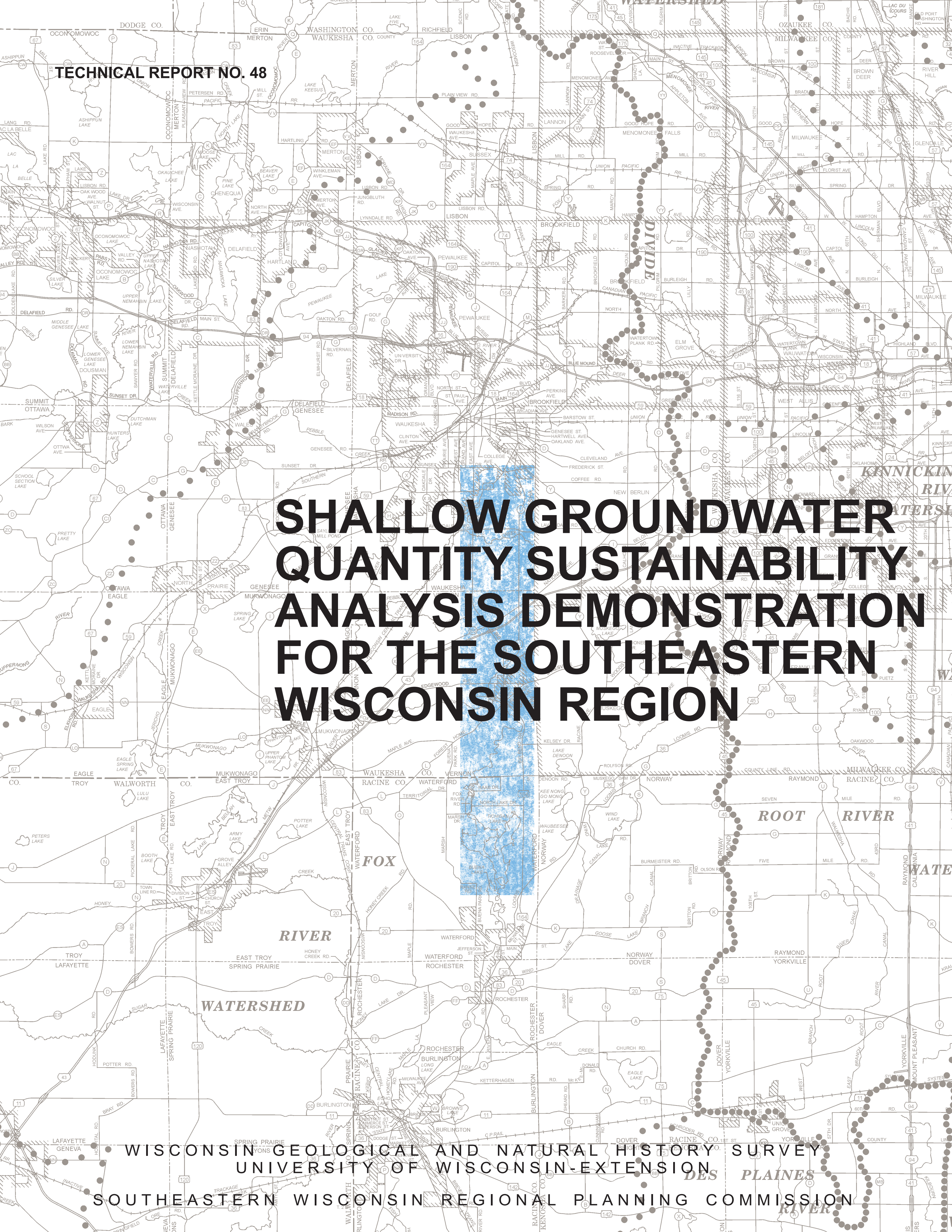

TECHNICAL REPORT NO. 48

SHALLOW GROUNDWATER QUANTITY SUSTAINABILITY ANALYSIS DEMONSTRATION FOR THE SOUTHEASTERN WISCONSIN REGION

WISCONSIN GEOLOGICAL AND NATURAL HISTORY SURVEY
UNIVERSITY OF WISCONSIN-EXTENSION

SOUTHEASTERN WISCONSIN REGIONAL PLANNING COMMISSION

TECHNICAL REPORT
NUMBER 48

SHALLOW GROUNDWATER QUANTITY SUSTAINABILITY ANALYSIS DEMONSTRATION FOR THE SOUTHEASTERN WISCONSIN REGION

Prepared by the

Wisconsin Geological and Natural History Survey
for the
Southeastern Wisconsin Regional Planning Commission

The authors of this report are
Kenneth R. Bradbury, Wisconsin Geological
and Natural History Survey
University of Wisconsin-Extension, and
Todd W. Rayne of Hamilton College, Clinton, NY

November 2009

$10.00

(This page intentionally left blank)

TABLE OF CONTENTS

(This page intentionally left blank)

INTRODUCTION

This report was prepared as part of a regional water supply planning effort undertaken by the Southeastern Wisconsin Regional Planning Commission (SEWRPC). The planning effort includes a comprehensive evaluation of existing and future water supply alternatives in the seven-county southeastern Wisconsin region. During the past 10 years, SEWRPC has funded and/or implemented a series of studies of groundwater resources in the region. In 2002 SEWRPC published Technical Report No. 37, *Groundwater Resources of Southeastern Wisconsin*, a compendium of groundwater information prepared cooperatively by SEWRPC and the Wisconsin Geological and Natural History Survey (WGNHS). That report contained baseline data that was utilized in the development of a sophisticated groundwater flow model for the Region. The flow model was completed in 2004 under a cooperative effort by a project team of U.S. Geological Survey (USGS), WGNHS, University of Wisconsin-Milwaukee scientists, and SEWRPC planners and engineers. The model development was funded, in part, by the water utilities in the Region which utilize groundwater as a source of supply. The groundwater model is documented in SEWRPC Technical Report No. 41, *A Regional Aquifer Simulation Model for Southeastern Wisconsin*, which includes two project reports (Feinstein and others, 2005a, Feinstein and others, 2005b) describing the model and its applications.

Current analyses and simulations of the regional hydrogeology of southeastern Wisconsin and simulations using the regional groundwater flow model indicate that continued extraction of groundwater from the deep sandstone aquifer may not be viable as a long-term water supply in the Region. Consequences of continued pumping from the deep aquifer include excessive drawdown, declining water quality (radium, total dissolved solids), reduced well yield, and increased production costs. As an alternative, many communities are turning to the shallow aquifers (either Pleistocene sand and gravel or Silurian dolomite) for water supply. Wells developed in the shallow aquifers often provide sufficient yield, but can impact nearby surface-water resources and are generally more vulnerable to contamination than deeper bedrock wells. Communities tapping the shallow aquifer also face choices between using individual low-capacity household wells or developing a community water system with homeowners connecting to shallow but higher-capacity community wells. In some cases, these communities have an overall negative groundwater balance because sewage treatment plant effluent leaves the community via surface water.

Significant questions relating to development of the shallow aquifer (sand-and-gravel or dolomite) include the following:

- what are the environmental impacts of shallow aquifer use (drawdown, baseflow reduction, effects on lake levels), and how can they be assessed?

- how do these effects differ in different parts of the SEWRPC region? Can distinct subareas be defined that have different density or water-use constraints?

- what is the relationship between development density (wells, homes, or water use per acre) and groundwater impacts such as baseflow reduction and shallow aquifer drawdown?

This report addresses these issues using a series of focused groundwater flow models developed for selected demonstration areas within the SEWRPC region. These flow models were developed using the existing regional model as a starting point, but incorporate local detail of geologic and hydrologic features that are not included in the regional model. These models simulate only the shallow (sand-and-gravel and/or Silurian dolomite) aquifer and demonstrate the impacts of groundwater use under various scenarios.

The report is intended to evaluate the potential impacts of the use of individual private wells to support ex-urban development. The use of community wells to serve such developments was not specifically addressed.

METHODOLOGY

Selection of Demonstration Areas

Six demonstration areas were selected based on township boundaries which were chosen to represent differing shallow hydrogeologic conditions found in the SEWRPC region. Figure 1 shows the locations of the demonstration areas, and Table 1 lists important hydrogeologic characteristics of each area. The main differences between the areas are aquifer type, ranging from primarily sand and gravel to primarily Silurian dolomite, hydraulic conductivity, ranging from 3-31 ft/day, and recharge rate, ranging from less than 1 in/yr to over 8 in/yr. In addition, La Grange is located west of the subcrop of the Maquoketa Shale, where the upper aquifer and deeper sandstone aquifers are better connected than other sites where the Maquoketa serves as a lower boundary to the upper aquifer system.

Table 1. Hydrogeologic characteristics of demonstration areas

Demonstration Area	County	Primary Domestic Aquifer	Approximate Depth to Groundwater (feet)	Simulated Hydraulic Conductivity (feet/day)	Simulated Recharge (inches/year)	Average Aquifer Thickness, (feet)
Cedarburg	Ozaukee	Dolomite	5-50	3	3-6	300
Jackson	Washington	Dolomite/sand and gravel	0-100	3	3-6	300
LaGrange	Walworth	Sand and gravel/dolomite	3-125	31	5.1-8.1	200
Lisbon	Waukesha	Dolomite	20-140	12.5	4-7	250
Raymond	Racine	Dolomite/sand and gravel	15-110	3	0.5	250
Wheatland	Kenosha	Sand and gravel/dolomite	2-70	14.2	7.9	130

Figure 1. SEWRPC region, showing demonstration areas.

Development Scenarios and Assumptions

Scenarios

The development scenarios simulated were established based upon consultation with the SEWRPC staff and the Advisory Committee guiding the regional water supply planning program. The scenarios are intended to represent a potential range of future conditions under maximum long-term residential development expansion. It is important to understand that these scenarios are for demonstration purposes only, and do not represent specific planned or expected development patterns in the demonstration areas. The two variables considered were lot size and wastewater disposal method. Larger lot sizes lead to less dense development and overall lower water use requirements. Wastewater options include either public sewers, which, typically, but not necessarily, remove wastewater from the area, or onsite disposal systems, which return a significant treated volume of water to near the points of use. The use of holding tanks for sewage storage and removal has a similar effect on groundwater recharge as sewerage systems.

In analyzing the impacts of the demonstration areas, it was assumed that development of the land involved in each demonstration area would utilize uniform lot sizes to achieve the represented density. For example, allowing for the allocation of 20 percent of the site area to streets, a 160-acre area developed at a density of one gross acre per dwelling unit, would have 160 0.8-acre lots and 160 relatively evenly spaced domestic wells. Similarly, allowing for the allocation of 10 percent of the site area to streets, a 160-acre area developed at a density of five gross acres per dwelling unit, would have 32 4.5-acre lots and 32 relatively evenly spaced domestic wells. It is recognized that there are an infinite combination of lot sizes, street areas, and open space areas which could be used to obtain a specified overall density on a development site. The use of cluster subdivision design, with relatively small lots, such as one-half- or one-quarter-acre lots, would permit the attainment of the desired overall density while preserving large areas of open space and have a lesser impact on stormwater runoff and, therefore, higher recharge amounts than the same lot sizes with no preserved open spaces. The impacts of combinations of lot sizes and open space preservation scenarios on groundwater quantity can be interpolated by comparing the average development site area per residential lot to the uniform lot spacing scenarios considered in this report. In this regard, if lots are clustered, there may be wells developed which serve multiple housing units.

The development scenarios considered were as follows:

- Medium-density and low-density urban, sub-urban, and rural residential development with lot sizes of one-half, one, three, and five gross acres for each single family unit. The actual net acreage devoted to the residential lot itself will typically vary from about 80 to 85 percent of the gross acreage.

- For each lot size, two wastewater disposal options: no return of wastewater (public sanitary sewer systems and holding tanks) and 90 percent return of wastewater (onsite sewage disposal systems).

Assumptions

Assumptions used during scenario development and subsequent modeling were as follows:

- No development in primary or secondary environmental corridors, parkland, or isolated natural resource areas;

- A per-capita water use of 65 gallons per person per day, which is typical for the SEWRPC region, and an average population density of 2.8 persons per home;[1]

---

[1]*The per capita water use of 65 gallons per capita per day was selected as a representative value for areas developed with private wells based upon water use data developed under the planning program as reported in SEWRPC Technical Report No. 43,* State-of-the-Art of Water Supply Practices*, assuming a 5 percent reduction over current usage over time for the effect of water conservation measures. The per capita water use value will vary depending upon a number of factors, including outdoor water use practices, and the number of fixture units per housing unit. During the year 2005, municipal utility residential water use within the Region ranged from 51 to 96 gallons per capita.*

- No consideration of impacts on groundwater quality;
- Uniform lot sizes for each scenario;
- All analyses were for steady-state conditions. No groundwater contribution from storage was assumed, which was considered to have reached a fixed condition; and
- Recharge rates were assumed to be constant, and unchanged by development.

Assessment Criteria

Groundwater use can affect local hydrologic systems in two ways. First, pumping can lower groundwater levels by causing drawdown near the pumping centers. Second, pumping can reduce the amount of groundwater available to discharge to local surface water resources – springs, streams, wetlands, and lakes. Accordingly, for each scenario the resulting drawdown and streamflow reduction were evaluated.

