Uncertainty of estimates of groundwater yield for the Cambrian-Ordovician Aquifer in northeastern Illinois

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Abstract

The aquifers underlying northeastern Illinois and southeastern Wisconsin are an important water resource for a rapidly growing region. These aquifers include the sandstone and dolomite formations collectively known as the Cambrian-Ordovician Aquifer. A series of studies conducted in the 1950's and 1960's determined that the best estimate of the 'maximum practical sustained yield' of this aquifer in northeastern Illinois is 65 million gallons per day (mgd). However, this estimate is based on inferred conceptual models and parameters whose uncertainties may affect the estimate of the practical sustained yield. Simple bounding estimates suggest that the practical sustained yield of this aquifer in northeastern Illinois could range from 28 to 180 mgd as a consequence of parameter and conceptual uncertainties. The analysis also suggests revising the current approach to estimating groundwater availability.

Introduction

Northeastern Illinois is home to approximately 7.7 million people, and includes Chicago, the third largest city in the U.S (Figure 1). The population of the six suburban counties surrounding Chicago is predicted to increase by almost 15 percent by 2020 (NIPC 2001). Similarly, the seven counties of southeastern Wisconsin have a rapidly growing population of approximately 2 million (SEWRPC 2002). This growth is expected to increase regional water demand, but regional water supply may be limited. While the region is adjacent to the Great Lakes, withdrawals from Lake Michigan are currently at the maxima allowed by U.S. Supreme Court decrees and international treaties. Many communities look to groundwater resources to meet growing demands, including the Cambrian-Ordovician Aquifer underlying the region.

This paper considers the Cambrian-Ordovician Aquifer to consist of several lithostratigraphic units under the region (Figure 2), as described in Suter et al. (1959) and Walton (1964). In descending order, these are the Galena-Platteville Dolomite, the Glenwood-St. Peter Sandstone, the Prairie du Chien Group, the St. Lawrence and Franconia formations, and the Ironton-Galesville Sandstone. In the Chicago area, the most productive units are the Glenwood-St. Peter Sandstone and the Ironton-Galesville Sandstone, which generally act as a single aquifer on a regional basis (Burch 2002). The upper units of the Eau Claire Formation hydraulically isolate the Cambrian-Ordovician Aquifer from the underlying Elmhurst-Mt. Simon Aquifer. This underlying aquifer consists of the basal unit of the Eau Claire Formation, known as the Elmhurst Sandstone

