Optimization of ground-water withdrawal in the lower Fox River communities, Wisconsin. [DNR-122] 1998

Walker, John F.; Saad, David A.; Krohelski, J. T.
Middleton, Wisconsin: U.S. Dept. of the Interior, U.S. Geological Survey, 1998

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U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 97-4218

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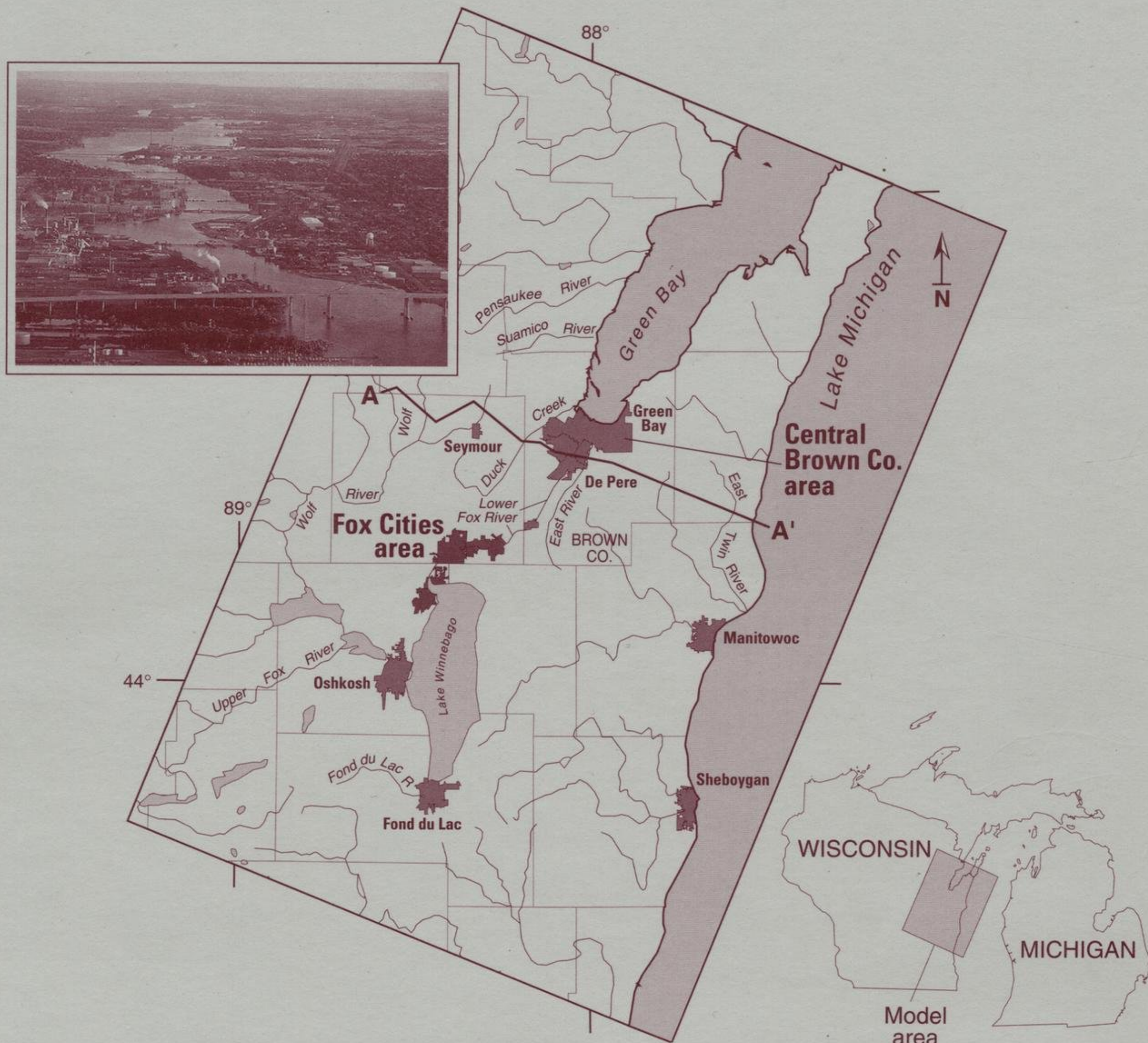

Prepared in cooperation with the
Wisconsin Department of Natural Resources

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OPTIMIZATION OF GROUND-WATER WITHDRAWAL IN THE LOWER FOX RIVER COMMUNITIES, WISCONSIN

By John F. Walker, David A. Saad, and James T. Krohelski

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U.S. DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To Obtain
	Length	
foot (ft)	0.3048	meter
	Area	
square mile (mi^2)	2.590	square kilometer
	Flow rate	
gallon per minute (gal/min)	0.06309	liter per second
million gallons per day (Mgal/d)	0.04381	cubic meter per second

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Elevation, as used in this report, refers to distance above or below sea level.

Optimization of Ground-Water Withdrawal in the Lower Fox River Communities, Wisconsin

By John F. Walker, David A. Saad, *and* James T. Krohelski

Abstract

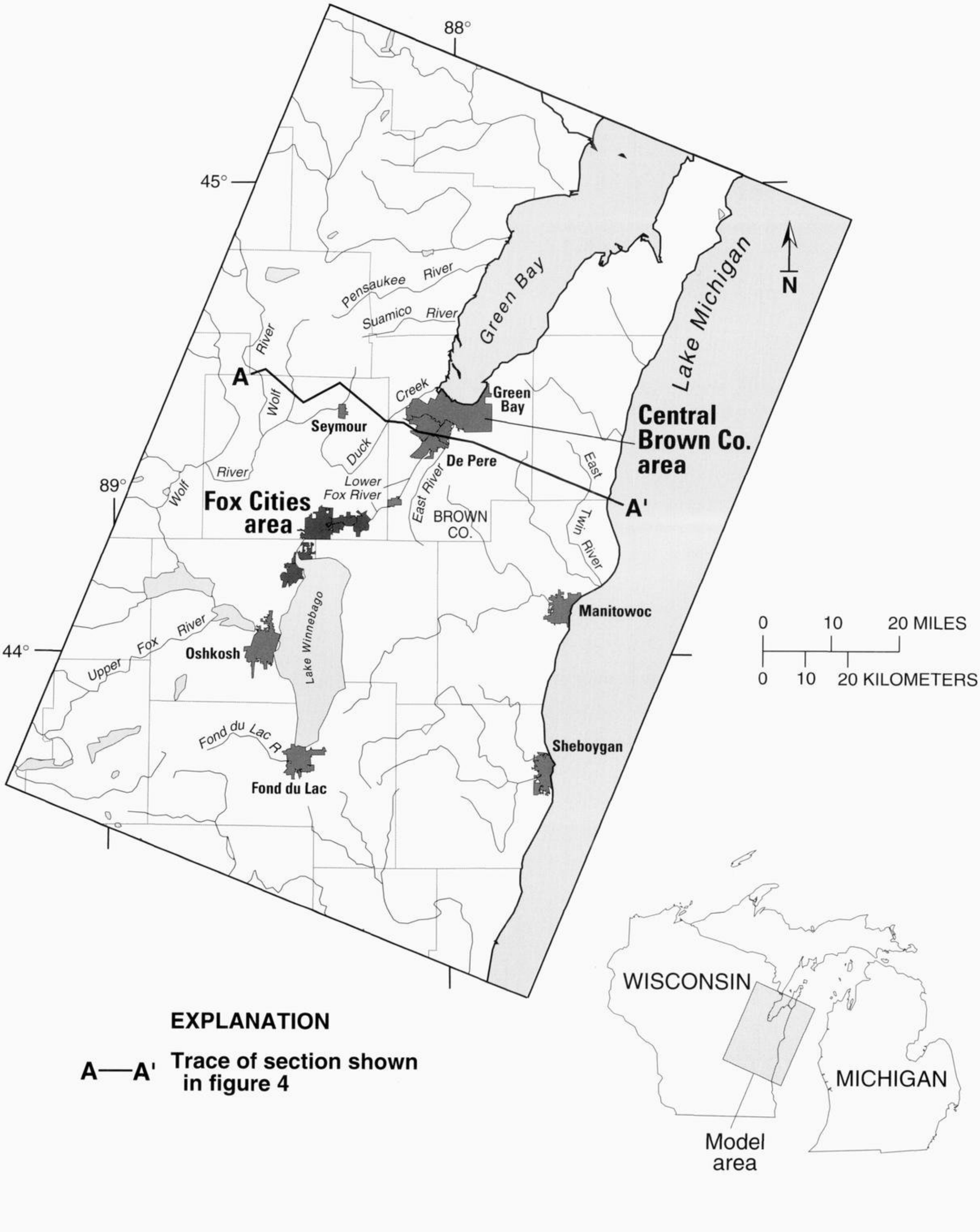
Pumping from closely spaced wells in the Central Brown County area and the Fox Cities area near the north shore of Lake Winnebago has resulted in the formation of deep cones of depression in the vicinity of the two pumping centers. Water-level measurements indicate there has been a steady decline in water levels in the vicinity of these two pumping centers for the past 50 years. This report describes the use of ground-water optimization modeling to efficiently allocate the ground-water resources in the Lower Fox River Valley.

A 3-dimensional ground-water flow model was used along with optimization techniques to determine the optimal withdrawal rates for a variety of management alternatives. The simulations were conducted separately for the Central Brown County area and the Fox Cities area. For all simulations, the objective of the optimization was to maximize total ground-water withdrawals. The results indicate that ground water can supply nearly all of the projected 2030 demand for Central Brown County municipalities if all of the wells are managed (including the city of Green Bay), 8 new wells are installed, and the water-levels are allowed to decline to 100 ft below the bottom of the confining unit. Ground water can supply nearly all of the projected 2030 demand for the Fox Cities if the municipalities in Central Brown County convert to surface water; if Central Brown County municipalities follow the optimized strategy described above, there will be a considerable shortfall of available ground water for the Fox Cities communities. Relaxing the water-level constraint in a few wells, however, would likely result in increased availability of water. In all cases examined, optimization alternatives result in a rebound of the steady-state water levels due to projected 2030 withdrawal rates to levels at or near the bottom of the confining unit, resulting in increased well capacity. Because the simulations are steady-state, if all of the conditions of the model remain the same these withdrawal rates would be sustainable in perpetuity.

INTRODUCTION

The Lower Fox River Valley includes two pumping centers, the Central Brown County area and the Fox Cities area near the north shore of Lake Winnebago (fig. 1). The Central Brown County municipalities include Allouez, Ashwaubenon, Bellevue, De Pere, Green Bay, Hobart, Howard, Lawrence, Ledgeview, Scott, Suamico, and the Oneida Tribe. The Fox Cities municipalities were divided into two groups: (1) Heart-of-the-Valley, comprised of Combined Locks, Darboy, Kaukauna, Kimberly and Little Chute; and (2) Western Towns, comprised of Appleton, Greenville, Neenah, and Menasha. Municipalities comprising these pumping centers have expressed concern over declining ground-water levels and the viability of long-term ground-water supplies.