A third assessment criterion is the ratio of groundwater use to local groundwater recharge within each demonstration area. For long-term sustainability of water resources, groundwater use cannot exceed the amount of replenishment. This is a somewhat simplified benchmark because most townships in the SEWRPC region receive or lose some groundwater as underflow across the township boundaries, and groundwater is also needed to sustain baseflow in streams and maintain water levels in lakes and wetlands. However, for planning purposes, it important to understand the relationship between local water use and local recharge, and the amount of local recharge might represent a practical upper limit for local shallow groundwater withdrawals.

Simulation Methodology

Modeling Code

The code GFLOW (Haitjema, 1995), a two-dimensional analytic element code, was used to simulate groundwater flow in the demonstration areas. A separate model was built for each demonstration area. Analytic element models simulate groundwater flow using a series of analytical equations, called elements, to represent sources and sinks of water. Typical elements include line sinks, which represent surface water features, and point sinks, which represent wells. The model code superimposes analytical solutions for each of these elements and solves the equations over a continuous flow field. The analytical nature of the model means that the solutions are mathematically exact regardless of the problem scale, allowing examination of results at both very small and very large scales. This type of model has several advantages that make it useful for application in the demonstration areas. It explicitly simulates the interaction of groundwater and surface water, which allowed testing of the effect of different lot sizes on the flow rate in nearby streams. GFLOW is ideal for large area models in which the effects of three-dimensional flow are less important because the vertical dimension of the model area is dwarfed by the horizontal scale. The model uses elevations of surface water bodies both close to the area of interest (the near field) and far away (the far field) to constrain the head in the aquifer.

Hydrogeologic Parameters
Model parameters of hydraulic conductivity, recharge rates, and aquifer thickness were obtained from several sources. Initial values of hydraulic conductivity and aquifer thickness of the shallow aquifer are from the SEWRPC regional model (Feinstein and others, 2005 a,b). Initial recharge values are from a recently-developed recharge map for the SEWRPC region (Hart and others, 2007). Those values were developed using a soil water mass balance model (Dripps and Bradbury, 2007) to estimate the spatial distribution of recharge in each demonstration area. The results were averaged and smoothed in ArcGIS to create recharge zones used in each model.

Calibration Targets
Model calibration is the process of comparing model output (simulated hydraulic heads and base flows) to measured water levels and streamflows, and then adjusting model parameters, within known ranges, until simulated results reproduce field measurements acceptably. Calibration targets for the demonstration models included water levels taken from well construction reports and stream baseflows taken from published U.S. Geological Survey (USGS) streamflow data (http://waterdata.usgs.gov/wi/nwis/) and from limited streamflow measurements conducted for this project (Appendix A). The calibration process was aided by the use of PEST (Doherty, 2004) an automated parameter-fitting code that connects directly with the GFLOW modeling code.

Quantification of Recharge Volumes
Comparing projected groundwater use to recharge in each demonstration area required a volumetric measure of recharge (cubic feet per second, for example) rather than the more common depth measure (inches per year). Recharge rates vary areally over each demonstration area, and so determining an overall recharge volume requires an integration of the variable recharge rates over each demonstration area. The GFLOW model uses overlapping and additive recharge zones, and does not directly quantify recharge volumes. However, GFLOW includes a routine for extracting finite-difference grids from the GFLOW output and populating the grid with appropriate parameters, including recharge rates. This grid-extract procedure was carried out for each demonstration model and then imported the extracted grid into MODFLOW, the USGS modular ground-water flow model (McDonald and Harbaugh, 1988). Using MODFLOW to re-solve the demonstration models produced a mass-balance result that quantified recharge volume for each area.

Implementation of Pumping Wells
The key element in simulating the demonstration areas was the inclusion of pumping wells at realistic scales and densities. Individual single-family private wells in Wisconsin have generally very low pumping rates compared to municipal or industrial wells. Based on an average per-capita water use of 65 gallons per day (GPD), and 2.88 people served per well, the pumping rate for each well is 25 ft^3/day (182 GPD).

The development scenarios were analyzed in two different ways. For two of the demonstration areas (Lisbon and Jackson-Cedarburg) specific hypothetical developments were simulated using assigned well densities and lot sizes. The purpose of these simulations was to help understand the impacts of development in realistic subdivision scenarios. Locations of the hypothetical developments were chosen to be in potential development areas outside of current developments and away from environmental restrictions. The lots were grouped in a simulated development with an area of 160 acres (1/4 section). For ease of addition to the model, the subdivisions were square and arranged in a regular grid. The total number of wells ranged from 32 in the five-acre lot size development at Lisbon to 320 in the one-half-acre lot size case at Cedarburg. Figure 2 shows an example of a dense development scenario in the Lisbon demonstration area.

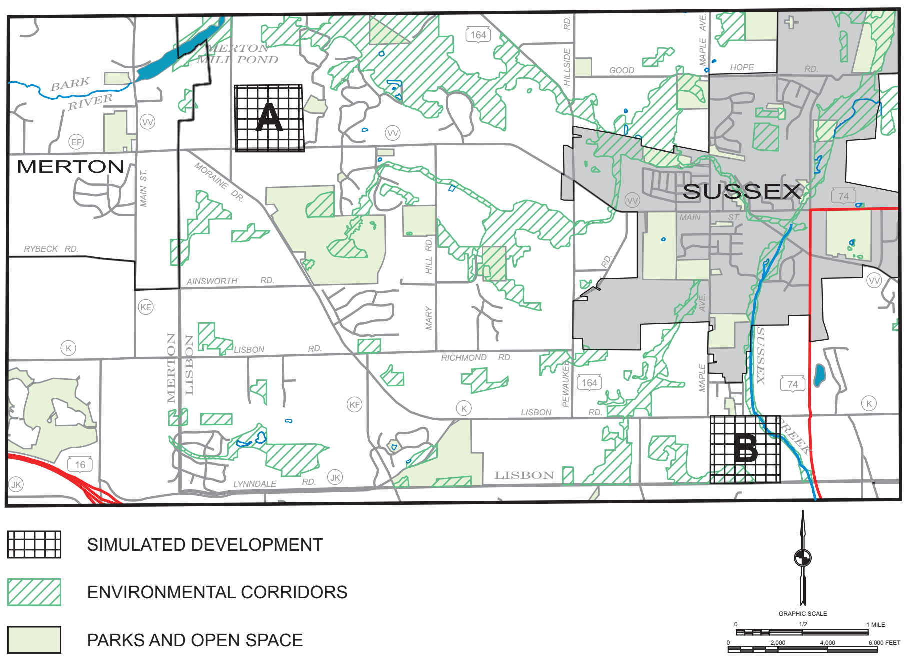

Figure 2. Locations of two simulated subdivisions (A and B) in the Lisbon demonstration area. Each development covers 160 acres and includes up to 320 domestic wells.

The choice of location of the development highly influences the resulting hydrologic impacts. For example, a development located adjacent to a lake might reduce groundwater discharge to the lake but have negligible impact on local groundwater levels. In contrast, a development located on top of a hill might create significant drawdown beneath it but have negligible impact on lakes several miles away. These locational variables make comparisons between demonstration areas difficult.

In order to facilitate comparisons between geographically-different demonstration areas, maximum development in each area was also simulated by locating hypothetical composite wells on quarter-quarter sections (40 acres) throughout each demonstration area and allocating pumping to each well based on the development density to be simulated. Each composite well simulates the impact of many individual wells. For example, under a one-acre lot scenario, each quarter section would contain 40 wells each pumping at 25 ft^3/day, and the model simulated each section using a single well pumping at 1,000 ft^3/day (25 ft^3/day/well x 40 wells). The wells were placed approximately at quarter-quarter section centers, and any wells that fell in environmentally restricted areas were removed. The total numbers of wells simulated in this fashion ranged from 265 for Cedarburg to 485 for Raymond. Figure 3 shows the arrangement of composite quarter-section wells for the same portion of the Lisbon demonstration area depicted in Figure 2. Notice that no wells are simulated inside the Village of Sussex limits or in environmentally sensitive open space areas.

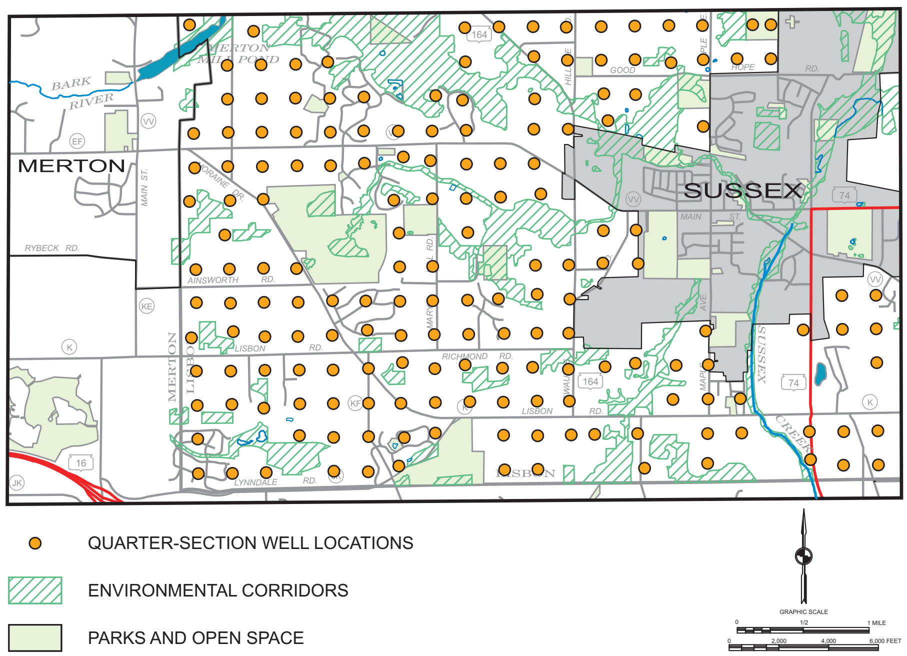

Figure 3. Lisbon demonstration area, showing arrangement of composite quarter-section wells used for areawide development simulations.

A comparison of results for the Lisbon area shows that the two simulation methods give almost identical results. Figure 4 and 5 show drawdowns beneath two hypothetical developments having a density of 2 wells per acre (half-acre lots) and no return of wastewater. In Figure 4, each well is simulated discretely, and the model contains 641 wells. In Figure 5, the same two developments are simulated using seven composite quarter-section wells (the eighth quarter-section well fell in an environmental corridor area and was removed). Thus, in Figure 5, the two developments are simulated as having 560 wells (seven composite wells serving 40 acres with two wells per acre). Simulated drawdowns for the two simulations are almost identical.

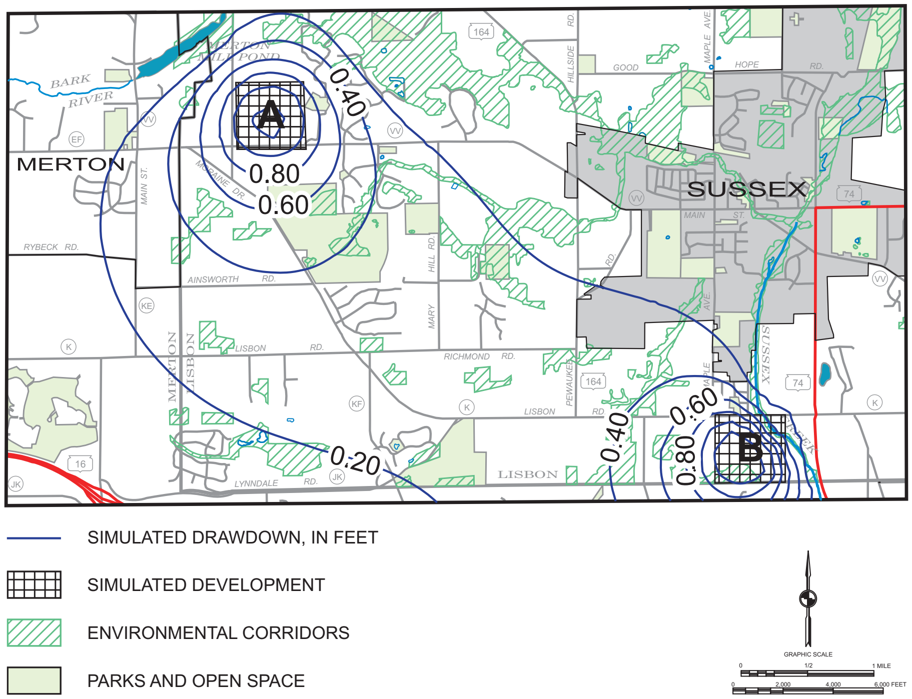

Figure 4. Drawdown (ft) in the Lisbon demonstration area from two hypothetical subdivisions each containing one well per half-acre lot. Total number of model wells is 641; individual wells not shown.

