be insufficient documentation of flow conditions of the type necessary for water supply assessment studies. Thus, reestablishment of streamgages in small watersheds near existing water supply reservoirs is necessary to maintain the quality of data available for future evaluations.

Net evaporation has a comparatively smaller influence in the estimate of net yield for most reservoirs. Thus, data collection activities to reduce uncertainty in evaporation estimates may not noticeably improve estimates of net yield for Illinois reservoirs as a whole. Thus, monitoring on-site climate data for evaporation analysis is not a high-priority data need.

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