Pumping from closely spaced wells has resulted in the formation of deep cones of depression in the vicinity of the pumping centers. These cones of depression have merged so that pumping in one center affects the other area, thus making declining water levels a regional problem. As early as 1953, researchers acknowledged that well interference was a problem in the Green Bay area, causing undesirable declines in water levels (Drescher, 1953). Since 1957, the city of Green Bay has used a combination of ground water and Lake Michigan water, via a pipeline, for most of their water supply. Ground water has been used as a supplemental supply to meet summer demands. The construction of the pipeline was prompted by excessive drawdown in the sandstone aquifer near the city of Green Bay. During the last several years, a proposal to build an additional pipeline to Lake Michigan has been



EXPLANATION

A—A' **Trace of section shown in figure 4**

Figure 1. Location of study and model area.

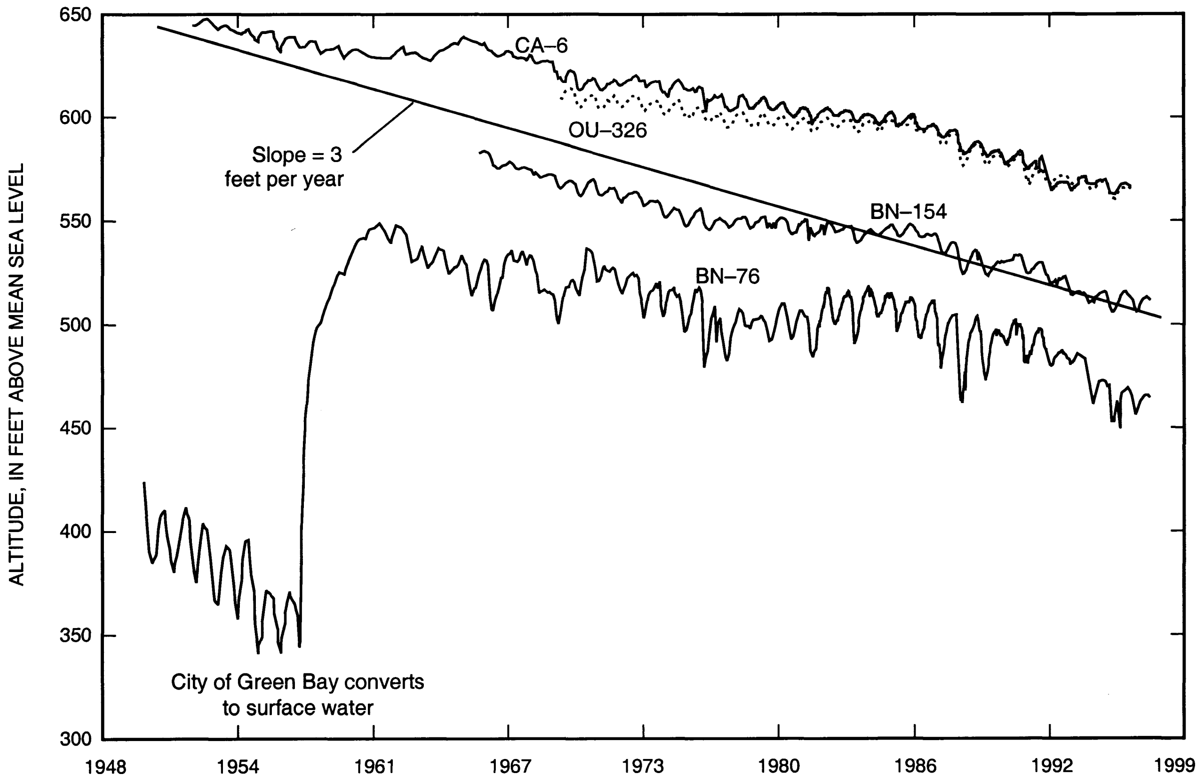


Figure 2. Ground-water levels and rate of decline in the Lower Fox River Valley.

discussed by Brown County's Potable Water Study Committee, which consists of representatives from communities in the vicinity of the Central Brown County area. Similar discussions have taken place in the Fox Cities.

Water-level measurements indicate there has been a steady decline in water levels in the vicinity of the two pumping centers for the past 50 years. Water levels measured in observation wells just to the north of the Central Brown County cone of depression (BN–76) and just to the south of the cone (BN–154) are shown in figure 2. The rate of the water-level decline in these wells is about 3 ft per year. Water levels measured in observation wells just to the north of the Fox Cities cone of depression (CA–6 and OU–326) indicate a rate of water-level decline of about 2 ft per year.

Using water-use projections for the year 2030 and a simulation from a previously developed ground-water flow model (Conlon, 1998), water levels in the year 2030 near the center of the cone of depression in the Central Brown County area are predicted to decline to near the elevation of the Precambrian bedrock surface (fig. 3). Should this occur, there will not be enough drawdown available to pump several wells located near the center of the cone. In the Fox Cities area near the center of the 1990 cone of depression, water levels in the year 2030 are predicted to drop about 60 ft below the top of the sandstone aquifer leaving about 480 ft of available drawdown (fig. 3). The center of the cone of depression in the Fox Cities will be slightly west of the 1990 center and water levels will be as much as 130 ft below the bottom of the confining unit there. Such declines would result in increased pumpage costs and a reduction in the amount of water that can be pumped from the sandstone aquifer.

The Central Brown County Water Commission (CBCWC) and East Central Wisconsin Regional Planning Commission (ECWRPC) and municipal representatives from the Lower Fox River Valley have expressed the need to approach water management

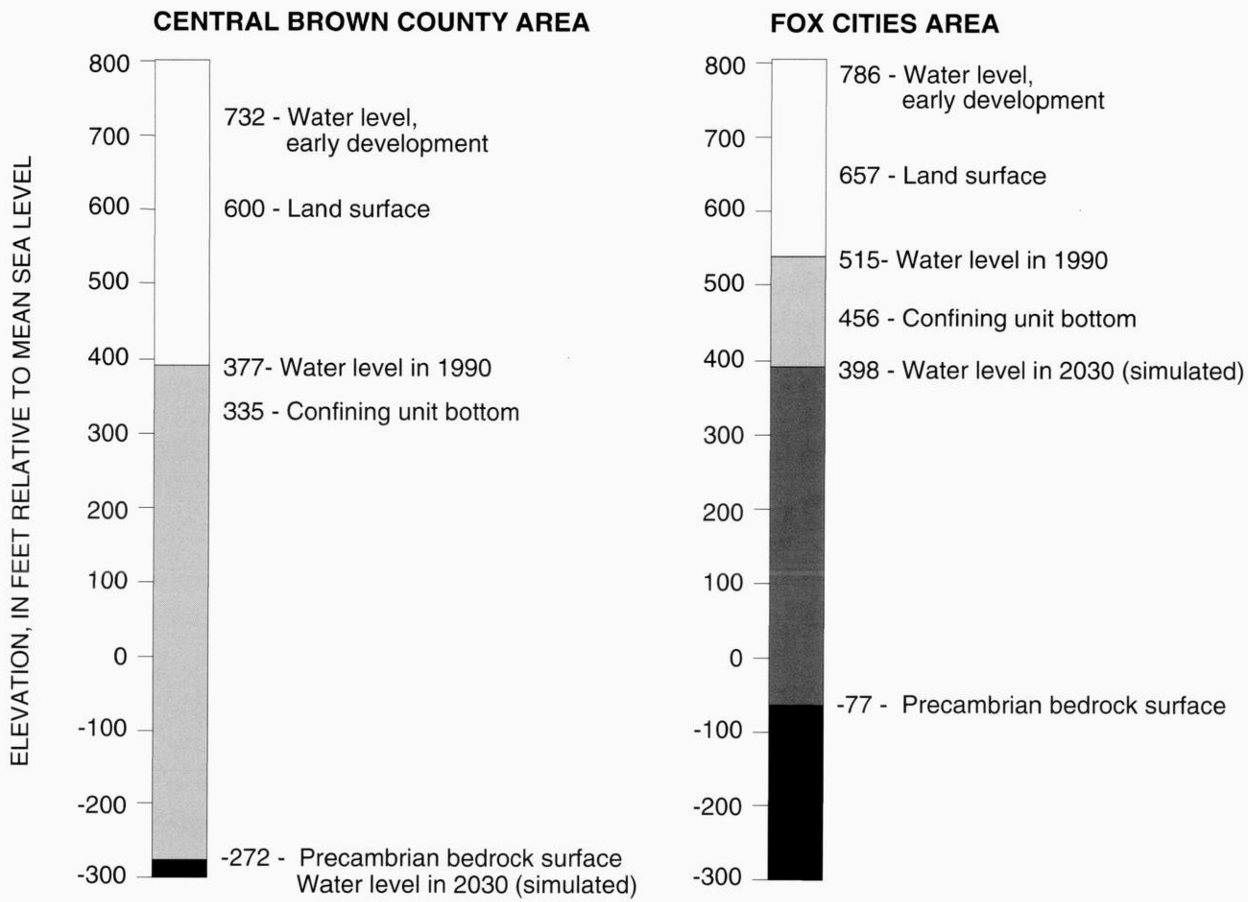


Figure 3. Simulated and measured elevation of water level in the sandstone aquifer, land surface, bottom of confining unit, and Precambrian bedrock surfaces near the centers of the cones of depression in the Central Brown County and Fox Cities areas.

from a regional perspective. To provide a regional approach, the use of an optimization model was proposed to the Wisconsin Department of Natural Resources (WDNR). In 1994, the U.S. Geological Survey in cooperation with WDNR initiated a study of ground-water management alternatives using a previously developed ground-water flow model, optimization techniques, and water-use projections provided by the CBCWC and ECWRPC.

Many studies have helped to define the ground-water resources of the Lower Fox River Valley and document the status of the ground-water system (Conlon, 1998; Batten and Bradbury, 1996; Consoer Townsend & Associates Inc., 1992; Feinstein and Anderson, 1987; Krohelski, 1986; Olcott, 1966; Knowles, 1964; Knowles, Dreher, and others, 1964; LeRoux, 1957; Drescher, 1953). Unlike previous studies, however, the present study attempts to determine if the sandstone aquifer is capable of providing the water demands of a growing population in the Lower Fox River Valley.

The purpose of this report is to demonstrate that efficient allocation of ground-water resources is feasible in the Lower Fox River Valley using ground-water optimization modeling. In the context of this report, optimization refers to maximizing withdrawals while limiting drawdown to specified levels. The techniques are applied to the regional ground-water model developed previously for the Lower Fox River Watershed (Conlon, 1998) and focus on management in two areas: the Central Brown County area and the Fox Cities area.