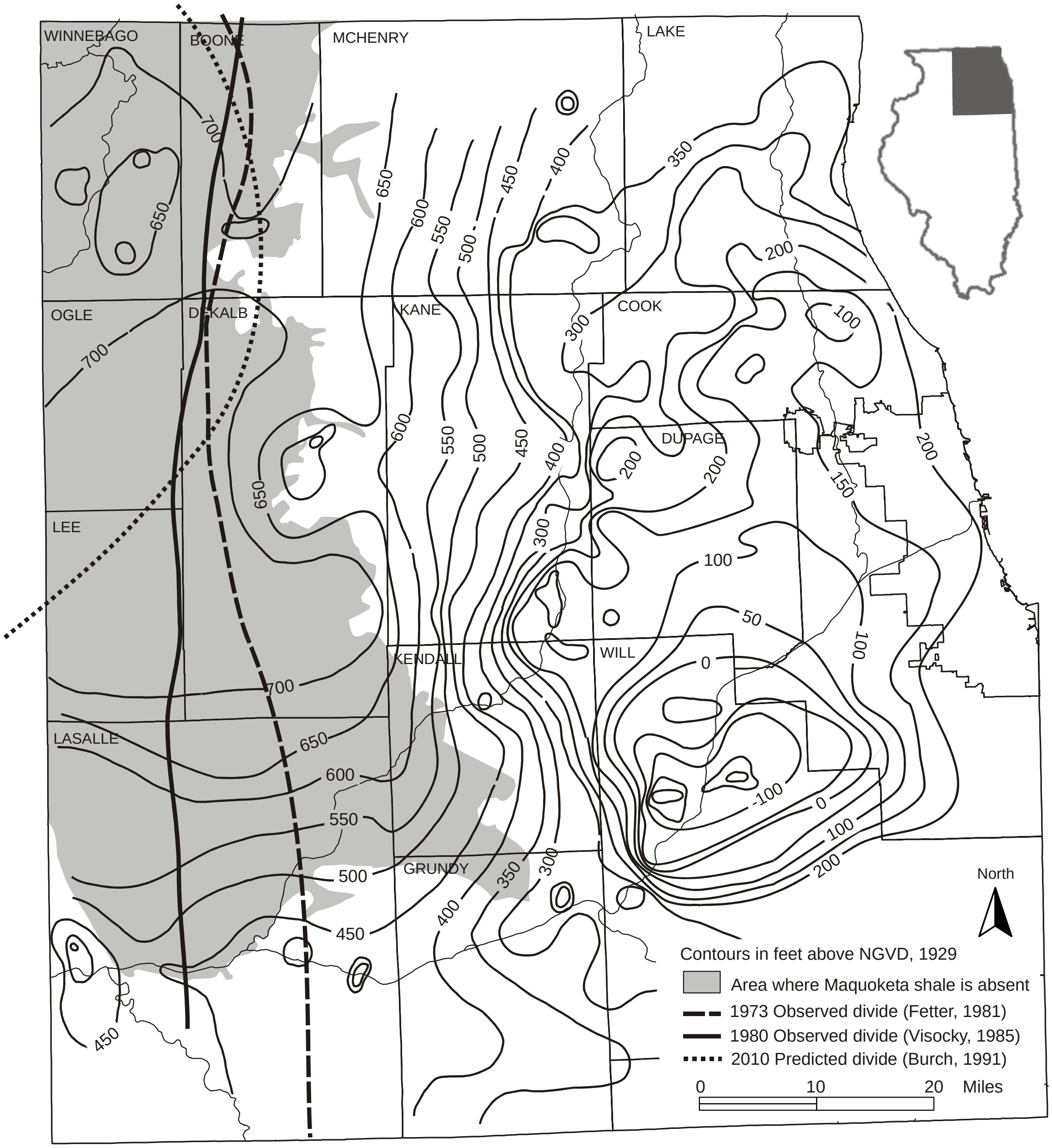

Figure 1. Study location map, showing equipotential contours of piezometric head observed in the year 2000 for the Cambrian-Ordovician Aquifer. The Maquoketa formation is absent in the shaded region.

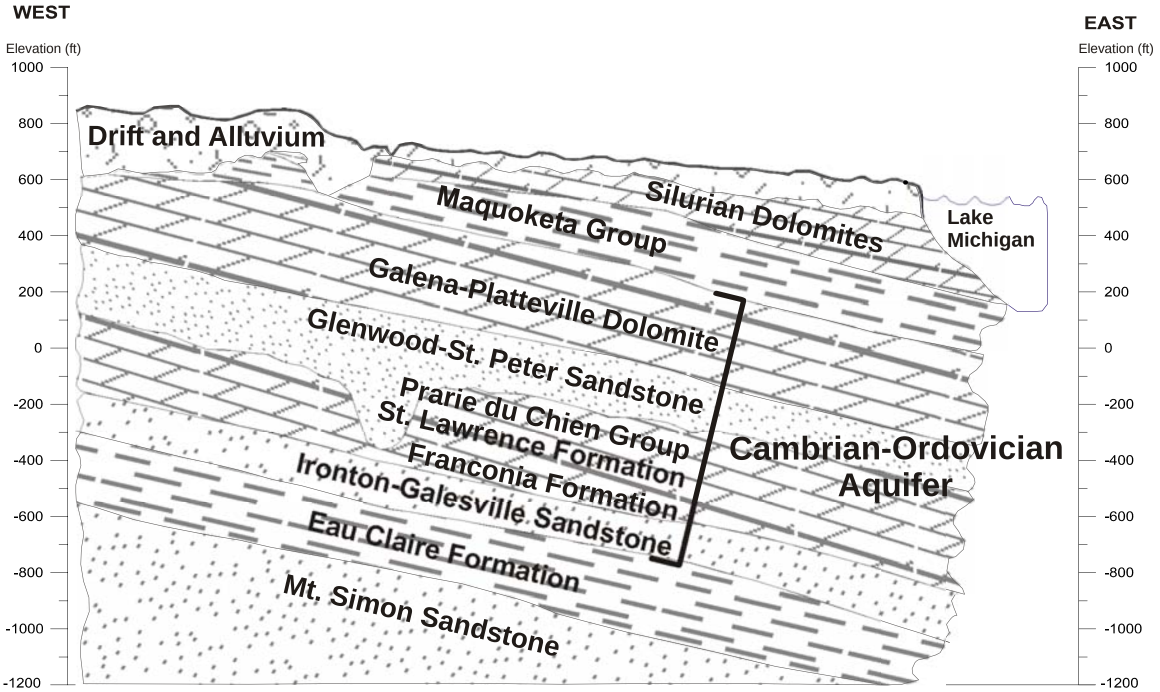

Figure 2. Geologic cross-section from the city of Dekalb, Illinois (west) through central Chicago (east), looking north.