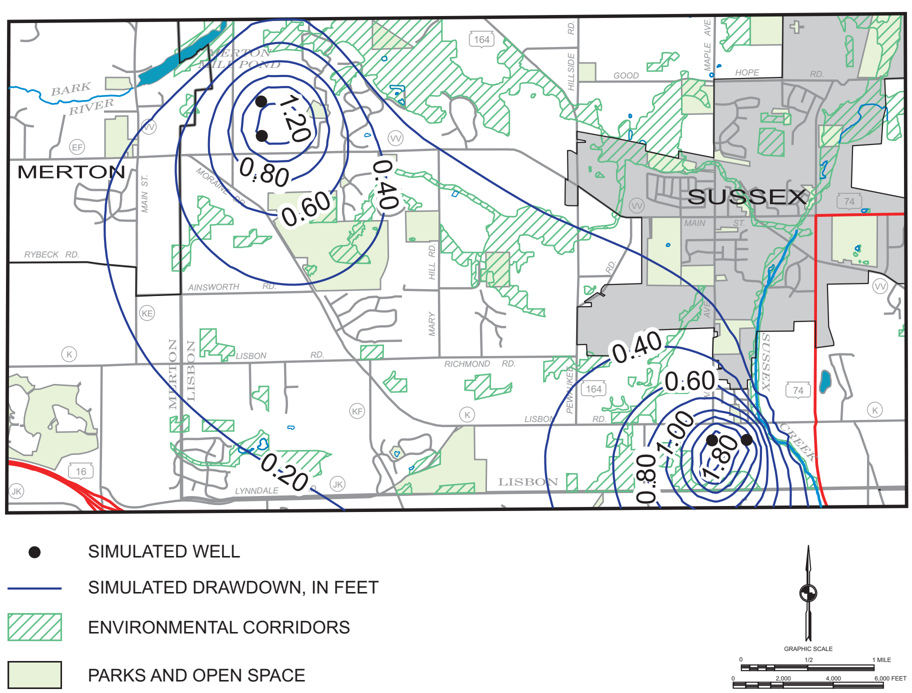

Figure 5. Drawdown (ft) in the Lisbon demonstration area from two hypothetical subdivisions simulated by composite quarter-section wells. Total number of model wells is seven. Each composite well represents 40, with two individual wells per acre.

Assessment of Results

For each demonstration scenario impacts were estimated as drawdown in and around the development area and as reduction of baseflow to nearby streams. For specific subdivision simulations drawdown below the center of the development and baseflow in nearby surface water features were estimated. For the simulations of entire townships using quarter-section composite wells, drawdown was estimated at three points: the town center, a point one-half mile diagonally from the southwest corner of the township, and a third point one-half mile diagonally from the northeast corner of the township.

RESULTS

Township-wide development analyses were conducted for all six demonstration areas. In addition, detailed smaller development analyses were conducted for three of the areas, Lisbon, Cedarburg, and Jackson in order to assess the differences in groundwater-surface water impacts and conclusions when considering limited area developments compared to township-wide development.

Detailed Development Simulations

Detailed development analyses were conducted for two hypothetical subdivisions in the Lisbon demonstration area, and for one hypothetical subdivision each in the Cedarburg and Jackson demonstration areas.

Lisbon Demonstration Area

In the Lisbon area two hypothetical subdivisions were postulated with four lot sizes: 0.5, 1, 3, and 5 acres. For subdivisions of each lot size, two cases were analyzed: one in which there was no wastewater return (i.e. the development was assumed to be connected to a municipal sewage treatment plant); and one in which 90 percent of the pumped water was returned as wastewater. The two hypothetical subdivisions (area A and area B) were located in different areas (Figure 2). The first development (A) was located west of the Village of Sussex, about one-quarter mile from Merton Pond and the Bark River. The second development (B) was located south of the Village of Sussex straddling Sussex Creek, a tributary of the Fox River. Each development scenario was evaluated by comparing the modeled stream discharges in Merton Pond (Bark River) and the Fox River tributary to discharges in the base model with no developments. Drawdown in the shallow aquifer in the area of the developments was also examined.

Table 2. Simulation results for specific developments in the Lisbon demonstration area

simulation	Maximum drawdown in development area, feet		Fox River tributary at Hwy K		Bark River at Merton Pond	
	Area A	Area B	simulated baseflow at test point, CFS	percent change in baseflow	simulated baseflow at test point, CFS	percent change in baseflow
Base Run, no new wells			1.41		0.52	
0.5 acre, no return	1.3	1.4	1.39	-1.4	0.49	-5.1
1 acre, no return	0.7	0.7	1.40	-0.7	0.51	-2.5
3 acres, no return	0.2	0.2	1.41	-0.3	0.52	0
5 acres, no return	0.2	0.2	1.41	0	0.52	0
0.5 acre, return	0	0	1.41	0	0.52	0
1 acre, return	0	0	1.41	0	0.52	0
3 acres, return	0	0	1.41	0	0.52	0
5 acres, return	0	0	1.41	0	0.52	0

Each of the simulated developments produced drawdown of the water table in the vicinity of the developments (Table 2). The largest change was produced by the smallest lot size (0.5 acre). This scenario had the greatest number of wells and hence the largest cumulative pumping rate and assumed no wastewater return. Maximum drawdown of the water table was slightly less than two feet in the 0.5-acre lot size development case. Figures 4 and 5 show simulated drawdowns for the 0.5-acre lot size without waste water return. At every lot size, adding back 90 percent of the pumped water in the form of wastewater return produced virtually no change in the water table elevation from the base (no development) case.

The simulated developments also resulted in decreased baseflow to both the Bark River and Fox River tributaries. The decrease in baseflow in most cases was small. For example, using a lot size of 0.5 acres and a 160-acre development produced a 1.4 percent decrease in modeled baseflow in Sussex Creek. As the lot size grew (*i.e.* fewer wells in the subdivision), changes in the modeled baseflow decreased. At the Bark River test point, no change in baseflow occurred in the three-acre lot and five-acre lot scenarios. Similarly, at the Sussex Creek test point, no change in baseflow occurred in the five-acre lot scenario. At every lot size, adding back 90 percent of the pumped water in the form of waste water return produced virtually no change in baseflow from the base (no development) case.

Increasing the size of the simulated development increased the reduction in baseflow. As noted above, using a lot size of 0.5 acres and a 160-acre development produced a 1.4 percent in modeled baseflow in Sussex Creek. A three-square-mile development in the same area produced a 6 percent decrease in modeled baseflow.

Cedarburg-Jackson Demonstration Area

The townships of Cedarburg and Jackson are adjacent, and a single groundwater model was constructed that included both areas (Figure 6). Two large hypothetical subdivisions were simulated separately. The first hypothetical subdivision was located northwest of the City of Cedarburg, covering an area of about 2.5 square miles; the second such subdivision was located south of the Village of Jackson and covers a similar sized area. Each simulated subdivision was located adjacent to Cedar Creek. The simulated developments contain no wells on land designated as environmental corridor, isolated natural area, or parkland. Simulated water levels (drawdown) at single points were simulated within each development and baseflow impacts were simulated at two points: Cedar Creek at STH 60 (Cedarburg development) and Cedar Creek at CTH Y (Jackson development).

Each of the simulated developments produced slightly decreased modeled baseflow in Cedar Creek when there was no wastewater return, and minimal change in the discharge of Cedar Creek when 90 percent onsite sewage treatment and disposal system return was assumed. The largest change was produced by the smallest (0.5-acre) lot size. This scenario had the greatest number of wells and hence the largest cumulative pumping rate. As the lot size grew larger (i.e. fewer wells in the subdivision), changes in the modeled baseflow decreased, with the 5-acre lots size scenario producing the smallest decrease in baseflow. In every case, adding back 90 percent of the pumped water in the form of wastewater return produced virtually no change from the no-development case. The decrease in baseflow in most of the cases was small. For example, using a lot size of 0.5 acres and a 2.25 square miles development in the Cedarburg area produced a 3.3 percent decrease in modeled baseflow in Cedar Creek. All the other development scenarios in both townships produced smaller percentage decreases in modeled baseflow.

The greatest drawdown was from the most closely-spaced wells (0.5 acre lot size cases) and was slightly greater than 5 ft in the Cedarburg development, and about 7 ft in the Jackson development. Figure 7 shows the simulated drawdown around the Cedarburg development.

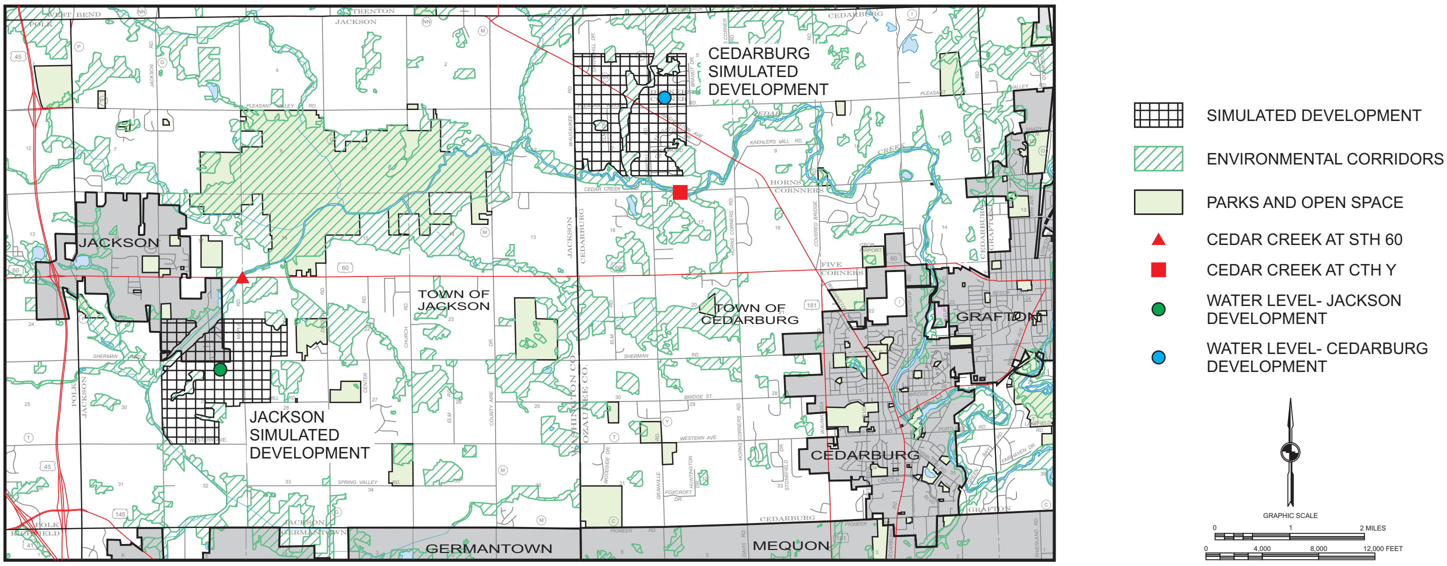

Figure 6. Simulated hypothetical developments in the Cedarburg-Jackson demonstration area.

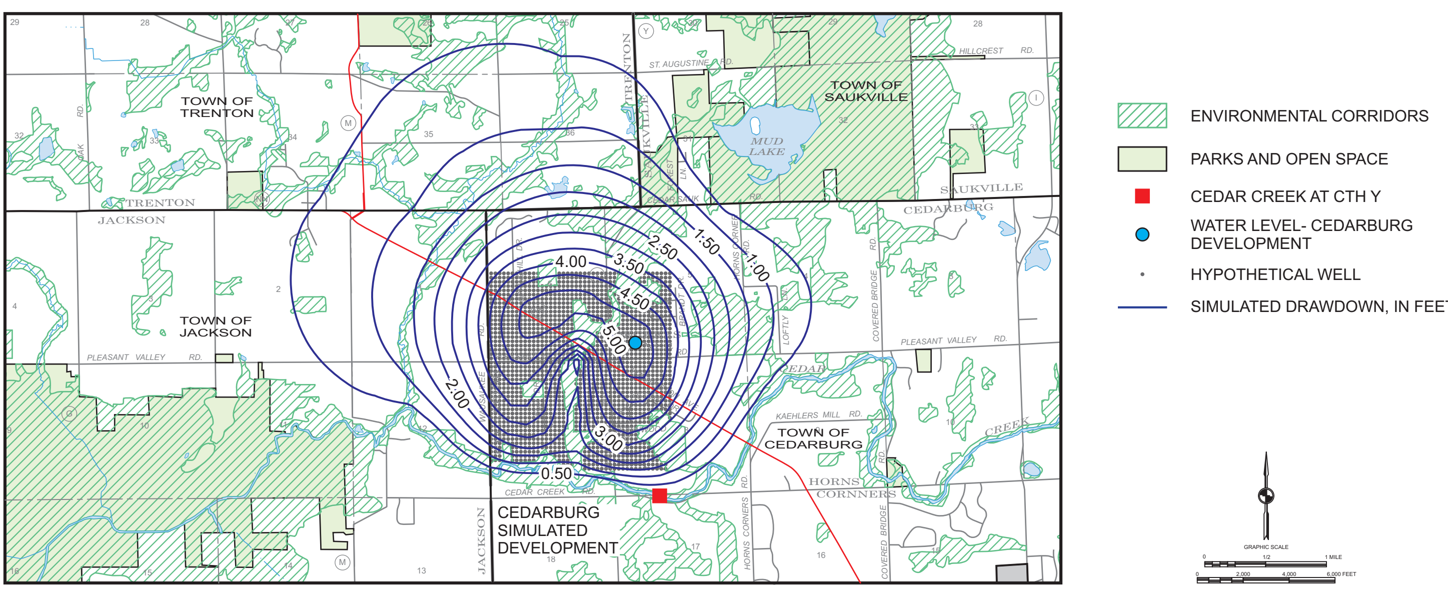

Figure 7. Detail of simulated drawdown for a hypothetical development near Cedarburg. Simulated lot size 0.5 acres, no return of wastewater.

Table 3. Simulation results for specific developments in the Cedarburg and Jackson demonstration areas.