Optimization modeling replaces the trial-and-error approach by identifying potential solutions based on a specified objective from a management plan. The technique quantifies solutions and allows comparison of solutions ranging from optimal to those that are clearly inferior or not feasible. In this report, optimization modeling is used to evaluate specific management plans with the objective of maximizing well yields while satisfying pre-defined constraints, such as not allowing water levels to decline below specified levels.

GROUND-WATER FLOW SYSTEM

Ground water in the Lower Fox River Basin moves through either shallow, local flow systems, or through a deeper, regional flow system that is highly confined in the Lower Fox River Valley. The geohydrology of the model area, water-use projections and descriptions of pumping wells are described briefly in this section. The geohydrology is described in more detail elsewhere (Conlon, 1998).

Description of Modeled Area

A previously developed ground-water flow model (Conlon, 1998), that includes the major ground-water pumping centers of the Central Brown County area and the Fox Cities area in the Lower Fox River watershed (fig. 1), was used for the optimization procedure. The modeled area extends to the north of the city of Green Bay and to the south of the city of Fond du Lac. The western extent includes the Wolf River and upper Fox River, the two largest rivers in the model area. The eastern extent includes part of Lake Michigan.

Geology

Unconsolidated deposits of Quaternary age overlie the bedrock and consist of sediments of glacial, alluvial, and lacustrine origin. Glacial deposits in the model area include tills, outwash, and extensive lacustrine deposits. Glacial deposits ranging from 0 ft thick in the west to more than 100 ft in the river valley cover the bedrock in most of the model area. Recent alluvial and lacustrine deposits are also present in river valleys and lakes, respectively.

Sedimentary rock of Cambrian and Ordovician age underlie the unconsolidated deposits in the western part of the model. In the east, sedimentary rock of Silurian age underlie the unconsolidated deposits. With the exception of the Maquoketa Shale, most sedimentary rocks consist of sandstone and dolomite. Crystalline rock of Precambrian age underlies the sedimentary rock in most of the model area (fig. 4) and directly underlies the glacial deposits in the northwestern part of the area.

Hydrology and Ground-Water Movement

The unconsolidated deposits and sedimentary rock in the model area have been grouped into aquifers and confining units (Conlon, 1998). The sedimentary rock beneath the Sinnipee Group forms the sandstone aquifer and the Maquoketa Shale and Sinnipee Group form a confining unit. Above the confining unit, the unconsolidated deposits and dolomites form an upper aquifer

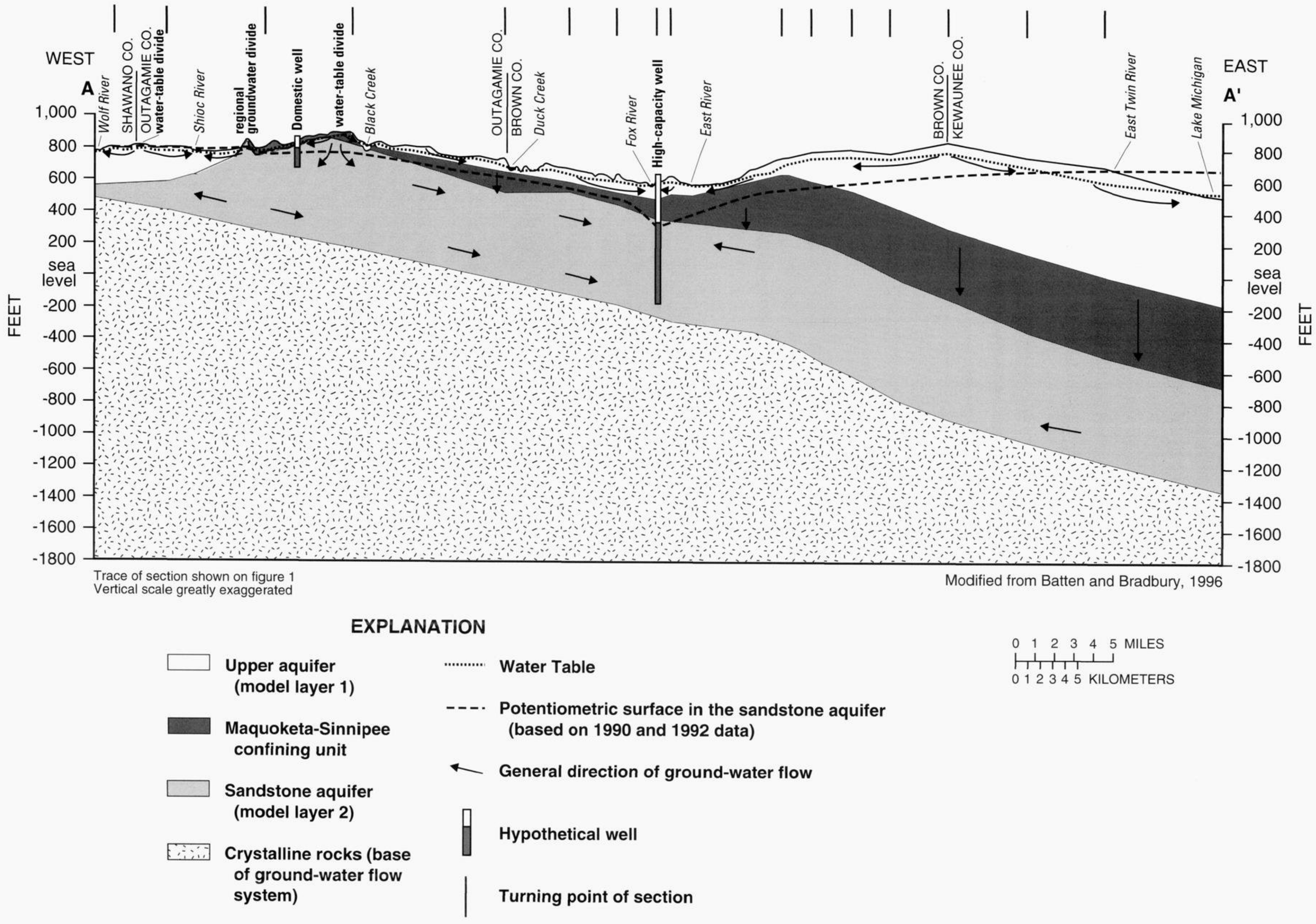


Figure 4. Generalized section showing aquifers, confining unit, and direction of ground-water flow.

(fig. 4). The Precambrian crystalline rock is assumed to form the base of the active ground-water flow system, because it is virtually impermeable.

In the upper aquifer, precipitation recharges ground water in topographically high areas and movement is toward discharge areas such as streams and lakes in nearby, topographically low areas. Recharge to the sandstone aquifer occurs mainly to the west of the Lower Fox River Valley, where the Maquoketa-Sinnipee confining unit is absent and the sandstone aquifer is in good hydrologic connection to the upper aquifer. Ground-water movement in the sandstone aquifer prior to development was generally west to east. Since development, the direction of ground-water movement is towards the Lower Fox River Valley near the Central Brown County and the Fox Cities pumping centers.

Water Use and Description of Wells

The CBCWC and ECWRPC provided estimates of municipal water use for the year 2030. These estimates were needed for the purpose of comparison of optimized to non-optimized solutions. In the Central Brown County area, a 240 percent increase for the period 1990 to 2030 is projected, from 7.32 to 24.7 Mgal/d (million gallons per day). In the Fox Cities Heart-of-the-Valley communities, a 41 percent increase for the period 1990 to 2030 is projected, from 3.9 to 5.5 Mgal/d. For the Fox Cities Western Towns, a 110 percent increase for the period 1990 to 2030 is projected, from 1.7 to 3.6 Mgal/d. Water use in the Fond du Lac area, in the southern portion of the model, was assumed to remain fixed at 1990 rates.

Numerous high-capacity wells in the Central Brown County area and Fox Cities area have had a regional effect on water levels in the sandstone aquifer. Wells withdrawing water from the upper aquifer are typically shallow domestic wells with low pumping rates of about 5 to 10 gal/min (gallons per minute). Such wells typically affect water levels only locally in the upper aquifer and can therefore be ignored. Wells withdrawing water from the sandstone aquifer are typically deep, high-capacity municipal, industrial, and commercial wells that pump about 500 to 1,000 gal/min. Pumping rates for 1990 and 2030, along with descriptions of the high-capacity wells included in the ground-water model, have been compiled and are included in the Appendix.

OPTIMIZATION MODELING

Optimization modeling is a general class of problems in which an objective function is either minimized or maximized subject to a series of constraints. The objective function and constraints are expressed as known mathematical functions of the variables of interest, termed decision variables. There are several classes of optimization models, depending in part on the form of the objective function and constraints. These include linear programming (linear objective function and constraints with continuous decision variables), integer programming (linear objective function and constraints with integer decision variables), mixed integer programming (linear objective function and constraints with integer and continuous decision variables), and nonlinear programming (nonlinear objective function and decision variables). Most introductory texts on operations research describe the classes of optimization models (for example, Gue and Thomas, 1968).

Ground-water optimization involves applying optimization modeling to problems of ground-water flow. A review of ground-water optimization techniques is given elsewhere (Gorelick, 1983). In most cases, linear programming has been applied to problems of ground-water flow due to its ability to handle large numbers of decision variables and constraints and the relative speed of the solution technique.

Specification of the objective function is a crucial step in optimization modeling. The objective function should represent the overall goal of the optimization. Typically the objective function is written using well pumping rates as the decision variables. Objective functions can range from a simple summation of pumping rates (for example, maximize total withdrawal) to a detailed function involving pumping rates and water levels (for example, minimize total cost).

The constraints impose limits on the decision variables and are very important in ensuring a realistic optimal solution. The constraints can vary from simple limits to more complex expressions. Examples of simple limits include upper bounds on pumping rates, lower bounds on water levels, and upper bounds on drawdowns. Examples of more complex limits include upper bounds on horizontal gradients and upper and lower bounds on flow velocity or direction.

Several approaches have been devised for representing the ground-water flow system as a linear system, but the most common approach is to use a response matrix to represent the response of the aquifer system to withdrawal rates at specified wells. This approach is attractive because it can use complex ground-water flow models to simulate the aquifer response, thus recent advances in ground-water flow modeling are incorporated into the final solution.