Member, and the Mt. Simon Sandstone. The Cambrian-Ordovician Aquifer is partially confined by the shales of the Maquoketa Group in the eastern portions of the region (Figure 1) (Walton 1964).

The earliest water-resources studies reported that wells tapping the Cambrian-Ordovician Aquifer in the Chicago area flowed at ground surface in 1864. Population growth led to increased groundwater use and declining piezometric levels, such that drawdowns as great as 900 ft were observed in Chicago by 1980 (Visocky et al. 1985). During this period, conflicts over diversions from the Great Lakes led to a 1967 U.S. Supreme Court decree, which allocated the amount of water diverted, by each state from the Great Lakes (Wisconsin v. Illinois, 1967). In 1980, the Court-appointed Special Master required that Illinois manage its Lake Michigan allocation "…with the goal of reducing withdrawals from the Cambrian-Ordovician aquifer" (Fetter 1981). A series of water-resources investigations estimated how much water was available from this aquifer to either the Milwaukee or Chicago metropolitan areas (Fetter 1981; Schicht et al. 1976; Suter et al. 1959; Walton 1964). While the uncertainties of these estimates were acknowledged, the authors presented only 'best-estimate' values for the yield of this aquifer, expressed as the practical sustained yield for a metropolitan area.

The practical sustained yield (PSY) of an aquifer is defined as "the maximum amount of water that can be continuously withdrawn by a pumping array without exceeding recharge or causing water levels to decline below critical levels" (Suter et al. 1959; Zeizel et al. 1962). This definition explicitly states most of its limitations: it is valid for a particular well field, for steady-state conditions, and for pre-determined critical water levels. For the Cambrian-Ordovician Aquifer in northeastern Illinois, the critical level is the top of the Ironton-Galesville sandstone (i.e., the withdrawals should not dewater this highly productive unit). The PSY also implicitly assumes a set of economic, legal, social, and climatological constraints, e.g., that the pumping array is economically feasible, that prior water rights are not infringed, and that precipitation will not vary (Walton 1970).

The recent international debate on global climate change highlights the importance of uncertainty in environmental modeling and its impact on public policy (NRC 2001). This debate also prompts an examination of the uncertainty of the estimated PSY of the Cambrian-Ordovician Aquifer in northeastern Illinois. As a prelude to detailed modeling studies, this paper assesses the uncertainty of the estimated PSY for this aquifer in northeastern Illinois, using the published ranges of parameters and simple scoping calculations. This paper also discusses the assumptions of the practical sustained yield and its general suitability as an expression of aquifer yield.

Practical Sustained Yield in Northeastern Illinois

Suter et al. (1959) estimated the PSY of the Cambrian-Ordovician Aquifer in northeastern Illinois for the 1958 configuration of pumping centers. This estimate was based on conceptual models and parameters developed during their comprehensive review of the hydrogeology of northeastern Illinois. They estimated that 5% of the annual precipitation recharges the 1.2×10^3 mi^2 area between the western limit of the Maquoketa and the 1958 piezometric divide of the aquifer, for a total of 1.0×10^8 gallons per day (gpd) of available recharge. They evaluated the effects of long-term pumping in the aquifer using an analytical model based on the method of superposition and image wells to represent the 1958 pumping centers, the western extent of the Maquoketa cover, and barrier boundaries east and south of Chicago. Walton and Walker (1961) refined the analytical model to include leakage through the Maquoketa, using parameters inferred from Walton's flow net analysis of leakage (Walton 1960). These studies estimated that the PSY of this aquifer in northeastern Illinois for the 1958 configuration of pumping centers was 4.6×10^7 gpd (46 mgd). Although this is less than the estimated total of available recharge of 1.0×10^8 gpd west of the Maquoketa cover, the analytical model predicted that the lateral gradient from the western recharge area to the 1958 pumping centers could not be increased without eventually dewatering the Ironton-Galesville sandstone. That is, the PSY of the 1958 configuration of pumping centers in northeastern Illinois was limited by the lateral transmission of groundwater from the recharge area, and did not capture all of the available recharge.