Simulation area	simulation	Maximum drawdown in development area, feet	simulated baseflow at test point, CFS	percent change in baseflow
Cedarburg	Base Run, no new wells	- -	12.98	- -
	0.5 acre, no return	5.31	12.54	-3.32
	1 acre, no return	3.00	12.73	-1.89
	3 acres, no return	1.01	12.89	-0.66
	5 acres, no return	0.60	12.92	-0.41
	0.5 acre, return	0.59	12.94	-0.28
	1 acre, return	0.25	12.95	-0.17
	3 acres, return	0.06	12.97	-0.04
	5 acres, return	0.02	12.97	-0.03
Jackson	Base Run, no new wells	- -	13.83	--
	0.5 acre, no return	6.88	13.37	-3.31
	1 acre, no return	4.06	13.54	-2.10
	3 acres, no return	1.28	13.72	-0.77
	5 acres, no return	0.74	13.77	-0.46
	0.5 acre, return	0.76	13.80	-0.20
	1 acre, return	0.42	13.80	-0.19
	3 acres, return	0.08	13.82	-0.04
	5 acres, return	0.05	13.83	-0.03

Conclusions for Detailed Development Scenarios

In summary, the detailed development simulations show that dense single-family subdivisions developed with onsite wells have the potential to impact groundwater levels and surface water flows, if wastewater is not returned to the area of use. The magnitude of impacts depends on development density, the location of the development, and on the character of existing water resources. However, the impacts are generally limited to a 5 percent or less change in baseflow and to seven feet or less in water table elevation. In particular, small streams, springs, and wetlands are expected to be typically far more sensitive to local reductions in baseflow than are larger surface water features. In all cases, returning treated wastewater to the area of use largely mitigates these water *quantity* impacts. However, such return might adversely impact water *quality*. Water quality impacts were not evaluated.

Townshipwide Development Simulations

Townshipwide development simulations assume development over entire township demonstration areas and are intended to allow comparisons of the relative impacts of developments in different parts of the SEWRPC Region. Such widespread development may never occur in the Region, and so these simulations are intended to show worst-case impacts under maximum buildout. These simulations allow comparison of the hydrologic impacts of development in the different townships without the effects of small-scale topography and proximity to surface water features that may obscure impacts within individual developments.

Appendices B through G describe details about the township-wide simulations at each demonstration area. Impact assessment considers three things: drawdown, surface water flows (baseflow), and the ratio of local water use to local recharge. For comparison purposes simulated drawdown at the center of each township and also at points one mile in from the SW and NE corners were evaluated. Simulated base flows in at least two streams were evaluated for each area. Figure 8 shows the layout for the LaGrange demonstration area. Each cross represents a well located in the approximate center of a quarter-quarter section. No wells are located in the areas of environmental corridors, isolated natural areas, and parkland. The figure shows the three locations of water-level evaluation points, and the two locations of flow evaluation - Steel Brook and the outlet of the Lauderdale Lakes. Contours on the figure represent simulated drawdown for a scenario of 1-acre lots with no return flow. Appendices B through H contain similar maps for each demonstration area.

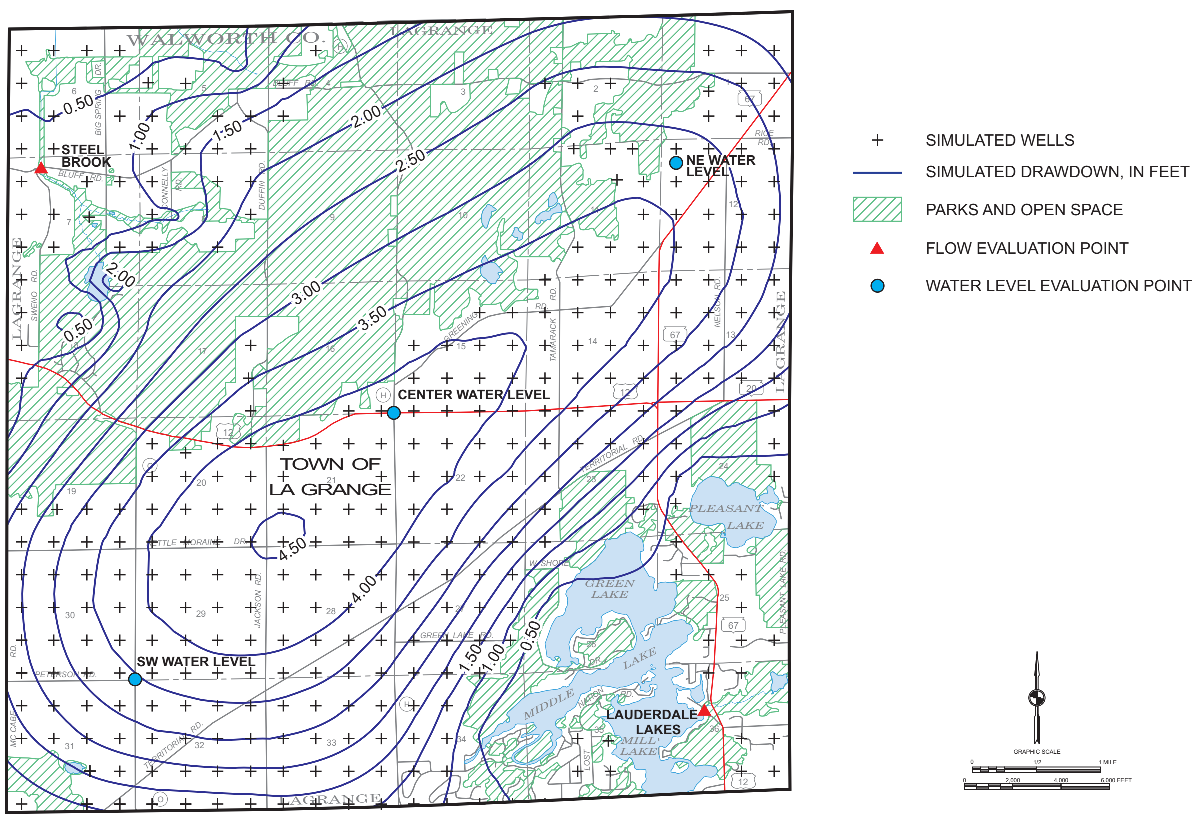

Figure 8. Areawide simulation for the Town of La Grange, Walworth County. Contours show drawdown of the water table resulting from full development of 1-acre lots across the area, with no return of wastewater.

Table 4 summarizes the numerical results for the simulations for La Grange. There are 7 model runs in all – one base run (no wells) plus three runs for the three lot sizes with and without return flow. The baseline run represents the calibrated model without any new wells added. For the baseline situation, recharge in the Town exceeds groundwater use, and groundwater flows outward at a net rate of 11.3 cfs (the model convention is that negative values represent outflow). This value of net outflow is called *boundary flux* in this report. There is of course no drawdown in the baseline condition, so the drawdown values are all zero. The baseline model baseflows are 2.3 cfs at the outlet of the Lauderdale Lakes and 2.8 cfs at Steel Brook, in the northwest corner of the Town. Under the most intense development scenario (1 acre lots with no return flow), the boundary flux decreases by 15.6 percent to 9.6 cfs. Maximum drawdown of the water table is 4 feet in the center of the Town, and 3.3 ft in the southwest and northeast quadrants. Groundwater flow (baseflow) to the Lauderdale Lakes decreases by almost 40 percent, and flow to Steel Brook decreases by 14 percent. Under the same situation with return flow, impacts are less significant. Drawdowns at the three test points are all less than one foot, and baseflow reductions are about 4 percent at Lauderdale Lakes and 1.5 percent at Steel Brook. Thus, with return flow, most of the impacts are minimal. This is because the La Grange area has sandy soils and its location in the Kettle Moraine results in significant recharge and relatively high hydraulic conductivity. Appendices B through H contain similar tables for each of the six demonstration areas.

Table 4. Simulated hydrologic impacts for the La Grange demonstration area

	Boundary flux		drawdown, ft			Lauderdale Lakes outlet		Steel Brook	
Run	cfs	% change	center	SW	NE	cfs	% change	cfs	% change
Baseline - no wells	-11.3	0.0	0.0	0.0	0.0	2.3	0.0	2.8	0.0
5 acre lots	-11.0	-3.1	0.9	0.9	0.9	2.2	-8.1	2.8	-2.9
3 acre lots	-10.8	-5.2	1.5	1.1	1.2	2.0	-13.6	2.7	-4.9
1 acre lots	-9.6	-15.6	4.0	3.6	3.3	1.4	-39.8	2.4	-14.4
5 acre lots w/return	-11.3	-0.3	0.0	0.2	0.0	2.3	-0.8	2.8	-0.3
3 acre lots w/return	-11.3	-0.5	0.3	0.3	0.2	2.3	-1.4	2.8	-0.5
1 acre lots w/return	-11.2	-1.5	0.5	0.3	0.5	2.2	-4.1	2.8	-1.5

In general, drawdown and baseflow reduction impacts are linearly related to well density (or inversely related to lot size (figures 9 and 10). Deviations from strict linearity result from the influence of local hydrologic features and heterogeneity on the pumping impacts.

The simulations show some significant differences in development impacts among the demonstration areas. Drawdowns and flow reductions are always most significant at smallest lot sizes (most intense development) coupled with no wastewater return flow. Drawdowns at the 1-acre lot size range from about one foot (Wheatland demonstration area) to over 25 feet (Raymond demonstration area). Baseflow reductions in small streams range from about 20 percent in the Wheatland area to nearly 40 percent in the LaGrange area (no small baseflow-dominated streams occur in the Raymond area).

Simulations with wastewater return (dashed lines on Figures 9 and 10) produce much smaller impacts.

Water Use as a Percentage of Recharge

Examining water use as a percentage of volumetric recharge in the demonstration areas is another way to compare the sustainability of the demonstration areas. Ignoring underflow across area boundaries, the volume of annual recharge represents a practical upper limit to the sustainable use of shallow groundwater. In practice, of course, groundwater also feeds environmental uses such as springs, streams, lakes, and wetlands, so that the environmentally sustainable rate of groundwater use is always less than the recharge rate. However, for comparison purposes, the ratio of water use to recharge represents a useful metric.

Examining the ratio of potential groundwater use to recharge reveals significant differences between the demonstrations areas. Table 5 and Figure 11 show these ratios. The Jackson demonstration area shows the lowest ratio of potential use to recharge, with a maximum of 21 percent for the highest-density development pattern. This means that even under a 1-acre lot size, wells pumping from the shallow aquifer will use far less water than enters the aquifer as local recharge. In contrast, the ratios of the three and one acre densities exceed 100 percent in the Raymond demonstration area, meaning that local recharge would not sustain intense shallow pumping there. Clayey soils in the Raymond area cause recharge rates to be low, and a lack of environmental corridors causes the number of potential wells to be relatively high.

Table 5. Summary of pumping as a percentage of recharge for the six demonstration areas

Area	Recharge in/yr	Recharge CFS	No. of wells simulated	Pumping as a percentage of recharge, for various lot sizes					
				With return flow			Without return flow		
				5 acre return	3 acre return	1 acre return	5 acre	3 acre	1 acre
La Grange	5-8	18.7	347	0.4	0.7	2.1	4.3	7.2	21.5
Wheatland	7.9	11.2	258	0.5	0.9	2.7	5.3	8.9	26.7
Lisbon	4-7	11.2	334	0.7	1.1	3.4	6.9	11.5	34.4
Cedarburg	3-6	9.8	265	0.6	1.0	3.1	6.3	10.4	31.3
Jackson	3-6	6.2	375	1.4	2.3	7.0	14.0	23.4	70.2
Raymond	0.5	1.4	485	7.8	13.0	39.0	78.0	129.9	389.8