The response matrix is based on the theory of superposition. For the purpose of illustration, assume there are several wells in the system where the optimal withdrawal rate is to be determined; these are termed managed wells. Further, assume there are various locations in the system where the water level needs to be determined; these are termed control points. The response matrix is determined by operating each of the managed wells in isolation from the other managed wells. If $d_{i,j}$ equals the drawdown at control point i due to well j pumping in isolation at rate Q_j, and $R_{i,j}$ equals the unit response at control point i due to well j, then it follows that

$$R_{i,j} = \frac{d_{i,j}}{Q_j}. \qquad (1)$$

Equation 1 can be rearranged to express drawdown as a function of an individual pumping rate and the unit response factor, thus

$$d_{i,j} = R_{i,j} \bullet Q_j \; . \qquad (2)$$

Consider a case with two managed wells (j=2) and three control points (i=3). With well 1 pumping in isolation at a rate of Q_1 (well 2 turned off), equation 2 results in the following drawdowns at the 3 control points:

$$d_{1,1} = R_{1,1} \bullet Q_1 \; , \qquad (3)$$

$$d_{2,1} = R_{2,1} \bullet Q_1 \; , \text{ and} \qquad (4)$$

$$d_{3,1} = R_{3,1} \bullet Q_1 \; . \qquad (5)$$

Likewise, with well 2 pumping in isolation at a rate of Q_2 (well 1 turned off), equation 2 results in the following drawdowns at the 3 control points:

$$d_{1,2} = R_{1,2} \bullet Q_2 \; , \qquad (6)$$

$$d_{2,2} = R_{2,2} \bullet Q_2 \; , \text{ and} \qquad (7)$$

$$d_{3,2} = R_{3,2} \bullet Q_2 \; . \qquad (8)$$

If both wells are pumping, then by superposition the drawdown at the three control points (s_1, s_2, and s_3) is the sum of the individual drawdowns due to each well pumping in isolation (equations 3–8), thus

$$s_2 = d_{1,1} + d_{1,2} = R_{1,1} \bullet Q_1 + R_{1,2} \bullet Q_2 \; , \qquad (9)$$

$$s_2 = d_{2,1} + d_{2,2} = R_{2,1} \bullet Q_1 + R_{2,2} \bullet Q_2 \; , \text{ and} \qquad (10)$$

$$s_3 = d_{3,1} + d_{3,2} = R_{3,1} \bullet Q_1 + R_{3,2} \bullet Q_2 \; . \qquad (11)$$

If we let H_i^u equal the water level at control point i when all managed wells are off and let H_i^m equal the water level at control point i when all managed wells are on, then equations 9–10 can be used to determine the managed heads at the three control points, thus

$$H_1^m = H_1^u - s_1 = H_1^u - (R_{1,1} \bullet Q_1 + R_{1,2} \bullet Q_2) \; , \qquad (12)$$

$$H_2^m = H_2^u - s_2 = H_2^u - (R_{2,1} \bullet Q_1 + R_{2,2} \bullet Q_2) \; , \text{ and} \qquad (13)$$

$$H_3^m = H_3^u - s_3 = H_3^u - (R_{3,1} \bullet Q_1 + R_{3,2} \bullet Q_2) \; . \qquad (14)$$

Equations 12–14 express the water level at the control points as a linear function of the withdrawals at the managed wells. Thus the response of the flow system can be written as a linear function of the decision variables, and linear programming techniques can be used to determine the optimal solution.

The response-matrix approach has been used by numerous investigators to solve a variety of ground-water-management problems. In each case, ground-water-flow simulation models were used to determine the response matrix, which in turn was used in the formulation of the optimization problem. In some cases, a simple summation of withdrawal rates at the managed wells is used as the objective function (for example, Heidari, 1982; Danskin and Freckleton, 1992). In other cases, the objective function represents net economic benefit (for example, Bredehoft and Young, 1970; Reichard, 1987).

OPTIMIZATION SIMULATIONS

Optimization modeling was used to evaluate several management alternatives for the Central Brown County area and the Fox Cities area. The MODMAN commercial package (International Groundwater Modeling Center, 1996) was coupled with an existing ground-water flow model for the model area to determine optimal withdrawal rates. The LINDO linear-programming package (Schrage, 1991) was used to determine the solutions to the linear program optimization programs formulated by MODMAN. The optimal simulations were compared to baseline conditions representing the 2030 projected withdrawals. The ground-water flow model will be described, the management alternatives will be discussed, and baseline conditions will be presented in this section. This section concludes with presentation and discussion of the results.

Lower Fox River Basin Ground-Water Model

The 3-dimensional finite difference MODFLOW model (McDonald and Harbaugh, 1988) developed in a separate study (Conlon, 1998) was used to simulate the ground-water system in the Lower Fox River Basin in northeastern Wisconsin. In this section, a brief description of the model is given; a complete description of model calibration and limitations is presented elsewhere (Conlon, 1998). The model area (fig. 1) was discretized by use of a finite-difference grid. The extent of the model area was chosen such that: (1) the western boundary includes the western ground-water divide in the sandstone aquifer and the discharge areas of the Wolf River in the west and the upper Fox River in the south; (2) the northern boundary was set to a sufficient distance to minimize the effects of pumping in the Lower Fox River Valley on water levels near the boundary; (3) the eastern boundary incorporates a ground-water discharge divide in Lake Michigan; and (4) the southern boundary includes the area of water withdrawals near the city of Fond du Lac. The grid is rotated 23° east of north to orient the northern and southern boundaries parallel to the primary direction of ground-water flow in the sandstone aquifer.

The model grid contains 141 rows and 102 columns and two layers: Layer 1 simulates conditions in the upper aquifer, and layer 2 simulates conditions in the sandstone aquifer. The Maquoketa-Sinnipee confining unit is not simulated as a model layer, but as a boundary that allows limited vertical flow between the upper aquifer (model layer 1) and the sandstone aquifer (model layer 2). The Precambrian crystalline rock is assumed to be the base of the ground-water system.

The upper aquifer is simulated as a water-table aquifer with a combination of no-flow, constant-head, and head-dependent-flux boundaries along the northern, western, and southern edges of the model. Constant head cells simulate Lake Michigan along the eastern edge of the model. Rivers, streams, and lakes in the upper aquifer are simulated as constant-head or head-dependent-flux cells.

The sandstone aquifer is simulated as a convertible model layer, that is, the aquifer is simulated as confined unless water levels in the layer fall below the bottom of the overlying confining unit, in which case the aquifer is simulated as unconfined. The northern, eastern, and western boundaries of the sandstone aquifer are simulated as no flow. The southern boundary is simulated as constant head because that location coincides with a mapped ground-water divide in the sandstone aquifer which exists between the Milwaukee metropolitan area and the Fond du Lac area. Wells are included only for the sandstone aquifer and are modeled as being open to the entire thickness of layer 2.

Description of Management Alternatives

The objective of all of the management alternatives is to maximize total ground-water withdrawal. Thus the objective function is the summation of pumping rates from the managed wells. General constraints included upper bounds on the pumping rates of individual wells and lower bounds on the water level at model cells containing the managed wells. Maintaining the water level at or above the bottom of the confining unit assures no loss of capacity from a well; however, for some alternatives this constraint was relaxed to increase the amount of water available for withdrawal. As noted previously, there are two main pumping centers of interest in the model area: the Central Brown County area and the Fox Cities area. Because these areas are assigned to separate planning agencies, simulations were conducted separately for each area.

The main issues in the Central Brown County pumping center include (1) whether the city of Green Bay wells are operated at fixed rates or are managed, and (2) whether potential future wells (growth wells) are installed at two communities (Rockland and Humboldt, each with a withdrawal rate of 0.5 Mgal/d). In addition, two alternatives are available for increasing the amount of water available for withdrawal: (1) relaxing the water-level constraint to a level below the bottom of the confining unit, and (2) installing additional wells in outlying areas. Twelve potential well locations were selected for the new wells based primarily on distance from the main cone of depression; the optimization procedure selects the best 8 locations. Thus four

Table 1. Summary of optimization results for the ten Brown County alternatives represented by four factors: Green Bay municipal wells, growth wells, water-level constraints, and additional wells
[Mgal/d, million gallons per day]

Alternative	Green Bay municipal wells	Growth wells	Water level constraints	Additional wells	Total yield, in Mgal/d
2030	—	—	—	—	24.7
BC–1	fixed	none	bottom of confining unit	none	8.1
BC–2	fixed	none	100 ft below confining unit	none	14.3
BC–3	fixed	Rockland	100 ft below confining unit	none	13.7
BC–4	fixed	Rockland and Humboldt	100 ft below confining unit	none	13.3
BC–5	managed	Rockland and Humboldt	100 ft below confining unit	none	16.1
BC–6	fixed	none	bottom of confining unit	best 8 of 12	9.7
BC–7	fixed	Rockland	bottom of confining unit	best 8 of 12	8.5
BC–8	fixed	Rockland and Humboldt	bottom of confining unit	best 8 of 12	7.3
BC–9	managed	Rockland and Humboldt	bottom of confining unit	best 8 of 12	14.6
BC–10	managed	Rockland and Humboldt	100 ft below confining unit	8 wells from BC–9	20.3

factors are to be considered: (1) Green Bay wells (fixed or managed); (2) Growth wells in the outlying communities (0, 1 or 2, each pumping at a fixed rate); (3) Water-level constraints (bottom of the confining unit or relaxed); and (4) Additional wells (none or best 8 of 12). If all the alternatives were explored completely, there would be 24 possible simulations; because this was beyond the scope of this report, a reduced set of 10 alternatives were chosen (table 1). Hereafter, these alternatives will be referred to as the Brown County alternatives. For all of the Brown County alternatives, it is assumed that the distribution networks of the individual communities are interconnected, and that the communities are willing to transfer water among one another.

The main issues in the Fox Cities area are whether the municipal wells are pumped at fixed rates or are managed, and whether the industrial wells are fixed or managed. Because of interference from wells in Central Brown County, an additional issue is drawdown in the Fox Cities resulting from ground-water withdrawals in Brown County. Two Brown County conditions were chosen, resulting in the highest and lowest water levels in the Fox Cities area. Thus there are 3 factors to be considered: (1) Municipal wells (fixed or managed); (2) Industrial wells (fixed or managed); and (3) Brown County water levels (high or low). This results in 8 distinct alternatives to be considered (table 2). Hereafter, these alternatives will be referred to as the Fox Cities alternatives.

The results of simulations of the Brown County alternatives were examined in detail to determine the alternative that resulted in the lowest water levels in the Fox Cities area. For each alternative, several locations in the Fox Cities area were checked. Alternative BC–10 (table 1) resulted in the lowest water levels in the Fox Cities area; thus, for the Fox Cities simulations, the individual optimal withdrawal rates from BC–10 were used as fixed rates for the low Brown County water-level alternatives. For the high Brown County water level conditions, all municipal wells in Central Brown County were reduced to 10 percent of their projected 2030 withdrawal rate. This simulates conversion of the Central Brown County municipalities to surface water, with some ground-water use for peak periods.