Walton (1964) extended the Suter et al. (1959) analysis to estimate the maximum PSY of the Cambrian-Ordovician Aquifer in northeastern Illinois. To determine the maximum PSY, Walton assumed that an ideal well configuration exits that could capture all recharge and leakage in northeastern Illinois without dewatering the Ironton-Galesville formation. Transient hydraulics and storage can be ignored in this instance because the PSY was defined for continuous withdrawal (steady state), thus the maximum PSY is equal to the maximum recharge and leakage. For this system, the components of leakage and recharge include downward leakage through the Maquoketa, upward leakage through the Eau Claire, and recharge between the western extent of the Maquoketa and the piezometric divide (Figure 1). Walton used the analytical model of

Table 1. Bounds on the maximum practical sustained yield for the Cambrian-Ordovician Aquifer in northeastern Illinois, based on the approach of Walton (1964) and the published ranges of parameters.

	K_v (gpd/ft^2)	Vertical Gradient	Rate/Area (gpd/mi^2)	Area (mi^2)	Rate (gpd)
Lower Bound					
Eau Claire Leakage	2 x 10^{-5}	8.6 x 10^{-1}		4.0 x 10^3	1.9 x 10^6
Maquoketa Leakage	2 x 10^{-5}	2.2		4.0 x 10^3	4.9 x 10^6
Western Recharge			2.2 x 10^4	9.5 x 10^2	2.1 x 10^7
				subtotal	**2.8 x 10^7**
Walton Estimate					
Eau Claire Leakage	3 x 10^{-5}	8.6 x 10^{-1}		4.0 x 10^3	2.9 x 10^6
Maquoketa Leakage	5 x 10^{-5}	2.2		4.0 x 10^3	1.2 x 10^7
Western Recharge			4.2 x 10^4	1200	5.0 x 10^7
				subtotal	**6.5 x 10^7**
Upper Bound					
Eau Claire Leakage	1 x 10^{-4}	8.6 x 10^{-1}		4.0 x 10^3	9.6 x 10^7
Maquoketa Leakage	1 x 10^{-4}	2.2		4.0 x 10^3	2.5 x 10^7
Western Recharge			8.6 x 10^4	1.8 x 10^3	1.5 x 10^8
				subtotal	**1.8 x 10^8**

Walton and Walker (1961) to estimate the piezometric head difference between the aquifers overlying the Maquoketa and the simulated drawdowns in the Cambrian-Ordovician Aquifer as approximately 430 ft. Dividing this by the average thickness of the Maquoketa (200 ft) yields an estimated gradient of 2.2 ft/ft. A flow net analysis of the 1958 piezometric surface (Walton 1960) provided a best estimate of the Maquoketa vertical hydraulic conductivity as 5 x 10^{-5} gpd/ft^2. Applying Darcy's law over the 4.0 x 10^3 mi^2 area of Maquoketa confinement yields 1.2 x 10^7 gpd for captured leakage. Walton estimated the gradient across the Eau Claire as the piezometric head difference between the Ironton-Galesville and the Mt. Simon (300 ft), divided by the average thickness of the Eau Claire (350 ft) for an estimated gradient of 8.6 x 10^{-1} ft/ft. The absence of data for vertical hydraulic conductivity of the Eau Claire forced Walton to assume it to be 3 x 10^{-5} gpd/ft^2 (similar to but less than that of the Maquoketa). Applying Darcy's law over the 4.0 x 10^3 mi^2 area yields 2.9 x 10^6 gpd of captured leakage through the Eau Claire Formation. For recharge west of the extent of the Maquoketa, Walton (1962) applied a flow-net analysis to estimate a rate of 2.1 x 10^4 gpd/mi^2 (0.9 in/yr). Assuming that an ideal distribution of wells might double this to 4.2 x 10^4gpd/mi^2 yields an estimated 5.0 x 10^7 gpd of recharge. The sum of these three components is the estimated maximum PSY of 6.5 x 10^7 gpd (65 mgd) available in northeastern Illinois. Walton (1964) suggested that the ideal well field to capture this maximum PSY might be approximated by shifting the 1958 pumping centers westward and increasing the spacing and number of wells.