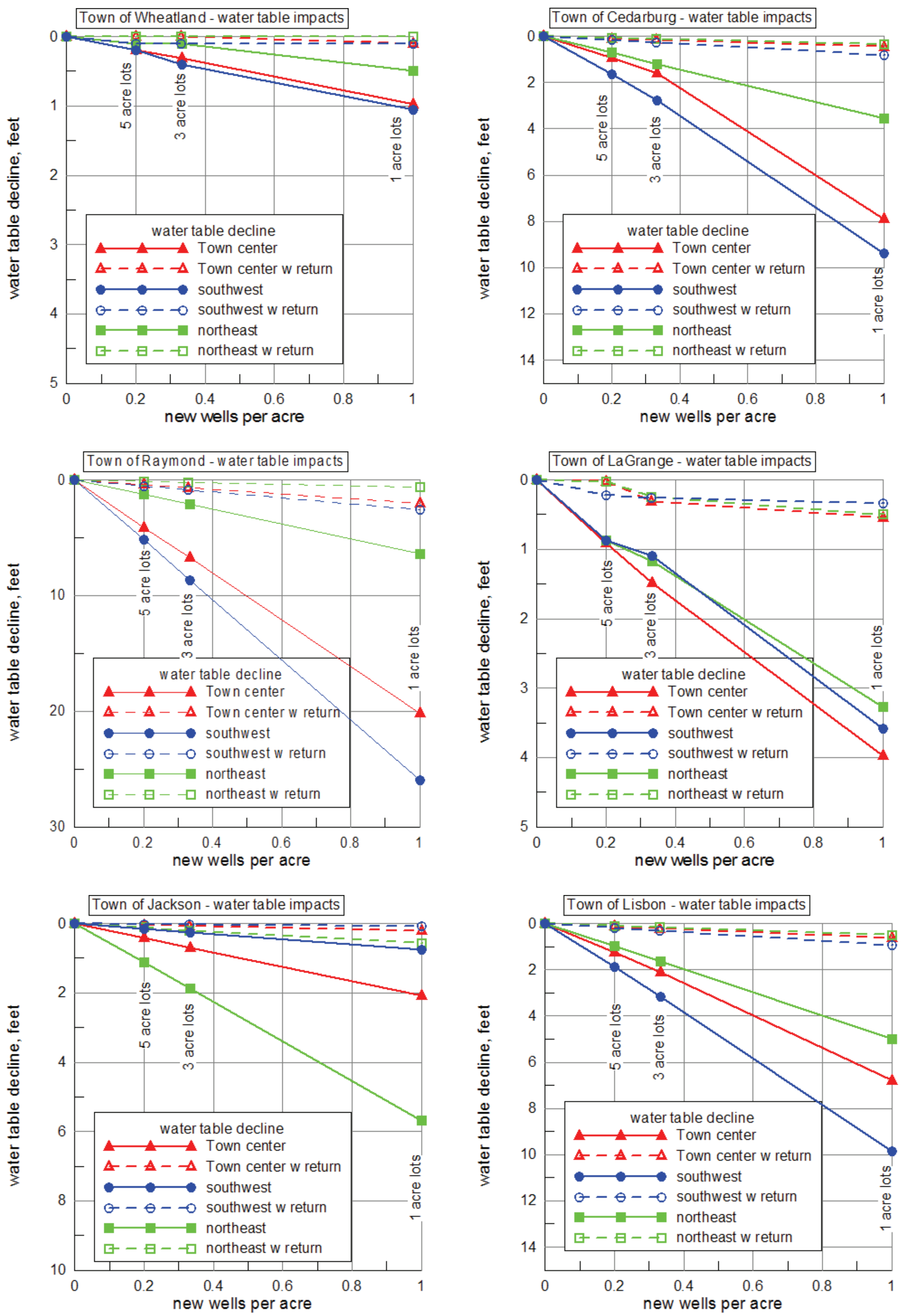

Figure 9. Simulated water-table decline in each demonstration area for various lot densities.

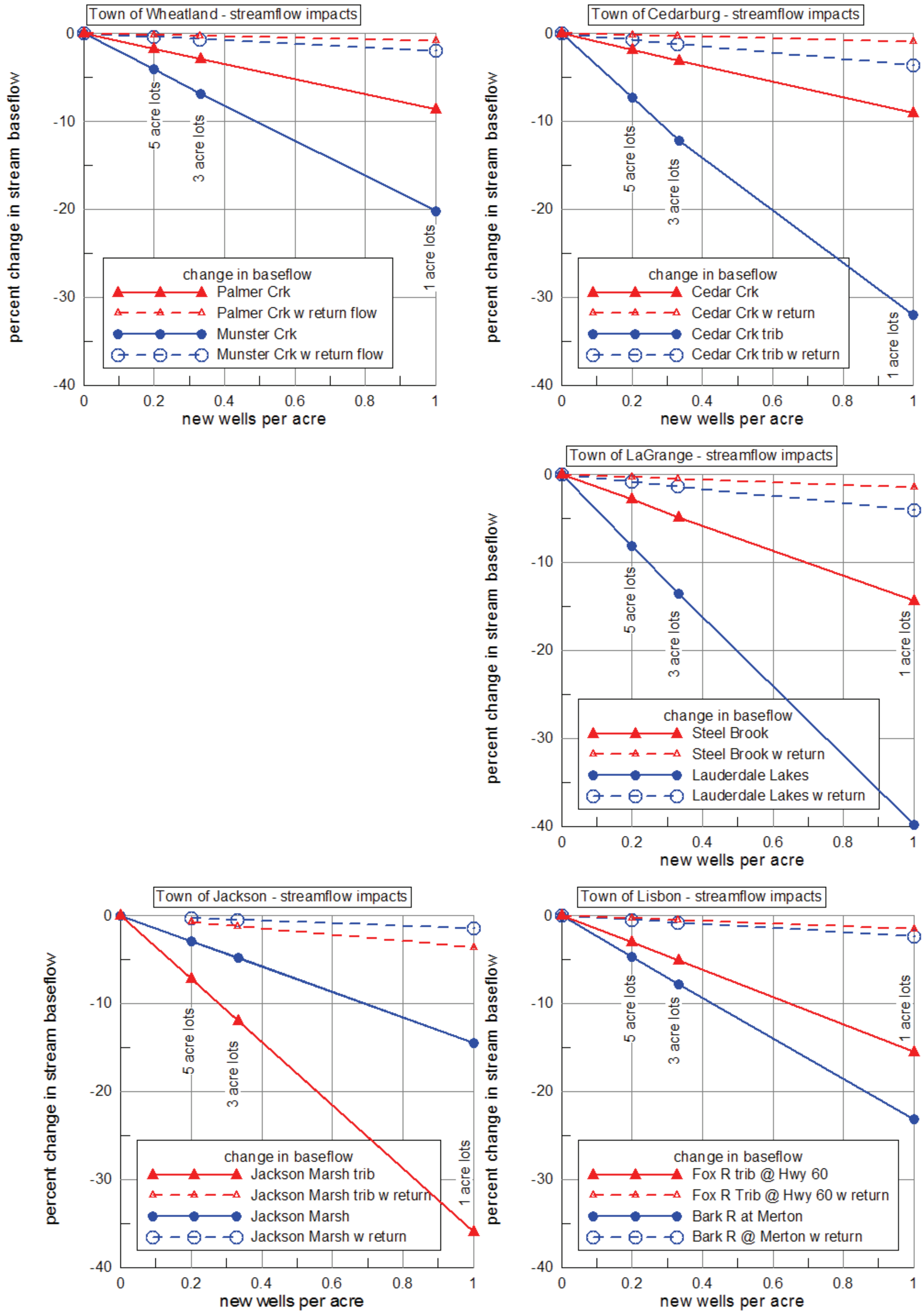

Figure 10. Simulated baseflow changes in each demonstration area for various lot densities.

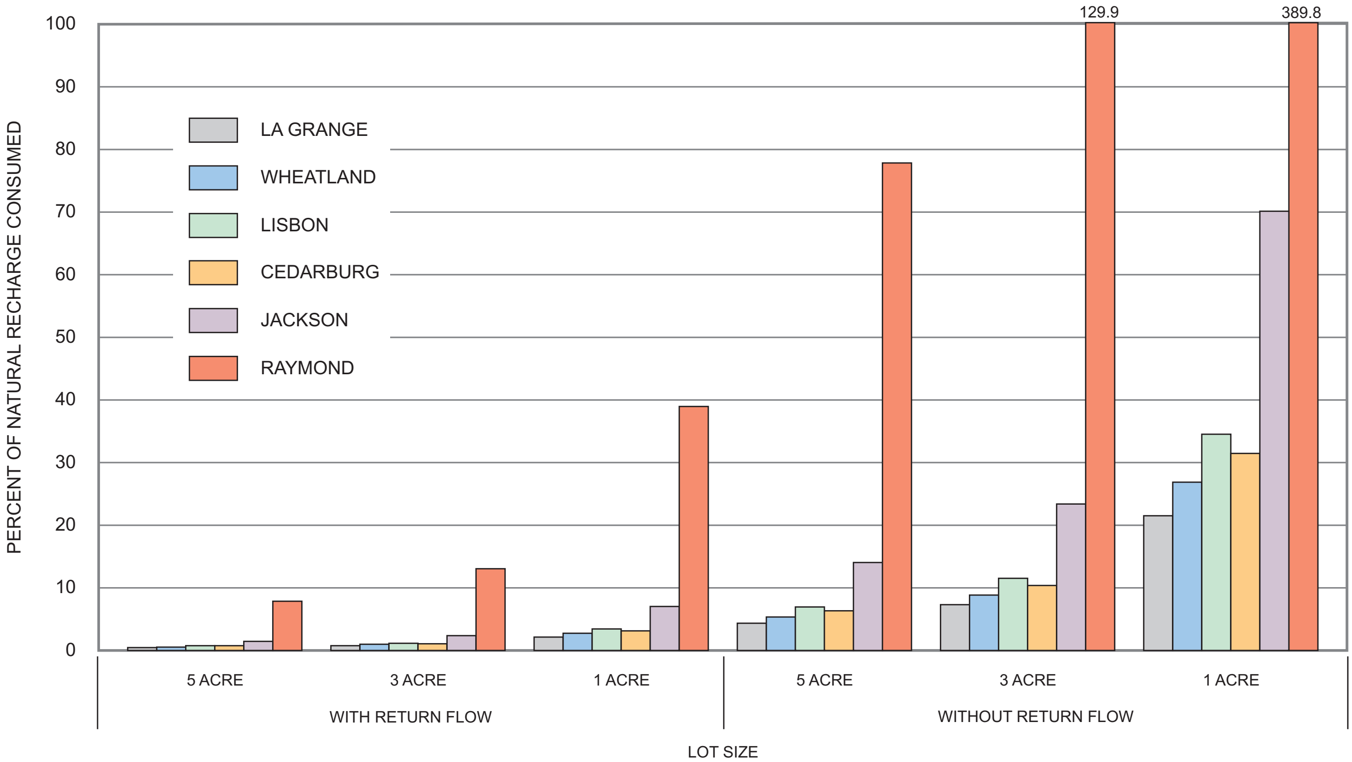

Figure 11. Simulated percentage of natural recharge consumed by pumping in each demonstration area for various lot sizes.

Regional distribution of recharge percentage

The distribution of potential sustainability for shallow developments is directly related to the hydrogeologic characteristics of shallow materials in the SEWRPC Region. Figure 12 (from SEWRPC/WGNHS, 2002, page 52) shows the relative hydraulic conductivity of shallow materials across the region. The highest hydraulic conductivities (greater than 10^{-3} cm/sec) occurs along a north-south band through the western part of the Region, corresponding mainly to the Kettle Moraine area. The lowest hydraulic conductivities occur in the clay-rich border moraines adjacent to Lake Michigan, and are usually less than 10^{-5} cm/sec. The figure shows that the demonstration areas consuming a relatively low percentage of their recharge (LaGrange, Jackson, Wheatland) occur mostly in places having high hydraulic conductivity. Areas of intermediate recharge percentage (Lisbon, Cedarburg) occur in areas of moderate hydraulic conductivity. The area with the highest percentage of consumed recharge (Raymond) occurs in the region of lowest hydraulic conductivity. Figure 12 suggests that the sandier areas in the western part of the Region can support more development than the clay-rich areas nearer Lake Michigan.

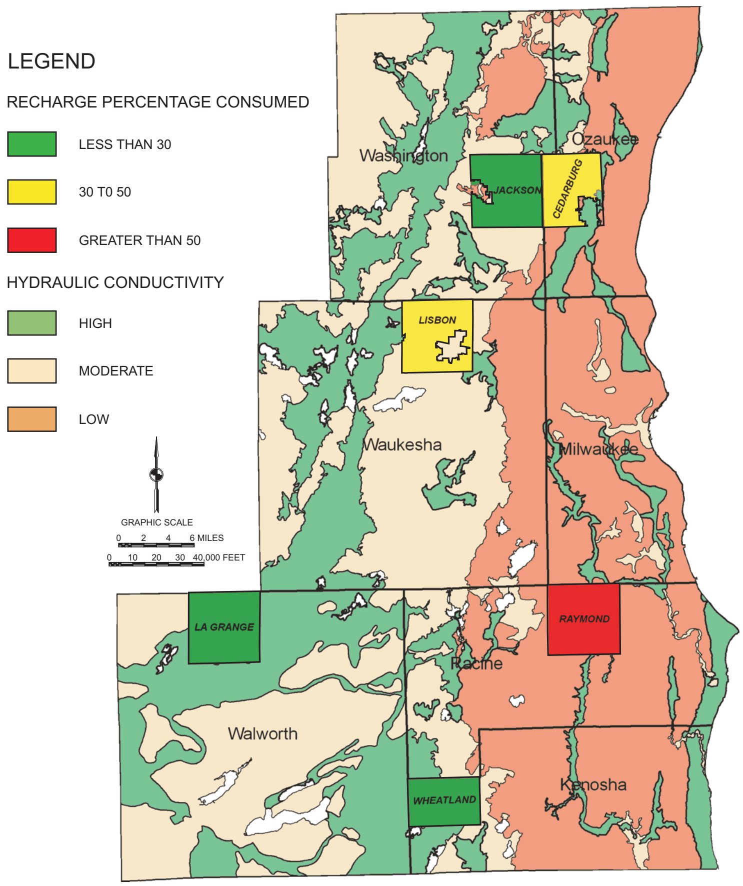

Figure 12. Recharge percentage consumed relative to the regional distribution of shallow hydraulic conductivity.

SUMMARY AND CONCLUSIONS

Over much of the SEWRPC Region, shallow (sand and gravel or dolomite) aquifers can provide sufficient water for domestic water supply in areas of medium- and low-density urban, sub-urban, and rural-density residential development. Simulation of shallow pumping in six different demonstration areas leads to the following conclusions:

- The use of shallow domestic wells has the potential to impact local groundwater levels and baseflows in surface-water bodies, and the potential extent of these impacts ranges from almost negligible to severe in different parts of the SEWRPC Region.

- Not surprisingly, lot size, or density of wells, represents a critical control on groundwater impacts. Both drawdown and reductions in stream baseflows increase linearly as lot size decreases. Under the most aggressive development scenarios (0.5 or 1.0 acre lots, no return flow), simulated drawdowns beneath developed areas range from 1 to 27 feet, and baseflow reductions range from 20 to 40 percent in nearby streams.