Table 2. Summary of optimization results for the eight Fox Cities alternatives represented by three factors: Brown County water levels, municipal wells, and industrial wells. Results are summarized for municipal and industrial withdrawals for the two groups of communities: Heart-of-the-Valley and Western Towns
[Mgal/d, million gallons per day]

Alternative	Brown County water levels	Municipal wells	Industrial wells	Total yield, in Mgal/d					
				Heart-of-the-Valley			Western Towns		
				Municipal	Industrial	Total	Municipal	Industrial	Total
2030	—	—	—	5.5	0.9	6.4	3.6	2.5	6.0
FC–1	high	fixed	fixed	3.9	0.0	3.9	3.6	2.5	6.0
FC–2	high	managed	fixed	4.1	0.0	4.1	3.6	2.5	6.0
FC–3	high	fixed	managed	1.8	0.0	1.8	3.6	2.5	6.0
FC–4	high	managed	managed	4.3	0.0	4.3	3.3	2.7	6.0
FC–5	low	fixed	fixed	2.4	0.0	2.4	3.6	2.5	6.0
FC–6	low	managed	fixed	2.7	0.0	2.7	3.6	2.5	6.0
FC–7	low	fixed	managed	2.6	0.0	2.6	3.6	2.5	6.0
FC–8	low	managed	managed	2.9	0.0	2.9	0.2	5.8	6.0

Constraints for the Fox Cities alternatives included upper limits placed on the withdrawal rates for individual wells, lower limits on the water levels in the municipal and industrial wells, and upper limits placed on the sum of withdrawal rates for two distinct groups of users. Because the 2030 rates result in the water level dropping considerably below the bottom of the confining unit, the "fixed" alternatives were simulated by allowing each well to withdraw up to the 2030 rate or until the water level dropped to 100 ft below the bottom of the confining unit. For the "managed" alternatives, the Fox Cities communities were divided into two groups: (1) Heart-of-the-Valley and (2) Western Towns. It seemed reasonable for the communities to distribute surplus withdrawals within each group, but that it was not feasible to distribute water between the two groups. Thus, additional constraints were included to set an upper limit for the total withdrawals within a group equal to the projected 2030 demand for that group or until the water level in an individual well dropped to 100 ft below the bottom of the confining unit. For the cases where municipal and industrial wells were both managed, it is assumed that excess withdrawals within the two groups could be distributed between the municipal and industrial users.

Baseline Conditions

Withdrawal rates for 1990 indicate that municipal wells in the Central Brown County area yielded about 7.3 Mgal/d and municipal wells in the Fox Cities area yielded about 5.6 Mgal/d. These rates and the high concentration of wells in a small area have resulted in the formation of deep cones of depression in the sandstone aquifer centered over the Central Brown County and Fox Cities areas. Simulation results for 1990 pumping conditions indicate that the lowest water levels are about 377 ft above sea level in the Central Brown County area and about 515 ft above sea level in the Fox Cities area (fig. 2). These water levels are about 42 and 58 ft, respectively, above the bottom of the confining unit. In general, water levels in the entire model area are above the bottom of the confining unit for 1990 pumping conditions (fig. 5).

Predicted pumping rates, based on expected population growth for the year 2030, indicate a need for about 24.7 Mgal/d from Brown County municipal wells and about 9.1 Mgal/d from Fox Cities municipal wells. Pumping rates for the Fond du Lac wells were held constant at the 1990 rates (fig. 6, Appendix). If water use increases as expected, water levels will continue to decline, resulting in less water available to wells and increased pumping costs. The location and pumping rates of wells for projected 2030 withdrawals are shown in figure 6. Simulation results based on these withdrawal rates indicate that water levels in the vicinity of several wells (Allouez #5, Ashwaubenon #2 and #5, De Pere #1, #3, and #4, and Fort Howard) in the Central Brown County area will be close to the bottom of the sandstone aquifer and water levels in the Fox Cities area will be less than 400 ft above sea level. This represents as much as 649 ft of increased drawdown in Central Brown County and as much as 117 ft in the Fox

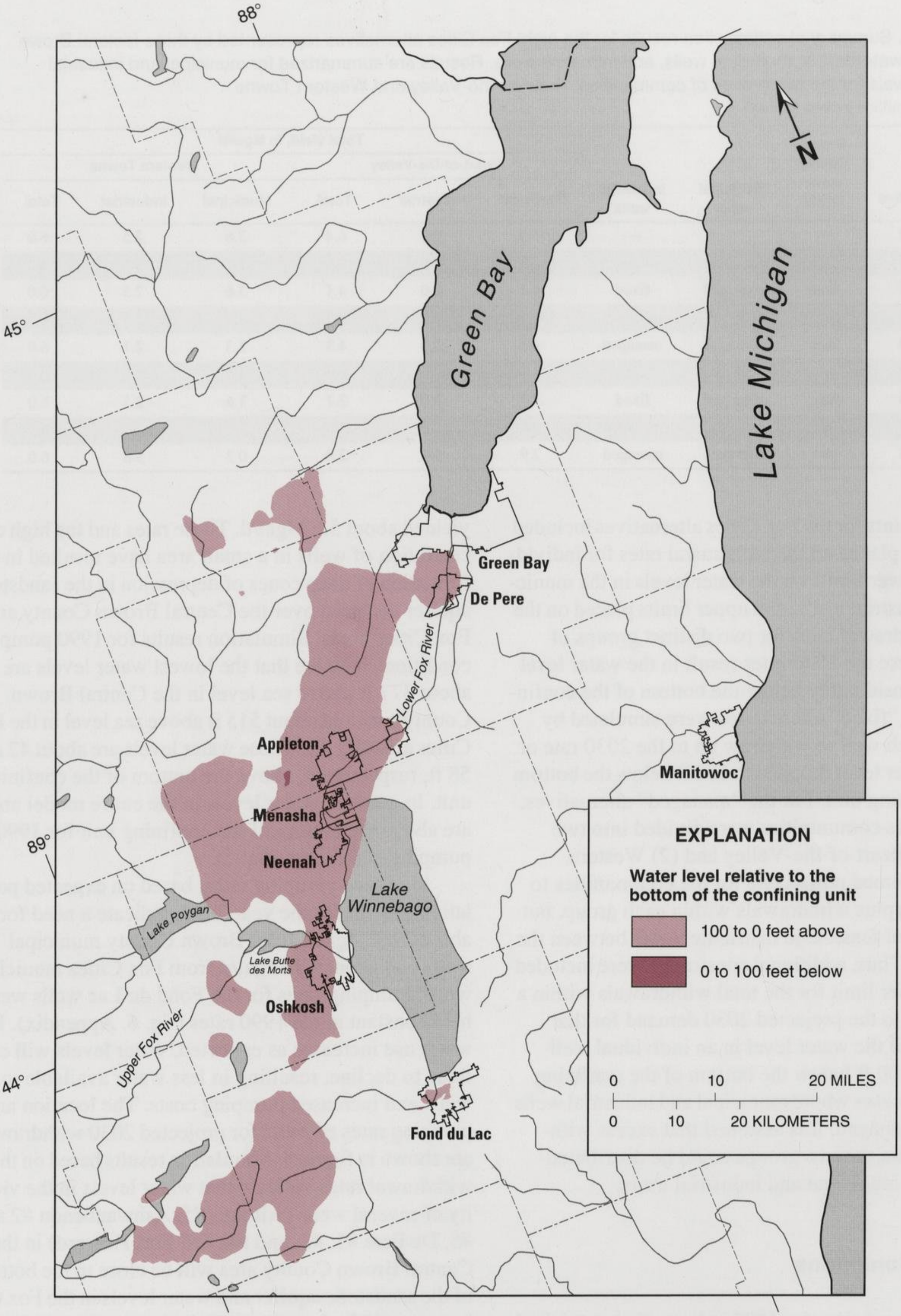


Figure 5. Water level relative to the bottom of the confining unit for 1990 withdrawal rates.

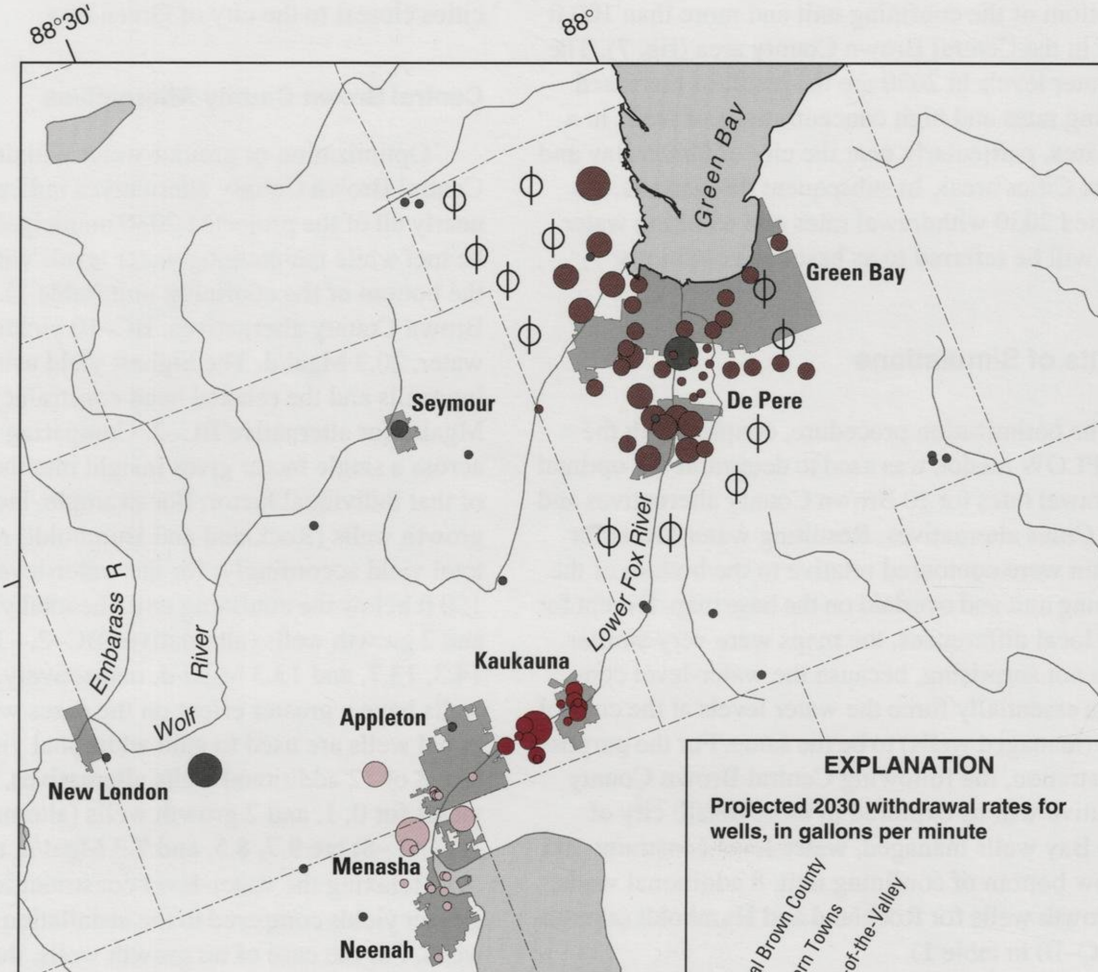


Figure 6. Projected 2030 withdrawal rates for high-capacity wells in the study area.