The above estimates of the PSY and the maximum PSY have been widely cited as the amount of water available from the Cambrian-Ordovician aquifer to the Chicago area.

In 1979, the actual withdrawals in the Chicago area increased to an estimated 183 mgd, causing piezometric levels to decline so rapidly that there was little doubt that they would eventually reach critical levels (Personal Comm., Visocky 2002). The State of Illinois petitioned the U.S. Supreme Court to modify the 1967 Lake Michigan allocation so that a number of communities could be shifted from using groundwater to using Lake Michigan water. That modification was granted in 1980, and withdrawals from the Cambrian-Ordovician Aquifer decreased to approximately 67 mgd by 1994 (NIPC 2001). From 1995 to 2000, the growth of the western Chicago suburbs resulted in shifting the pumping centers westward, and by 2000 withdrawals had increased slightly to an estimated 72 mgd. Together, these changes allowed piezometric levels to recover more than 100 feet in large areas of the easternmost counties, with recoveries of approximately 300 ft in some locations (Burch 2002). Fetter (1981) argued that groundwater withdrawals in the Chicago area should be limited to 46 mgd, and that withdrawals exceeding this estimate inflated the cost of pumping in southeast Wisconsin. The Northeastern Illinois Planning Commission (NIPC) suggested that 65 mgd is an upper bound for the PSY. NIPC noted that withdrawals still exceed 65 mgd and concluded that the growing demand for water would need to be met from other water sources and by conservation (NIPC 2001).

Uncertainties and their Impacts

Although the PSY estimates for the Cambrian-Ordovician Aquifer in the Chicago area are used to support plans and policies, there has been little examination of their robustness and reliability. Visocky (1982) updated the numerical model of Prickett and Lonnquist (1971) to account for withdrawals in the Milwaukee area and used the revised model to simulate the 1980 configuration of pumping centers operating continuously at 65 mgd. That analysis showed that the piezometric surface would eventually stabilize well above the Ironton-Galesville formation, suggesting that 65 mgd was a reasonable estimate of the maximum PSY. However, Visocky noted that the numerical model had uncertainties and did not evaluate alternative configurations of pumping centers. Burch (2002) commented that the recharge areas were uncertain, and might be more extensive than those cited in Suter et al. (1959) and Walton (1964). Burch also noted that drawdowns as great and extensive as those predicted by Prickett and Lonnquist (1971) have never been observed, even though withdrawals have exceeded 65 mgd every year since the mid-1960’s. Such uncertainties warrant further investigation, including field studies, analysis, modeling, and the evaluation of alternative conceptual models. As a prelude to more extensive studies, this paper examines the uncertainty of the maximum PSY for the Cambrian-Ordovician aquifer in the Chicago area using the approach of Walton (1964) and the published ranges of parameter values.

The lower bound for the maximum PSY is estimated by repeating Walton’s (1964) calculations using the lowest values published for all parameters. Walton (1964) gives the lowest value for the Maquoketa vertical hydraulic conductivity as 2×10^{-5} gpd/ft^2. In the absence of other published estimates, the area of Maquoketa confinement is assumed to be 4.0×10^3 mi^2 and the vertical gradient is assumed to be 2.2 ft/ft, as in the best estimate of Walton (1964). Applying Darcy’s law, these yield a lower bound estimate of 4.9×10^6 gpd for downward leakage across the Maquoketa. For upward leakage through the Eau Claire, Walton (1964) and Mandel and Kontis (1992) suggested that the vertical hydraulic conductivity is the same as that of the Maquoketa, taken here as 2 x 10^{-5} gpd/ft^{2}. No other estimates for the gradient or area have been published, so this component is otherwise unchanged from Walton (1964). Substituting into Darcy's law, the lower bound estimate for upward leakage across the Eau Claire is 1.9 x 10^{6} gpd. Hoover and Schicht (1967) estimated that the recharge west of the Maquoketa cover was 1.1 x 10^{4} gpd/mi^{2} in the 1960's. Similar to Walton (1964), this value is doubled to represent the increased capture of recharge due to the maximum development of the aquifer. Fetter (1981) estimated that the piezometric divide was farther east than did Suter et al. (1959), so that the estimated area receiving recharge between the divide and the western extent of the Maquoketa is just 9.5 x 10^{2} mi^{2} for an estimated recharge of 2.1 x 10^{7} gpd. Taking these three components together yields an estimated lower bound of the maximum PSY of 2.8 x 10^{7} gpd (28 mgd).