- The reinfiltration of treated wastewater, or return flow, significantly mitigates the impacts of development on groundwater levels and baseflows. Assuming 90 percent wastewater return, simulated drawdowns under the most aggressive development scenarios (1.0 acre or smaller lots) decrease from 1 to 27 to 1 to 3 feet, and baseflow reductions range from 2 to 5 percent. However, wastewater return flow might degrade local groundwater and surface water quality; analysis of quality impacts is beyond the scope of this report.

- In general, impacts are inversely proportional to recharge rate and hydraulic conductivity. As recharge rates and/or hydraulic conductivity increase, the impacts of local pumping decrease. For example, clayey soils in the Raymond demonstration area cause the recharge rate to be very low, and groundwater impacts to be severe. In contrast, the La Grange area has sandy soils, relatively high recharge, and only minor simulated pumping impacts.

- For sustainable development, the amount of water withdrawn from a given area should not exceed the local recharge rate. Even under the most aggressive development scenarios, most of the demonstration areas would withdraw less than 40 percent of the local recharge. However, simulated withdrawals in the Raymond area, with its clayey soils and low infiltration, exceed 100 percent of natural recharge for lots three acres and smaller without return of wastewater. It must be recognized that sustainability of groundwater use must be considered within the context of the impacts of such use on the surface water features potentially impacted. Such consideration and associated analyses requires consideration of site-specific factors, such as surface water type, functions, and use objectives.

- The impacts of development on local surface water bodies depends on the distance of pumping from the water body and on the relative size of the water body. For example, a 0.5 cfs reduction to a stream having a predevelopment discharge of 5 cfs represents only a 10 percent decrease, while the same reduction to a 1 cfs stream represents a 50 percent flow decrease.

- Based upon the analyses conducted under this study, as well as professional judgments concerning the potential for groundwater contamination, it would appear that the use of individual wells and onsite sewage disposal systems is a viable option for residential development at rural densities, that is, in areas having a minimum lot area of five acres or more per dwelling unit.

- This study suggests that a number of residential development scenarios using individual wells and onsite sewage disposal systems could be viable from a groundwater quantity perspective. However, other factors must be taken into account, including, particularly, impacts on groundwater quality. Additional factors include the type of onsite sewage treatment and disposal, and such site-specific factors as setback requirements, separation distances between wells and the onsite sewage disposal systems, and replacement sewage disposal distribution system area requirements. Accordingly, it is recommended that a more comprehensive evaluation of the long-term viability of development scenarios considered in this report be developed under a subsequent work effort. Such evaluation would include a groundwater quality component relying on groundwater quality modeling and the most up-to-date information regarding the movement and transport of both conventional and emerging contaminants.

- The development scenarios evaluated in this report which consider urban or sub-urban developments utilizing private wells in areas beyond the planned urban service areas are at variance with the regional land use plan.[1] These development scenarios were specifically assumed to represent potential extremes in development patterns in order to bracket the potential associated impacts. The negative impacts identified as potentially associated with selected development scenarios utilizing private wells would be largely avoided if the recommendations of the regional land use plan are followed. That plan focuses the new urban development near existing urban centers in areas that can be readily served by public water supply, as well as public sanitary sewerage systems, mass transit, and police and fire protection services.

[1]*SEWRPC Planning Report No. 48,* A Regional Land Use Plan for Southeastern Wisconsin: 2035*, June 2006.*

REFERENCES

Buchanan, T.J., and W.P. Sommers. 1969. *Discharge measurements at gaging stations*. Techniques of Water-Resources Investigations of the United States Geological Survey. Book 3, Chapter A8. 65 p.

Dripps, W.R., and K.R. Bradbury. 2007. A simple, daily soil-water balance model for estimating the spatial and temporal distribution of groundwater recharge in temperate humid areas. *Hydrogeology Journal*. v15, p 433-444.

Doherty, J. 2004. *PEST: Model-independent parameter estimation. Users manual: 5th edition*. Watermark Computing.

Feinstein, D.T., T.T. Eaton, D.J. Hart, J.T. Krohelski and K.R. Bradbury. 2005a. *Regional aquifer model for southeastern Wisconsin - Report 1: Data collection, conceptual model development, numerical model construction and model calibration*. Technical Report 41, Southeastern Wisconsin Regional Planning Commission, 81p.

Feinstein, D.T., D.J. Hart, J.T. Krohelski, T.T. Eaton and K.R. Bradbury. 2005b. *Regional aquifer model for southeastern Wisconsin - Report 2: Model results and interpretation*. Technical Report 41, Southeastern Wisconsin Regional Planning Commission, 63 p.

Haitjema, H. M. (1995). *Analytic Element Modeling of Groundwater Flow*. Academic Press, Inc.

Hart, D., P. Schoephoester, and K.R. Bradbury. 2007. Groundwater Recharge in Southeastern Wisconsin Estimated By a GIS-Based Water-Balance Model. Memorandim report to the Southeastern Wisconsin Regional Planning Commission. 35 p.

McDonald, M.G. and Harbaugh, A.W., 1988. *A modular three-dimensional finite-difference ground-water flow model*, Techniques of Water-Resources Investigations of the United States Geological Survey. Book 6, Modeling techniques; chapter A1, 576 p.

Southeastern Wisconsin Regional Planning Commission (SEWRPC), in preparation. Regional Water Supply Plan for Southeastern Wisconsin. SEWRPC Planning Report 52.

SEWRPC/WGNHS, 2002. *Groundwater resources of southeastern Wisconsin.* Southeastern Wisconsin Regional Planning Commission Technical Report 37. 203 p. (available online at http://www.sewrpc.org/data_publications/default.shtm)

APPENDICES

(This page intentionally left blank)

APPENDICES

Appendix A: Streamflow Measurement

Measurements of stream flows were collected from sites in several of the demonstration areas (Lisbon, Wheatland, La Grange, and Raymond). These measurements were later used to supplement other flow calibration targets in the various numerical models developed for this study. Streamflow measurements took place during November and December, 2006, when water levels were generally low and local streams were judged to be near baseflow conditions. Smaller streams were chosen for measurement because such streams are potentially more sensitive to local pumping impacts and to local model calibration.

Measurements were conducted using a Marsh-McBirney Flo-Mate 2000 electromagnetic flowmeter mounted on a wading rod. Flow measurements were made using the six-tenths-depth method described by Buchanan and Sommers (1969). The nature of the stream bed was also recorded. Table A1 summarizes these results.

Table A1. Summary of streamflow measurements.

Lisbon area							
Description	Date	Flow (cfs)	Location				Bottom
			qtr/qtr	Sec	Twn	Rng	
Fox Riv tributary at Hwy VV in Village of Sussex	11/24/06	0.95	NE/NW	26	8N	19E	rocky
Fox River at Hwy K	11/24/06	4.99	NW/SE	31	8N	20E	rocky
Bark River at Hwy 164	11/24/06	5.33	SW/SW	4	8N	19E	gravel
Bark R at Hwy K	11/24/06	15.05	NE/NW	35	8N	18E	rocky
Upper Bark River at Willow Creek Road	11/24/06	0.50	SE/SW	26	9N	19E	gravel
Wheatland area							
Description	Date	Flow (cfs)	Location				Bottom
			qtr/qtr	Sec	Twn	Rng	
North Branch Nippersink Crk at Hwy B	11/25/06	8.82	SW/NW	33	1N	18E	sandy mud
North Branch Nippersink Crk at Westside Road	11/25/06	1.92	SW/NW	18	1N	18E	
West Branch Nippersink Crk at Deignan Road	11/25/06	4.22	NW/NE	28	1N	18E	muddy
Unnamed tributary at Hwy F	11/25/06	0.38	NW/SE	12	1N	18E	
Creek North of Lake Ivanhoe at Hwy 50	11/25/06	2.53	NE/SW	35	2N	18E	hard
New Munster Creek at Hwy O	11/25/06	2.47	SW/SE	33	2N	19E	
Powers Lake inlet at Hwy F	11/25/06	0.19	NE/NE	18	1N	19E	
Palmer Creek at Hwy 50/83	11/25/06	2.46	NW/NE	2	1N	19E	muddy, soft
Unnamed Creek at Hwy 83	11/25/06	2.21	NE/NE	27	2N	19E	muddy
La Grange area							
Description	Date	Flow (cfs)	Location				Bottom
			qtr/qtr	Sec	Twn	Rng	
Lauderdale Lakes outlet at Hwy 12/67	12/20/06	3.00	SE/NW	36	4N	16E	hard
Outlet of Blue Spring Lake at Hwy H	12/20/06	5.05	SW/SE	33	5N	16E	hard
Steel Brook Creek at Bluff Road	12/20/06	2.68	NE/NW	7	4N	16E	firm
Bluff Creek at Hwy P	12/20/06	11.58	NE/NE	23	4N	15E	firm
Raymond area							
Description	Date	Flow (cfs)	Location				Bottom
			qtr/qtr	Sec	Twn	Rng	
Root River tributary at Sevenmile Road	11/27/06	2.86	SW/SE	1	4N	21E	sandy
Tributary to West Branch Root River Canal at Fourmile Road	11/27/06	3.57	NE/NE	27	4N	21E	hard, sandy
East Branch Root River Canal at Twomile Road	11/27/06	5.89	NE/NW	1	3N	21E	
East Branch Root R Canal at HWY K (Fourmile Road)	11/27/06	7.24	NW/NE	26	4N	21E	rocky

Appendix B: Cedarburg Demonstration Area

The Cedarburg demonstration area which consists of all of U.S. Public Land Survey system Township 10 North, Range 21 East, is located in south-central Ozaukee County. Cedar Creek bisects the Township and joins the Milwaukee River just southeast of the Township boundary. The City of Cedarburg is located in the southeast part of the Township. Local geology consists of clayey till and lake sediment 50-150 feet thick over dolomite bedrock of Silurian age. The City operates five high capacity wells-all finished in the Silurian dolomite. Soils are generally clayey or silty, and recharge is generally lower than in sandier areas to the west. Based on water-balance recharge modeling and model calibration, the best-fit groundwater model used a uniform hydraulic conductivity of 3 ft/day and variable recharge rate of 3-6 in/yr. Model flux evaluation points were located at Cedar Creek at Columbia Avenue in Cedarburg and at a small tributary to Cedar Creek along Highway 60 just west of the Township.

Simulated water-table contours show that local groundwater flows generally northeast and southeast toward Cedar Creek (fig B1). There is a local water-table high near the southwest corner of the Township. Major areas of planned open space correspond to riparian areas along surface-water features (fig B2). Maximum potential water-table decline based on no return of wastewater flows is nearly 12 feet in this south central portion of the demonstration area (fig B2), reflecting the clayey soils.

Table B1. Simulated hydrologic impacts for the Cedarburg demonstration area.

	Boundary flux		Drawdown in feet			Cedar Creek trib at Hwy 60		Cedar Creek at Columbia Ave	
Run	cfs	% change	center	SW	NE	cfs	% change	cfs	% change
Baseline - no wells	-0.8	0.0	0.0	0.0	0.0	1.4	0.0	23.6	0.0
5 acre lots	-0.7	13.1	0.9	1.6	0.7	1.3	-7.3	23.2	-1.9
3 acre lots	-0.6	22.0	1.6	2.8	1.2	1.2	-12.2	22.9	-3.1
1 acre lots	-0.2	69.5	7.9	9.4	3.5	1.0	-32.0	21.5	-9.0
5 acre lots w/return	-0.8	1.3	0.1	0.2	0.1	1.4	-0.7	23.6	-0.2
3 acre lots w/return	-0.8	2.2	0.2	0.3	0.1	1.4	-1.2	23.6	-0.3
1 acre lots w/return	-0.8	6.6	0.5	0.8	0.4	1.4	-3.6	23.4	-1.0

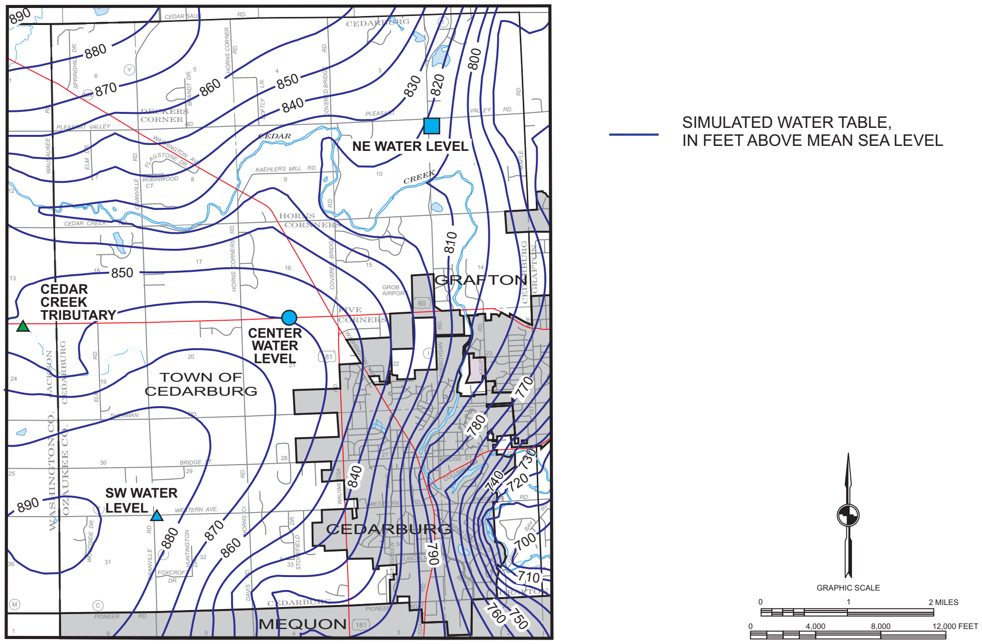

Figure B1. Cedarburg demonstration area, showing simulated water table and locations of water-level and streamflow test points.