Cities area. Under 2030 withdrawal rates, water levels in much of the Lower Fox River Valley will be below the bottom of the confining unit and more than 100 ft below in the Central Brown County area (fig. 7). The low water levels in 2030 are the result of increased pumping rates and high concentrations of wells in a small area, particularly near the city of Green Bay and the Fox Cities areas. In subsequent discussions, the projected 2030 withdrawal rates and resulting water levels will be referred to as baseline conditions.

Results of Simulations

The optimization procedure, coupled with the MODFLOW model, was used to determine the optimal withdrawal rates for 10 Brown County alternatives and 8 Fox Cities alternatives. Resulting water levels for each run were contoured relative to the bottom of the confining unit and overlaid on the base map. Except for subtle local differences, the maps were very similar. This is not surprising, because the water-level constraints essentially force the water levels at the control points (managed wells) to be the same. For the purpose of illustration, the following Central Brown County alternative will be explored in more detail: city of Green Bay wells managed, water-level constraint 100 ft below bottom of confining unit, 8 additional wells, and growth wells for Rockland and Humboldt (alternative BC–10 in table 1).

Simulation results from alternative BC–10 indicate that water levels in the Green Bay area would be as much as 428 ft higher than for the baseline conditions (fig. 8). For the Fox Cities area, water levels based on the example alternative would drop as much as 15 ft compared to the baseline conditions. The reason for the increase in water levels in the Green Bay area and the slight decline in water levels in the Fox Cities area is the redistribution of pumping suggested by the optimization. Based on the results of alternative BC–10, the high concentration of pumping in the Green Bay area has been redistributed to locations away from the city of Green Bay (fig. 9). The redistribution spreads out the pumping and eliminates the large drawdowns in the Green Bay area. This optimization alternative turns off many of the wells proposed for use in 2030 in the Green Bay area (fig. 9) and increases withdrawals from many of the outlying and additional wells to much higher rates. The redistribution and use of the additional wells would also increase some Brown County withdrawals closer to the Fox Cities. This would result in slightly lower water levels in the Fox Cities area, particularly cities closest to the city of Green Bay.

Central Brown County Alternatives

Optimization of ground-water withdrawals for Central Brown County alternatives indicates that nearly all of the projected 2030 municipal demand can be met while maintaining water levels within 100 ft of the bottom of the confining unit (table 1). Of the 10 Brown County alternatives, BC–10 yields the most water, 20.3 Mgal/d. The highest yield using only existing wells and the relaxed head constraint is 14.3 Mgal/d for alternative BC–2. Comparing total yields across a single factor gives insight into the importance of that individual factor. For example, including the growth wells (Rockland and Humboldt) reduces the total yield accordingly; for the water-level constraint 100 ft below the confining unit, the total yields for 0, 1, and 2 growth wells (alternatives BC–2, –3, and –4) are 14.3, 13.7, and 13.3 Mgal/d, respectively. The growth wells have a greater effect on the cases where additional wells are used to gain additional yield; for the best 8 of 12 additional wells alternatives, the total yields for 0, 1, and 2 growth wells (alternatives BC–6, –7, and –8) are 9.7, 8.5, and 7.3 Mgal/d, respectively.

Relaxing the water-level constraint results in greater yields compared to the installation of additional wells. For the case of no growth wells, the relaxed water-level constraint (alternative BC–2) results in 14.3 Mgal/d compared to 9.7 Mgal/d for the installation of additional wells (alternative BC–6). This difference increases across the growth well alternatives; for 2 growth wells, the relaxed water-level constraint (alternative BC–4) results in 13.3 Mgal/d compared to 7.3 Mgal/d for the installation of additional wells (alternative BC–8). Finally, managing the wells in the city of Green Bay substantially increases the available yield. For the relaxed water-level constraint and 2 growth wells, managing the city of Green Bay wells (alternatives BC–4 and –5) increases total yield from 13.3 to 16.1 Mgal/d. The increased yield is even greater for the installation of additional wells, where managing the city of Green Bay wells (alternatives BC–8 and –9) increases total yield from 7.3 to 14.6 Mgal/d.

The results for alternative BC–10 turn off most of the wells in the cities of Green Bay and De Pere, and significantly increase the withdrawal rates at the wells remaining in service (fig. 9). This result is due to the

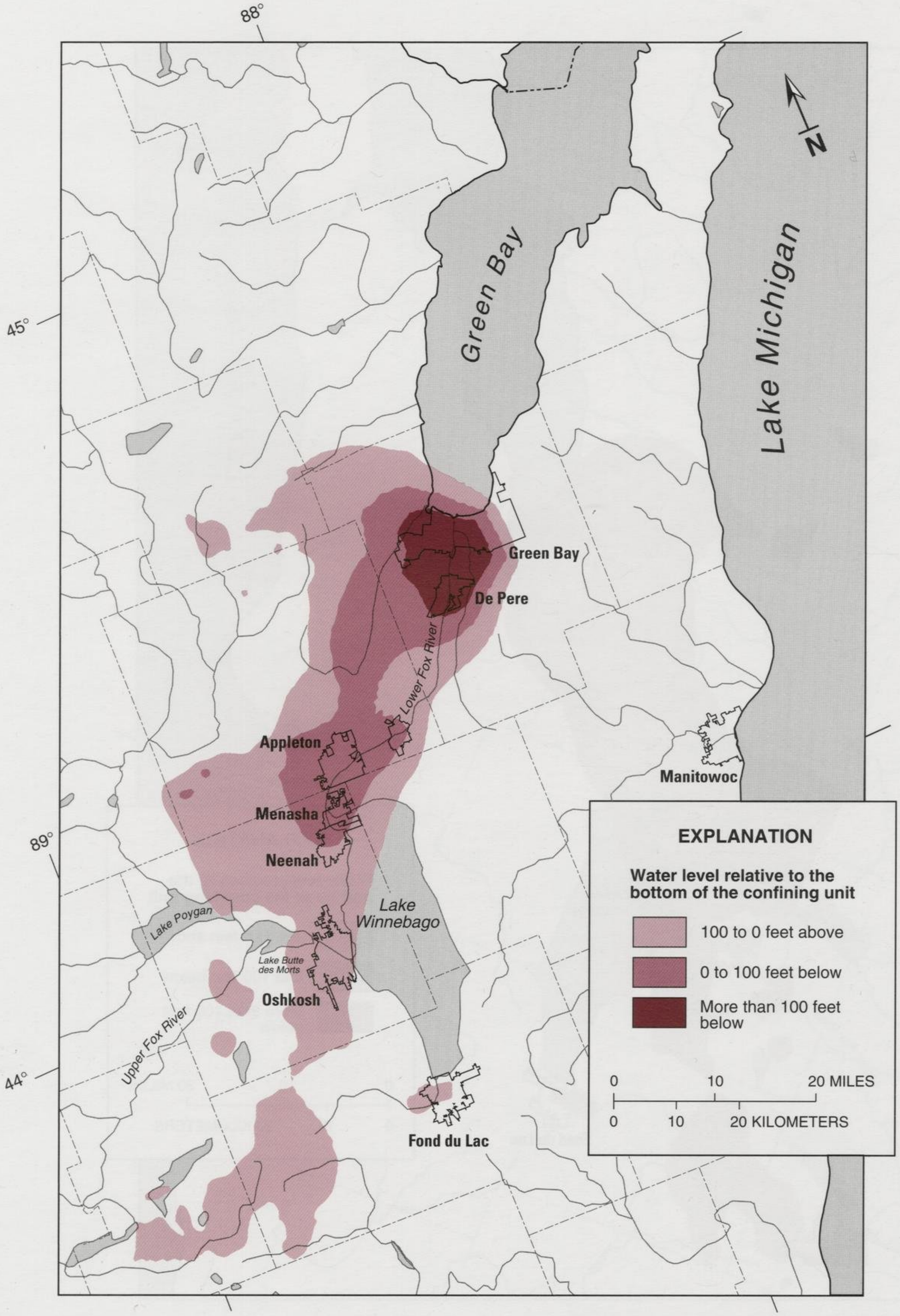


Figure 7. Water level relative to the bottom of the confining unit for projected 2030 withdrawal rates.