The upper bound estimate repeats the previous calculations using the greatest published estimates for all parameters. For downward leakage through the Maquoketa, the greatest published value for vertical conductivity is 1 x 10^{-4} gpd/ft^{2} (Walton 1960). There are no other published estimates for the gradient or the area, thus this calculation is otherwise unchanged from that of Walton (1964) for an estimated 2.5 x 10^{7} gpd of downward leakage. For upward leakage through the Eau Claire, the vertical hydraulic conductivity again is assumed to be the same as that of the Maquoketa, 1 x 10^{-4} gpd/ft^{2}. No other estimates for this upward gradient or the area of leakage have been published, so this estimate is otherwise unchanged from Walton (1964) and yields 9.6 x 10^{7} gpd for upward leakage across the Eau Claire. In the western recharge area, Suter et al. (1959) estimated that 5% of precipitation (approximately 8.6 x 10^{4} gpd/mi^{2}) might be available as recharge. Burch (1991) updated the model of Prickett and Lonnquist (1971) and found that the piezometric divide would shift westward by 2010 in response to increased groundwater withdrawals (Figure 1). This increases the western recharge area contributing to the Chicago pumping centers to 1.8 x 10^{3} mi^{2}, so that the estimated available recharge is 1.5 x 10^{8} gpd. Assuming that all the available recharge and leakage is captured, the upper bound estimate for the maximum PSY is the total of these three components 1.8 x 10^{8} gpd (180 mgd).

Discussion

The preceding analysis has estimated the bounds on the maximum practical sustained yield (PSY) of the Cambrian-Ordovician Aquifer for the pumping centers in Chicago. This analysis used the approach of Walton (1964) to estimate the maximum continuous rate of groundwater withdrawal by an ideal pumping array without dewatering the most productive formations. Using the minimum and maximum of the published estimates for parameters and recharge areas, the analysis suggests that maximum PSY of the Cambrian-Ordovician Aquifer in the Chicago area lies between 28 and 180 mgd. While neither extreme of this range is necessarily an appropriate target for managing the development of this aquifer, the width of the range indicates that the oft-cited best estimate of 65 mgd (Walton 1964) is uncertain enough to affect regional planning, and thus warrants a formal analysis.

It is important to note that this analysis has a number of limitations and should not be considered more than a simple scoping calculation for the impact of uncertainties. The analysis has neglected uncertainties regarding the conceptual model of the system, the inferred parameter distributions, and measurement errors, each of which may affect the estimated bounds. This analysis also has not determined the characteristics of the ideal well field, even though this may be why the 1979 configuration of pumping centers could not sustain a rate approximately equal to the estimated upper bound. The estimated bounds neglect aspects of the system that may be important to planners, such as the transient behavior, the amount of water released from storage, and the impacts of climate change. These estimates also have ignored withdrawals in the Milwaukee area, even though these two pumping centers are believed to interfere with each other (Fetter 1981). Ongoing research projects include computer models of groundwater flow that will address these and other limitations of the present study.

As an expression of groundwater availability, the practical sustained yield is problematic for various reasons. The definition includes the phrase ‘without exceeding recharge’, which implies that recharge is constant. Similarly, the definition includes the phrase ‘continuously withdrawn’, which implies a steady-state system where the captured recharge balances the withdrawals. When faced with the reality that captured recharge varies with withdrawal rates and land use (Bredehoeft 2002) and that much recharge discharges to streams (Sophocleous 2000), the practical sustained yield is difficult to estimate, explain, and use.

Perhaps the greatest uncertainties in the maximum PSY are its implicit assumptions regarding economic, legal, social, and climatic conditions. Walton’s (1964) estimate of 65 mgd for the maximum PSY assumed an ideal well configuration that would double the captured recharge, based on his experience with groundwater development in Illinois. However, changes in water quality, consumer preferences, or climate might change demand for groundwater such that a more expensive ideal well configuration would become feasible. Such a well field might capture recharge more effectively and result in a greater withdrawal rate for the PSY, but also might lead to impacts that could be considered unacceptable. William C. Walton, the originator of many of the estimates of the PSY for this aquifer, summarized these difficulties:

> "It is seldom that any single value of practical sustained yield can be correct for an extended time, in part due to economic conditions. Any determination of practical sustained yield is based on specified conditions, either existing or assumed and any changes in these conditions will change yield". (Walton 1970)

That is, the practical sustained yield will assume a range of values corresponding to the range of physical and economic conditions that might be imposed.