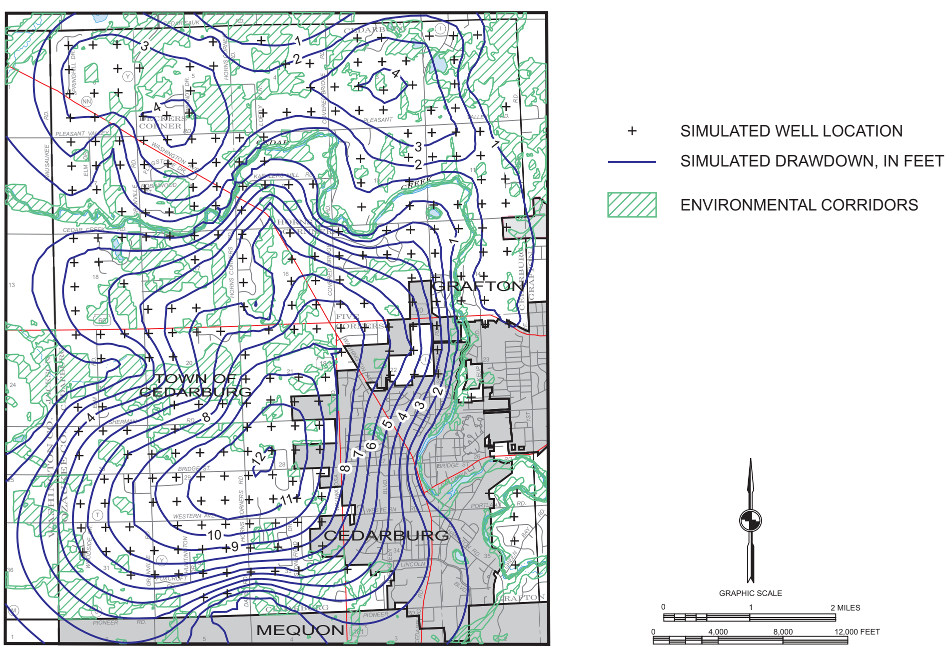

Figure B2. Cedarburg demonstration area, simulated drawdown, 1 acre lots, no return flow.

Appendix C: Jackson Demonstration Area

The Jackson demonstration area consists of all U.S. Public Land Survey system Township 10 North, Range 20 East, located in northeastern Washington County, just west of the Cedarburg demonstration area in Ozaukee County. The Town surrounds the Jackson Marsh and associated wildlife area. Cedar Creek flows toward the east across the Township just south of the marsh. The Village of Jackson is located in the western part of the Township, and the Village operates three high-capacity wells – two finished in sand and gravel and one in Silurian dolomite. Local geology consists of sand and gravel 0-100 feet thick over dolomite bedrock of Silurian age. Soils are mostly silty or sandy, and recharge rates are moderate. Based on water-balance recharge modeling and model calibration, the best-fit groundwater model used a uniform hydraulic conductivity of 3 ft/day and variable recharge rate of 3-6 in/yr.

Simulated water-table contours show that local groundwater flows generally toward the center and to the eastern portion of the Township, discharging to the Jackson Marsh and to Cedar Creek and its tributaries (fig C1). Major areas of planned open space correspond mainly to riparian areas near the Jackson Marsh (fig C2). Due to the locations of the planned open space, and the location of the Village of Jackson, potential future groundwater development might occur mostly in the northern and southern portions of the Township. Maximum potential water-table decline based on no return of wastewater flows is between 6 and 11 feet in these areas (fig C2).

Table C1. Simulated hydrologic impacts for the Jackson demonstration area.

	Boundary flux		Drawdown in feet			Jackson Marsh		Cedar Creek west tributary	
Run	cfs	% change	center	SW	NE	cfs	% change	cfs	% change
Baseline - no wells	4.9	0.0	0.0	0.0	0.0	2.8	0.0	0.8	0.0
5 acre lots	5.1	-3.3	0.4	0.1	1.1	2.8	-2.9	0.7	-7.2
3 acre lots	5.2	-5.5	0.7	0.3	1.9	2.7	-4.8	0.7	-12.0
1 acre lots	5.7	-16.6	2.1	0.8	5.7	2.4	-14.5	0.5	-36.0
5 acre lots w/return	4.9	-0.3	0.0	0.0	0.1	2.8	-0.3	0.8	-0.7
3 acre lots w/return	4.9	-0.6	0.1	0.0	0.2	2.8	-0.5	0.8	-1.2
1 acre lots w/return	5.0	-1.7	0.2	0.1	0.6	2.8	-1.4	0.7	-3.6

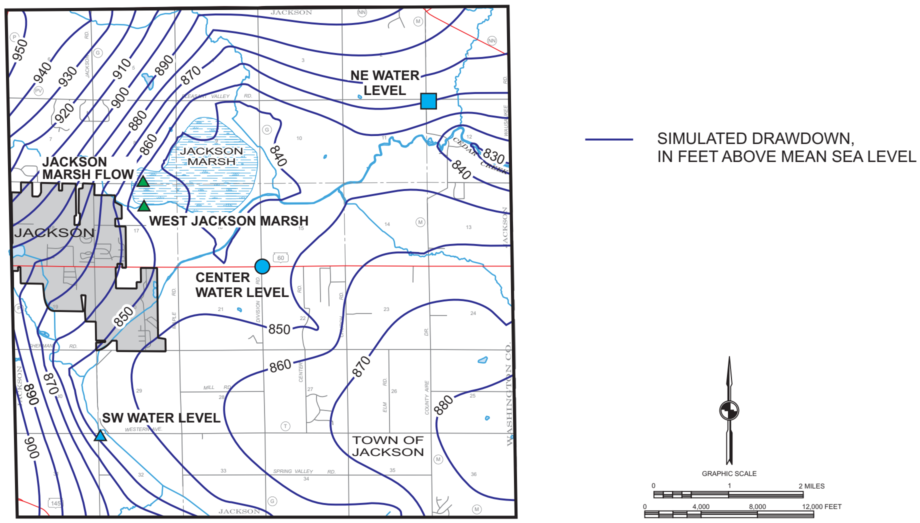

Figure C1. Jackson demonstration area, showing simulated water table and locations of water-level and streamflow test points.

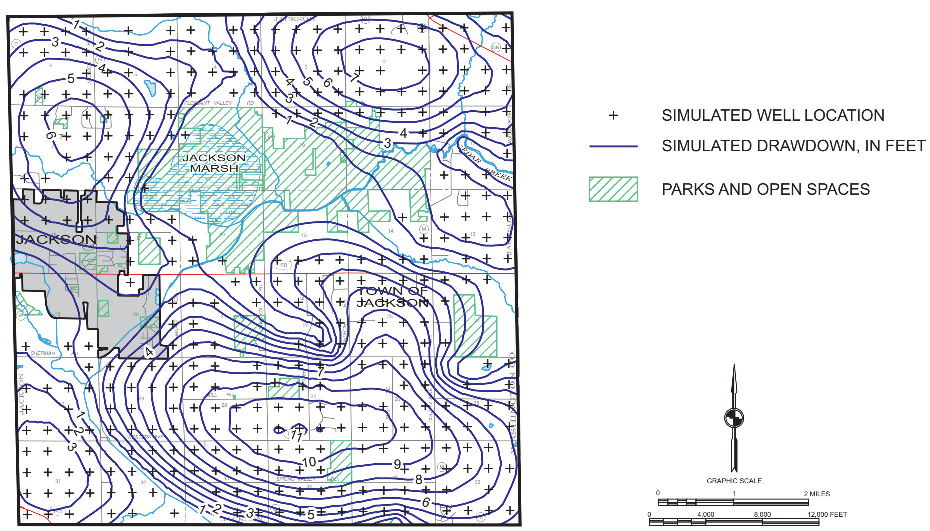

Figure C2. Jackson demonstration area, simulated drawdown, 1 acre lots, no return flow.

Appendix D: La Grange Demonstration Area

The La Grange demonstration area, which consists of all of the Town of La Grange and all of U.S. Public Land Survey system Township 4 North, Range 16 East, is located in northwestern Walworth County, and straddles a hydrologic divide between the Rock River Basin to the northwest and the Fox River Basin to the southeast. Locally, Bluff Creek, Steel Brook, and Spring Creek are spring-fed streams draining northwest. The three Lauderdale lakes drain eastward through Honey Creek. The Township is primarily rural, and currently contains no municipal wells. LaGrange encompasses part of the well-known Kettle Moraine, a hummocky landscape containing numerous glacially-deposited features such as kettle holes, kames, eskers, and moraines. Large portions of the Township lie within the Kettle Moraine State Forest. Local geology consists of thick sand and gravel over dolomite bedrock of Silurian age. Depth to bedrock ranges from 50 to 200 feet, and depth to the water table ranges from 0 to over 120 feet. Soils are generally sandy, and recharge can be rapid. Based on water-balance recharge modeling and model calibration, the best-fit groundwater model used a uniform hydraulic conductivity of 31 ft/day and variable recharge rate of 5-8 in/yr.

Simulated water-table contours show that local groundwater flows generally northeast (toward Steel Brook) and southwest (toward Lauderdale Lakes) from a water-table divide near the center of the Township (fig D1). Major areas of planned open space correspond to the Kettle Moraine State Forest and riparian areas near the Lauderdale Lakes (fig D2). Due to the locations of the planned open space, potential future groundwater development might occur mostly in the central portion of the Township. Maximum potential water-table decline based on no return of wastewater flows is about 4.5 feet in this area (fig D2).

Table D1. Simulated hydrologic impacts for the La Grange demonstration area

	Boundary flux		Drawdown in feet			Lauderdale Lakes outlet		Steel Brook	
Run	cfs	% change	center	SW	NE	cfs	% change	cfs	% change
Baseline - no wells	-11.3	0.0	0.0	0.0	0.0	2.3	0.0	2.8	0.0
5 acre lots	-11.0	-3.1	0.9	0.9	0.9	2.2	-8.1	2.8	-2.9
3 acre lots	-10.8	-5.2	1.5	1.1	1.2	2.0	-13.6	2.7	-4.9
1 acre lots	-9.6	-15.6	4.0	3.6	3.3	1.4	-39.8	2.4	-14.4
5 acre lots w/return	-11.3	-0.3	0.0	0.2	0.0	2.3	-0.8	2.8	-0.3
3 acre lots w/return	-11.3	-0.5	0.3	0.3	0.2	2.3	-1.4	2.8	-0.5
1 acre lots w/return	-11.2	-1.5	0.5	0.3	0.5	2.2	-4.1	2.8	-1.5

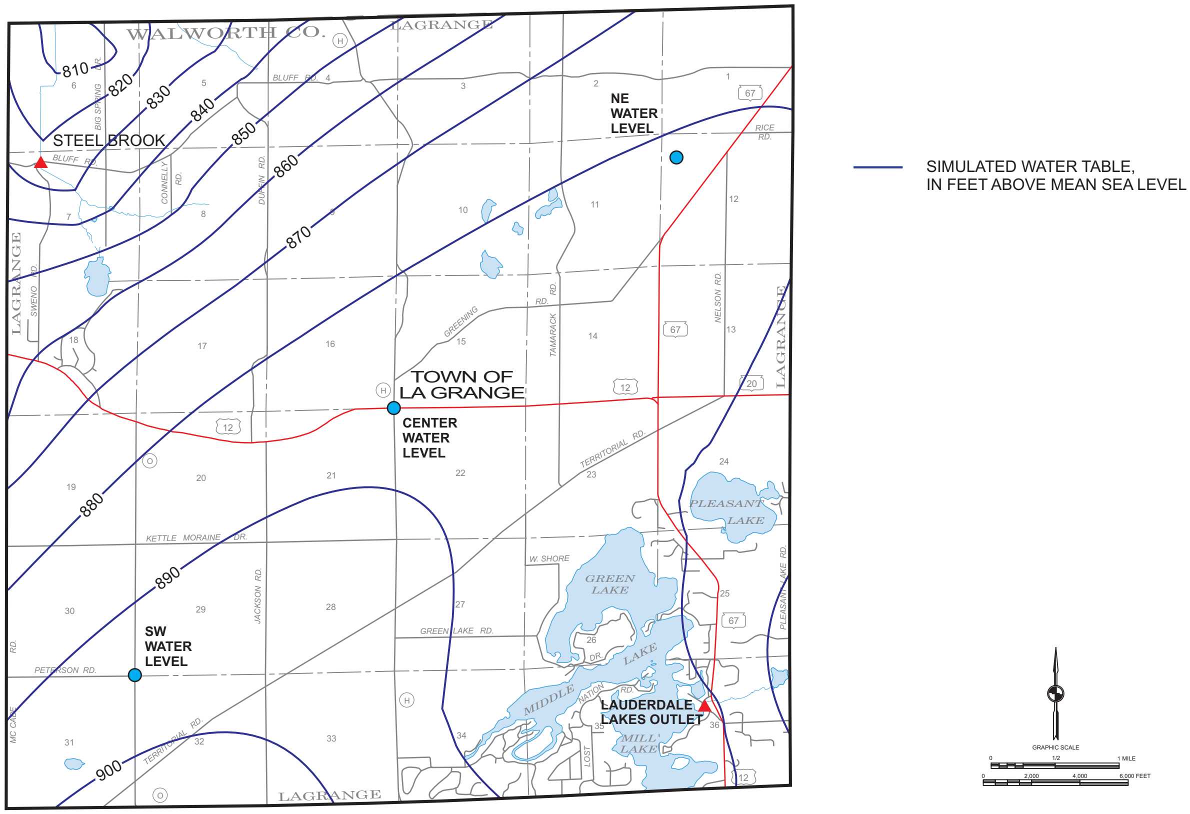

Figure D1. La Grange demonstration area, showing simulated water table and locations of water-level and streamflow test points.