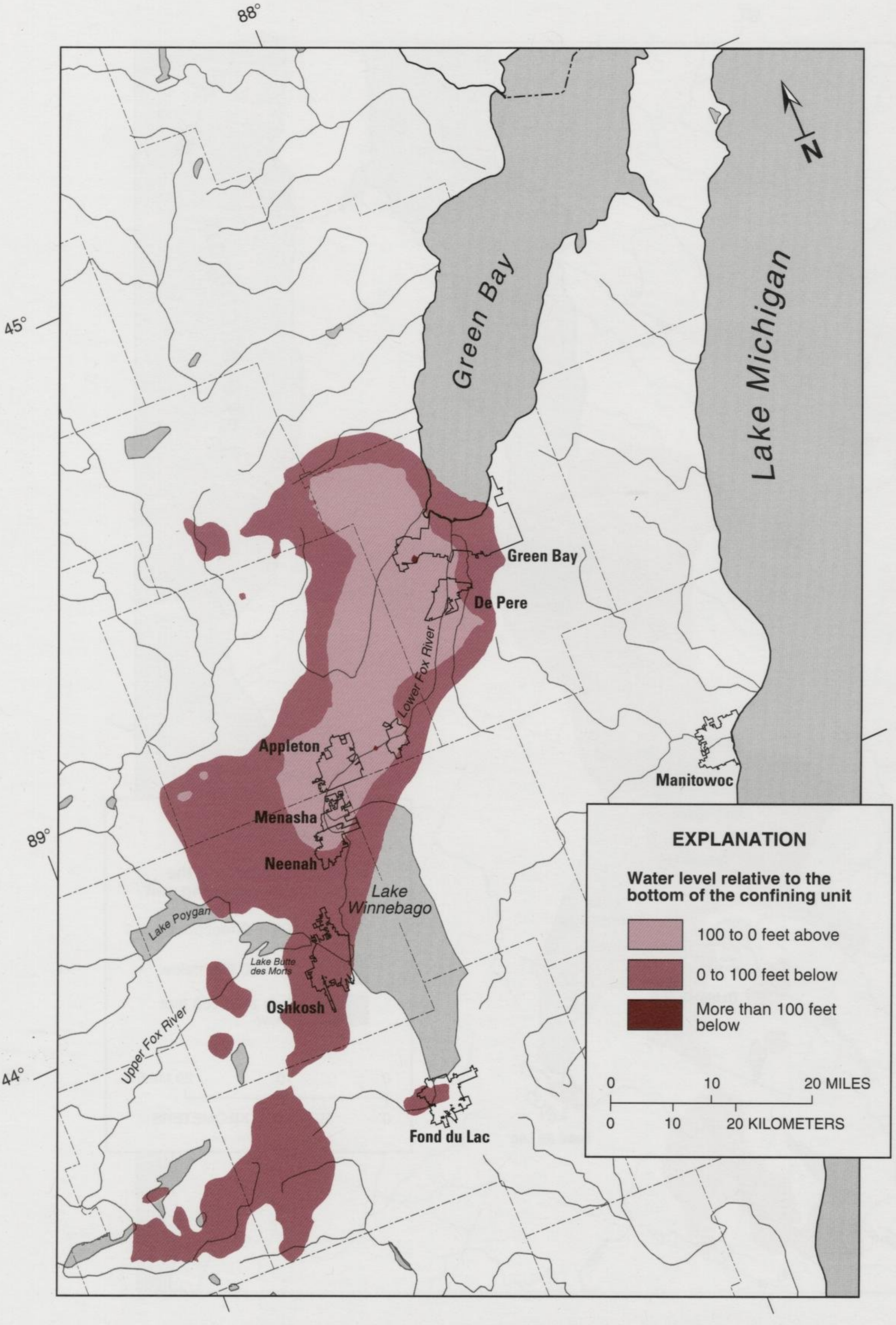


Figure 8. Water level relative to the bottom of the confining unit for optimized conditions: city of Green Bay wells managed, water level constraint 100 feet below bottom of confining unit, 8 additional wells, and growth wells for Rockland and Humboldt (alternative BC–10).

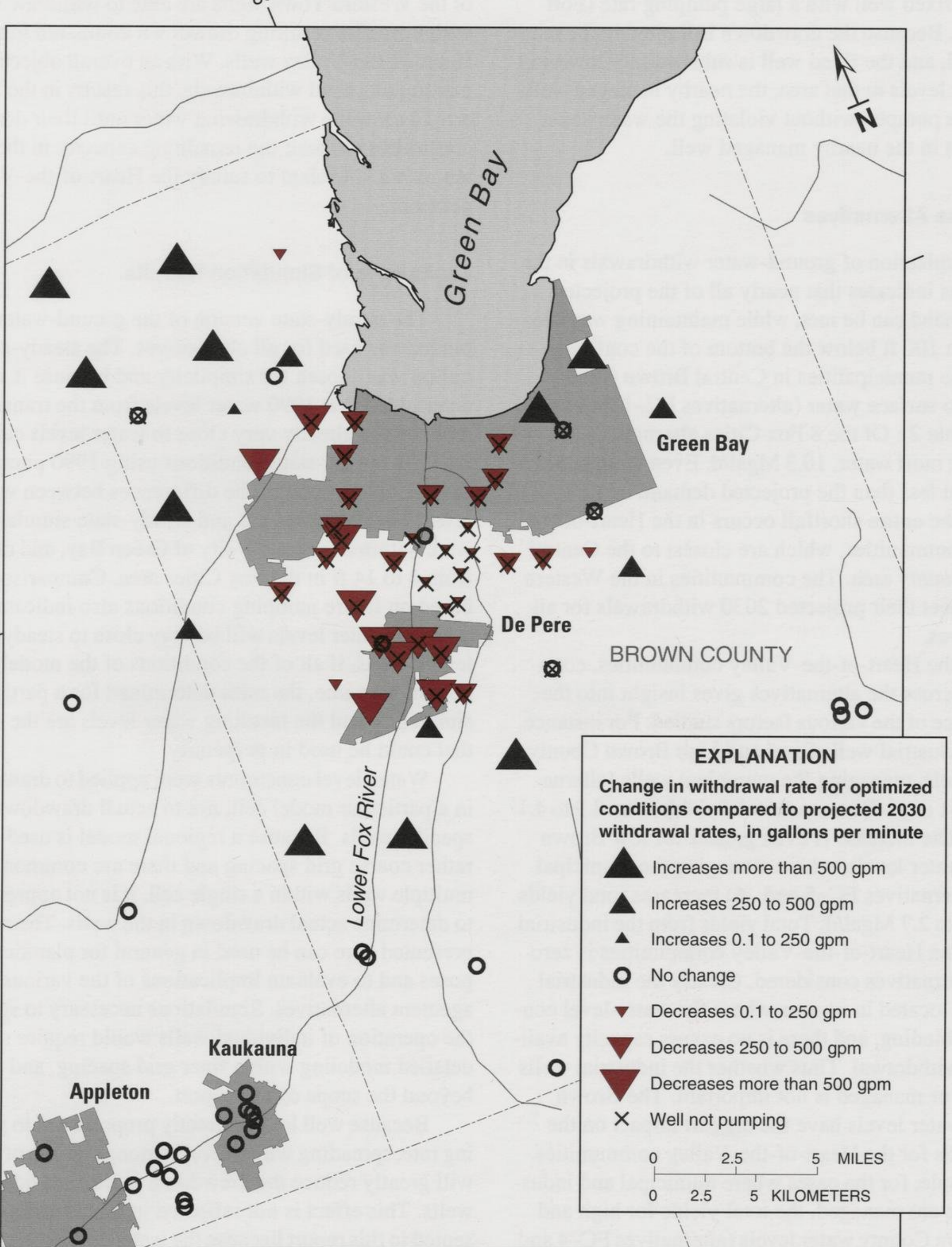


Figure 9. Change in withdrawal rates for optimized conditions: city of Green Bay wells managed, water-level constraint 100 feet below bottom of confining unit, 8 additional wells, and growth wells for Rockland and Humboldt (alternative BC–10) compared to projected 2030 withdrawal rates.

location of a managed well (Ashwaubenon #1) adjacent to a fixed well with a large pumping rate (Fort Howard). Because the drawdown is limited in the managed well, and the fixed well is substantially lowering the water levels in that area, the nearby managed wells cannot be pumped without violating the water-level constraint in the nearby managed well.

Fox Cities Alternatives

Optimization of ground-water withdrawals in the Fox Cities indicates that nearly all of the projected 2030 demand can be met, while maintaining water levels within 100 ft below the bottom of the confining unit, if the municipalities in Central Brown County convert to surface water (alternatives FC–1 through FC–4, table 2). Of the 8 Fox Cities alternatives, FC–4 yields the most water, 10.3 Mgal/d. Even though this is somewhat less than the projected demand of 12.4 Mgal/d, the entire shortfall occurs in the Heart-of-the-Valley communities, which are closest to the Central Brown County area. The communities in the Western Towns meet their projected 2030 withdrawals for all alternatives.

For the Heart-of-the-Valley communities, comparison across the alternatives gives insight into the importance of the various factors studied. For instance, for the industrial wells fixed and high Brown County water levels, managing the municipal wells (alternatives FC–1 and –2) increases total yields from 3.9 to 4.1 Mgal/d. The increase is even greater for low Brown County water levels, where managing the municipal wells (alternatives FC–5 and –6) increases total yields from 2.4 to 2.7 Mgal/d. Total yields from the industrial wells in the Heart-of-the-Valley communities is zero for all alternatives considered. Clearly the industrial wells are located in an area where the water-level constraint is binding, and there is no excess capacity available for withdrawal. Thus whether the industrial wells are fixed or managed is not important. The Brown County water levels have the biggest impact on the total yields for the Heart-of-the-Valley communities. For example, for the cases where municipal and industrial wells are managed, the total yields for high and low Brown County water levels (alternatives FC–4 and FC–8) are 4.3 and 2.9 Mgal/d, respectively.

Examining the simulation results across the Fox Cities alternatives reveals that the water levels in several Western Town wells control much of the capacity for withdrawals in the Heart-of-the-Valley communities. Because of differences in aquifer properties, some of the Western Town wells are able to withdraw water with a smaller resulting drawdown compared to the Heart-of-the-Valley wells. With an overall objective of maximizing total withdrawals, this results in the Western Town wells withdrawing water until their demand constraints are met; the remaining capacity in the system is not sufficient to satisfy the Heart-of-the-Valley demands.

Limitations of Simulation Results

The steady-state version of the ground-water model was used for all alternatives. The steady-state option was chosen for simplicity and because it was determined that 1990 water levels from the transient model were already very close to water levels calculated for steady-state conditions using 1990 pumping rates (Conlon, 1998). The differences between water levels for 1990 transient and steady-state simulations were within 2 ft near the city of Green Bay, and ranged from 6 to 14 ft in the Fox Cities area. Comparisons based on future pumping conditions also indicate that transient water levels will be very close to steady-state levels. Thus, if all of the conditions of the model remain the same, the rates determined for a particular simulation and the resulting water levels are the rates that could be used in perpetuity.

Water-level constraints were applied to drawdown in a particular model cell, not to actual drawdown in specific wells. Because a regional model is used with rather coarse grid spacing and there are commonly multiple wells within a single cell, it is not appropriate to determine actual drawdown in the wells. The results presented here can be used in general for planning purposes and to evaluate implications of the various management alternatives. Simulations necessary to specify the operation of individual wells would require more detailed modeling with a finer grid spacing, and are beyond the scope of this report.

Because well loss is directly proportional to pumping rate, spreading withdrawals among a group of wells will greatly reduce the drawdown in the individual wells. This effect is not reflected in the results presented in this report because the water-level constraints were applied to drawdown in the model cells.

For both the Brown County and Fox Cities simulations, the results were controlled in part by water-level constraints applied to either a single well or a few wells in a small area. For the Brown County simulations, a single managed well near a fixed well resulted in numerous wells being shut off. For the Fox Cities simulations, a few wells control the withdrawals in the Heart-of-the-Valley communities due to preferential withdrawals for Western Town wells. Because the water-level constraints were somewhat arbitrary, it would be possible to obtain increased yield by further relaxing the constraints at the individual wells.

For two of the fixed wells in the model (Fort Howard and Hortonville), the projected 2030 withdrawal rate exceeds the capacity of the existing well (see Appendix). For the simulations presented in this report, the projected 2030 rate was used. To meet these rates, the capacities of the existing wells would have to be increased accordingly.

CONCLUSIONS

The results presented in this report verify that optimization is a valuable tool for allocating ground-water resources. This statement is valid given the underlying assumptions of the analysis: (1) managed wells are not allowed to inject water into the aquifer; (2) the maximum withdrawal rate of a particular well is fixed based on the well's actual capacity; (3) the distribution systems of communities sharing water are interconnected; (4) the calibrated ground-water flow model is a realistic representation of the flow system; and (5) all solutions are steady state, thus represent sustainable withdrawals in perpetuity if all conditions of the model remain the same.