As scientists and engineers began to understand aquifer storage and the response of water levels to pumping, they developed expressions of groundwater availability similar to the practical sustained yield. Among the first of these was the ‘safe yield’ of an aquifer, defined as the rate at which water can be withdrawn without depleting the aquifer to the extent that withdrawal at that rate is no longer economically feasible (Meinzer 1923). This definition was later generalized to the maximum withdrawal rate without an undesirable result (Alley et al. 1999; Chow 1964). Similar to the practical sustained yield, some authors have proposed the term ‘sustainability’, meaning a use that meets the needs of the present without compromising the needs of the future (Brundtland 1987). However, Wood (2001) pointed out that these measures of groundwater availability require value judgments whose assessment lies outside the realm of science or engineering.

Future growth in northeastern Illinois is in part predicated on the availability of water from aquifers in the region, and planners and policymakers need to understand the possible outcomes of management alternatives. Like Walton, we conclude that the oft-cited, single-value estimates of the practical sustained yield are inadequate as expressions of water availability. Future analyses by the Illinois State Water Survey of the Cambrian-Ordovician Aquifer will move away from defining the practical sustained yield, and towards sensitivity and uncertainty analyses of the impacts of management alternatives.

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Appendix: Annotated references for the parameter values used in Uncertainty of estimates of groundwater yield for the Cambrian-Ordovician Aquifer in northeastern Illinois, by D.D. Walker, S.C. Meyer, and D. Winstanley.

	Parameter Values	Source and comments
Upward leakage through Eau Claire Fm		
K_v, vertical hydraulic conductivity [gpd/ft^2]	Walton: 3×10^{-5}	Walton (1964) gives this as the best estimate of the K_v of this formation.
	Low: 2×10^{-5} High: 1×10^{-4}	Mandle and Kontis (1992) suggested that K_v of the Eau Claire might be similar to that of the Maquoketa; this study assumed low and high values of K_v equal to those of the Maquoketa.
Vertical gradient [ft./ft.]	8.6×10^{-1}	Walton (1964) estimated this gradient using an average thickness of 350 ft (Suter et al., 1959) and assuming full development of the Ironton-Galesville, for an average head difference of 300ft. No other published estimates are available, so this estimate is also used for the high and low values
Area [mi^2]	4.0×10^3	Walton (1960) estimated this as the area covered by the Maquoketa fm. and within the recharge area; see fig 10b that report. Includes Lake, McHenry, Kane, Cook, Will, and Dupage counties, and about 1/6 of Boone, 1/3 of Dekalb, 1/2 of Kendall, and 1/6 of Grundy counties. No other published estimates are available, so this estimate is also used for the high and low values.

Downward leakage through Maquoketa Fm		
K_v, vertical hydraulic conductivity [gpd/ft^2]	Walton: 5 x 10^{-5}	Walton (1960) best estimate
	Low: 2 x 10^{-5}	Walton (1960) lowest estimate
	High: 1 x 10^{-4}	Walton (1960) highest estimate
Vertical gradient [ft./ft.]	2.2	Undocumented, but can be determined from Darcy’s law and the values given by Walton (1964). No other published estimates are available, so this estimate is also used for the high and low values.
Area [mi^2]	4.0 x 10^3	The same area used for estimating the leakage through the Eau Claire, Walton (1960) estimated this as the area covered by the Maquoketa fm. and within the recharge area. No other published estimates are available for this area, so this estimate is also used for the high and low values.
Western Recharge		
Recharge rate [gpd/mi^2]	Walton: 4.2 x 10^4	Walton (1964) estimated that full development would double the captured recharge, and so doubled the estimate of Walton (1962).
	Low: 2.2 x 10^4	Hoover and Schicht (1967) estimated the observed recharge, which this study doubled to account for full development (after Walton, 1965).
	High: 8.6 x 10^4	This is 5% of the annual precipitation, as speculated by Suter et al. (1959).
Area [mi^2]	Walton: 1.2 x 10^3	The area estimated by Suter et al. (1959).
	Low: 9.5 x 10^2	Determined in this study via rough planimetry of the figure of Fetter (1981).
	High: 1.8 x 10^3	Determined in this study via rough planimetry of the figure of Burch (1985).