Three general conclusions are specific to the results of the individual management alternatives presented. First, ground water can supply nearly all of the projected 2030 demand for Central Brown County municipalities if all of the wells are managed (including the city of Green Bay), 8 new wells are installed, and the water levels are allowed to decline as much as 100 feet below the bottom of the confining unit. Second, if the municipalities in Central Brown County convert to surface water, there is a substantial increase in ground water available to the Fox Cities. Third, optimization alternative results indicate steady-state water levels due to projected 2030 withdrawal rates will rebound to levels within 100 ft of the bottom of the confining unit, resulting in increased well capacity.

Two conclusions pertain to the general use of optimization modeling for ground-water management. First, in some cases either a single managed well or a few closely spaced wells can control the results of an entire simulation. Second, comparisons with other factors remaining constant indicate that managing withdrawals will result in increased withdrawals and a more uniform water-level distribution.

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APPENDIX

Appendix. Elevation of bottom of confining unit, 1990 and projected 2030 withdrawal rates, and well capacities by model location and well name

Layer	Row	Column	Name	Elevation of bottom of confining unit, in feet	1990 withdrawal rate, in gal/min	Projected 2030 withdrawal rate, in gal/min	Well capacity, in gal/min
			Brown County municipal wells				
2	38	77	Allouez Well # 1	318	88.4	181	1000
2	40	79	Allouez Well # 2	308	101	181	1000
2	45	77	Allouez Well # 3	351	233	181	1000
2	44	78	Allouez Well # 4	337	17.5	181	1000
2	42	74	Allouez Well # 5	365	231	181	1000
2	38	80	Allouez Well # 6	290	354	181	1000
2	35	79	Allouez Well # 7	290	60.6	181	1000
2	36	73	Ashwaubenon Well # 1	344	151	141	650
2	39	70	Ashwaubenon Well # 2	387	241	368	790
2	39	62	Ashwaubenon Well # 3	445	404	474	1000
2	45	66	Ashwaubenon Well # 4	437	386	537	1250
2	37	64	Ashwaubenon Well # 5	424	234	728	1000
2	43	57	Ashwaubenon Well # 6	495	42.2	474	1000
2	37	91	Bellevue Well # 1	192	83.5	398	800
2	38	89	Bellevue Well # 2	231	150	398	850
2	39	84	Bellevue Well # 3	271	148	398	800
2	39	92	Bellevue Well # 4	160	0	398	800
2	49	74	De Pere Well # 1	389	306	541	600
2	51	71	De Pere Well # 2	416	311	541	410
2	49	69	De Pere Well # 3	426	206	541	600
2	50	76	De Pere Well # 4	375	280	541	800
2	55	76	De Pere Well # 5	384	198	541	600
2	57	68	De Pere Well 6 Shuering	443	111	541	600
2	20	88	GB # 2 Highway 54 & 57	205	3.47	424	1200
2	24	83	GB # 3 Eastman & Danz	245	3.47	424	1200
2	29	83	GB # 4 Deckner and Henry	256	3.47	424	1200
2	31	81	GB # 5 Cass and Goodell	271	3.47	424	1200
2	31	75	GB # 6 Mason and Adams	306	3.47	424	1200
2	31	65	GB # 7 7th and Military	395	3.47	424	1200
2	35	63	GB # 8 Highland	423	3.47	424	1120
2	26	64	GB # 9 Bond and Military	392	3.47	424	1220
2	22	65	GB #10 Military & Tower	382	3.47	424	1300
2	28	54	Hobart SD #1	458	0	610	1000
2	22	60	Howard Well # 1	418	4.48	583	450
2	21	50	Howard Well # 2	478	208	583	1040
2	17	57	Howard Well # 3	427	377	583	1750
2	63	70	Lawrence SD	427	0	308	500
2	55	79	Ledgeview SD # 2	362	0	347	500
2	48	45	Oneida area 1	596	0	167	1000
2	17	91	Scott S.D.	117	122	322	1000
2	12	56	Suamico SD	398	0	1000	1000
			Total withdrawal, in Mgal/d		7.32	24.7	

Appendix. Elevation of bottom of confining unit, 1990 and projected 2030 withdrawal rates, and well capacities by model location and well name—Continued

Layer	Row	Column	Name	Elevation of bottom of confining unit, in feet	1990 withdrawal rate, in gal/min	Projected 2030 withdrawal rate, in gal/min	Well capacity, in gal/min
			Heart-of-the-Valley municipal wells				
2	90	47	Darboy SD 1	517	19.5	77.9	330
2	89	46	Darboy SD 2	524	76.5	306	330
2	79	55	Kaukauna #4	451	319	370	300
2	80	55	Kaukauna #5	452	236	274	300
2	82	53	Kaukauna #6	468	89.7	104	185
2	76	54	Kaukauna #8	454	333	386	400
2	79	51	Kaukauna #9	478	57.1	66.2	185
2	85	43	Kimberly #1	674	179	179	400
2	86	45	Kimberly #2	674	381	381	400
2	87	40	Kimberly #3	669	315	315	400
2	83	46	Little Chute #1	513	576	1100	380
2	83	44	Little Chute #3	530	140	267	400
			Total withdrawal, in Mgal/d		3.92	5.51	
			Heart-of-the-Valley industrial wells				
2	78	54	Appleton Papers	457	309	309	1000
2	78	54	Combined Locks Paper Co	457	309	309	1000
2	78	55	Thilmany Paper & Pulp Co	450	2.24	2.24	1000
			Total withdrawal, in Mgal/d		0.893	0.893	
			Western Towns municipal wells				
2	93	15	Greenville	726	0	514	1000
2	108	21	Menasha SD4 3	607	209	344	720
2	109	22	Menasha SD4 4	650	5.38	8.88	720
2	102	32	Menasha SD4 5	626	391	645	500
2	106	21	Menasha SD4 6	514	580	957	1620
			Total withdrawal, in Mgal/d		1.71	3.56	
			Western Towns industrial wells				
2	113	28	American Can Co	656	243	243	1000
2	97	26	Badger Dairy Coop a	652	67.8	67.8	1000
2	98	26	Badger Dairy Coop b	629	84.8	84.8	1000
2	94	33	Foremost McKesson Inc	619	4.93	4.93	1000
2	116	29	Galloway Milk Co	660	177	177	1000
2	114	25	Kimberly-Clark a	660	178	178	1000
2	114	25	Kimberly-Clark b	540	108	108	1000
2	114	26	Kimberly-Clark c	528	238	238	1000
2	114	28	Kimberly-Clark d	565	174	174	1000
2	113	29	Marathon/Am Can/James River	651	113	113	1000
2	118	27	Menasha Corp	672	26	26	1000
2	98	27	Miller Electric Mfg Co	648	44.9	44.9	1000
2	97	26	Morning Glory Farms b	652	67.8	67.8	1000
2	97	26	Morning Glory Farms c	652	84.8	84.8	1000
2	98	26	Morning Glory Farms d	629	84.8	84.8	1000
2	97	26	Stokely Van Camp Co	652	3.14	3.14	1000
2	114	20	Stowe-Woodward Co	695	11.2	11.2	1000
			Total withdrawal, in Mgal/d		2.46	2.46	

Appendix. Elevation of bottom of confining unit, 1990 and projected 2030 withdrawal rates, and well capacities by model location and well name—Continued

Layer	Row	Column	Name	Elevation of bottom of confining unit, in feet	1990 withdrawal rate, in gal/min	Projected 2030 withdrawal rate, in gal/min	Well capacity, in gal/min
			Other wells in the model (fixed rates)				
2	83	29	Aid Assoc Lutherans #2 a	627	38.6	38.6	1000
2	84	29	Aid Assoc Lutherans #2 b	628	39.9	39.9	1000
2	124	19	Algoma	713	0	578	1000
2	112	9	Private #1	758	20.2	20.2	1000
2	57	31	Black Creek Village of a	693	178	178	370
2	65	9	Black Creek Village of b	525	10.8	10.8	370
2	125	8	City of Omro a	697	88	88	225
2	125	8	City of Omro b	697	69.6	69.6	225
2	66	2	Consolidated Foods Corp a	609	76.3	76.3	1000
2	91	4	Consolidated Foods Corp b	632	141	141	1000
2	57	96	Denmark Well # 1	172	94.2	78.8	600
2	56	96	Denmark Well # 2	174	47.6	78.8	480
2	56	96	Denmark Well # 3	174	76.3	78.8	600
2	131	75	Fond du Lac well 10	483	289	289	580
2	131	72	Fond du Lac well 11	498	531	531	1000
2	132	74	Fond du Lac well 12	491	705	705	1000
2	131	74	Fond du Lac well 13	488	247	247	500
2	131	78	Fond du Lac well 14	470	234	234	580
2	131	74	Fond du Lac well 15	488	295	295	1000
2	134	76	Fond du Lac well 16	480	176	176	500
2	135	77	Fond du Lac well 17	475	311	311	450
2	135	75	Fond du Lac well 18	483	236	236	350
2	134	71	Fond du Lac well 19	506	214	214	500
2	135	71	Fond du Lac well 20	503	298	298	700
2	132	67	Fond du Lac well 21	540	252	252	500
2	36	74	Fort Howard	335	486	1180	1000[a]
2	68	39	Freedom	574	0	228	1000
2	74	90	Holland	218	17.9	17.9	300
2	93	6	Hortonville Village of	729	72.2	1410	350[a]
2	20	93	Humboldt	45	0	347	1000
2	49	69	Morning Glory Farms a	426	51.2	51.2	1000
2	131	64	North Fond du Lac well 2&3	556	264	264	265
2	122	26	Parkview Hlth Cntr a	656	20.6	20.6	1000
2	122	26	Parkview Hlth Cntr b	656	20.2	20.2	1000
2	19	55	Procter and Gamble Paper	446	12.1	12.1	1000
2	13	17	Pulaski a	993	56.5	167	300
2	13	20	Pulaski b	675	215	167	1000
2	116	14	Ridgeway Country Club	388	25.1	25.1	1000
2	135	9	Ripon well 5 (WP&L)	743	198	198	600
2	135	8	Ripon well 8 (WP&L)	788	298	298	600
2	59	76	Rockland	715	0	347	1000
2	52	17	Seymour City of	544	458	458	550
2	125	25	Private #2	695	8.52	8.52	1000
2	123	8	Village of Winneconne	700	114	182	350
2	122	26	Winnebago Mental Health	656	125	125	1000
2	69	82	Wrightstown S.D. #3	275	27.8	40.6	300
2	69	68	Wrightstown Well # 1	353	19.3	45.3	250
2	69	68	Wrightstown Well # 2	353	15.3	45.3	300
			Total withdrawal, in Mgal/d		10.3	15.7	

[a]Projected 2030 rate exceeds current capacity; to meet this rate, existing equipment will have to be modified.

Optimization of Ground-Water Withdrawal in the Lower Fox River Communities, Wisconsin

WRIR 97-4218