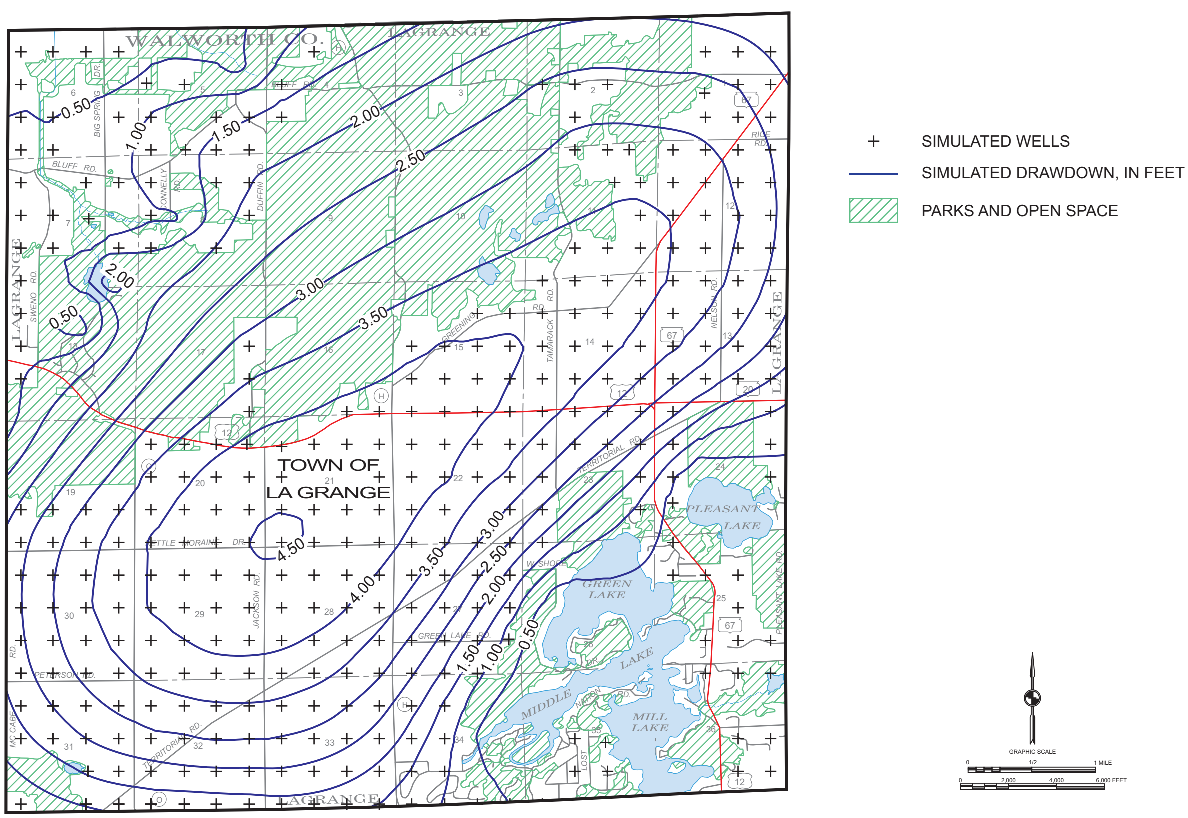

Figure D2. La Grange demonstration area, simulated drawdown, 1 acre lots, no return flow.

Appendix E: Lisbon Demonstration Area

The Lisbon demonstration area consists of all of U.S. Public Land Survey system Township 8 North, Range 19 East, and is located in northeastern Waukesha County. The Township lies on a hydrologic divide between the Bark River to the west and the headwaters of the Fox River to the southeast. The Village of Sussex is located in the southeast part of the Township, and the Village operates several high-capacity wells finished in Cambrian sandstone. A number of both abandoned and currently operating dolomite quarries are located in and around the Township, and dewatering of these quarries has significantly influenced the local shallow groundwater aquifer. Local geology consists of sand and gravel 50-100 feet thick over dolomite bedrock of Silurian age. Soils are generally sandy, and recharge can be rapid. Based on water-balance recharge modeling and model calibration, the best-fit groundwater model used a uniform hydraulic conductivity of 12.5 ft/day and variable recharge rate of 4-7 in/yr.

Simulated water-table contours show that local groundwater flows generally northwest (toward the Bark River) and southeast (toward the Fox River headwaters) from a water-table divide near the center of the Township (fig E1). Major areas of planned open space correspond to riparian areas along surface-water features (fig E2). Due to the locations of the planned open space, and the location of the Village of Sussex, potential future groundwater development might occur mostly in the central portion of the Township. Maximum potential water-table decline based on no return of wastewater flows is between 5 and 10 feet in this area (fig E2).

Table E1. Simulated hydrologic impacts for the Lisbon demonstration area

	Boundary flux		Drawdown in feet			Bark R at Merton		Fox trib at Hwy K	
Run	cfs	% change	center	SW	NE	cfs	% change	cfs	% change
Baseline - no wells	-3.4	0.0	0.0	0.0	0.0	7.6	0.0	3.0	0.0
5 acre lots	-3.1	-8.4	1.3	1.9	1.0	7.3	-4.7	2.9	-3.0
3 acre lots	-3.0	-13.9	2.1	3.2	1.6	7.0	-7.8	2.8	-5.1
1 acre lots	-2.0	-42.2	6.8	9.9	5.0	5.9	-23.2	2.5	-15.6
5 acre lots w/return	-3.4	-0.8	0.1	0.2	0.1	7.6	-0.5	3.0	-0.3
3 acre lots w/return	-3.4	-1.4	0.2	0.3	0.2	7.6	-0.8	2.9	-0.5
1 acre lots w/return	-3.3	-4.2	0.6	0.9	0.5	7.5	-2.3	2.9	-1.5

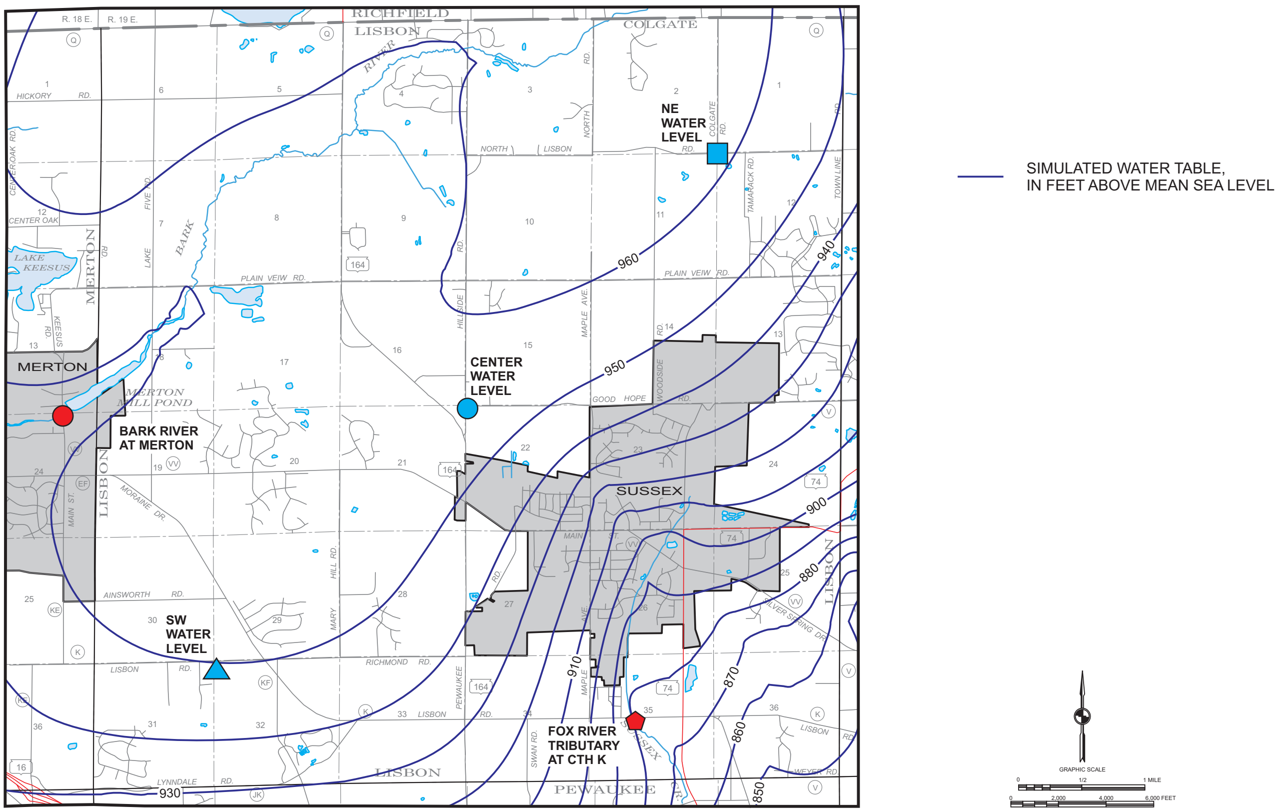

Figure E1. Lisbon demonstration area, showing simulated water table and locations of water-level and streamflow test points.

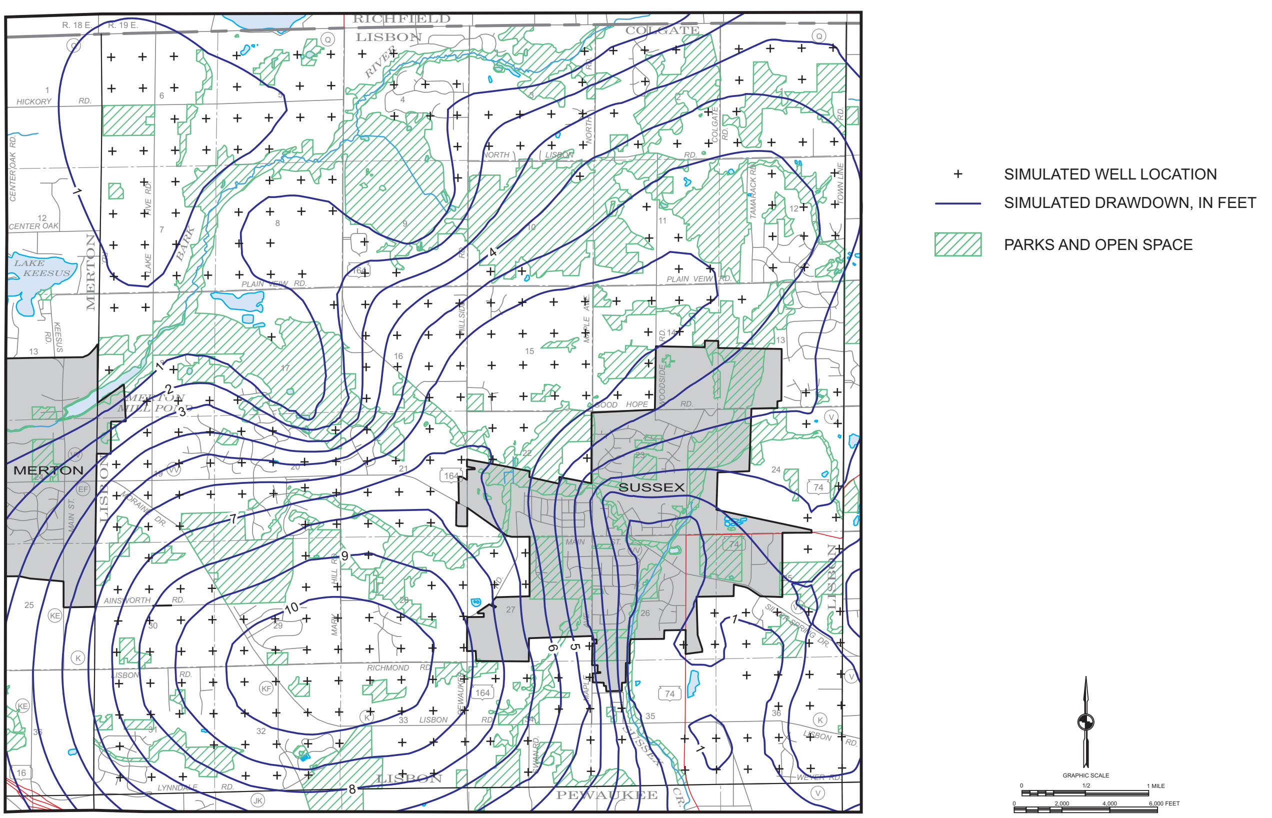

Figure E2. Lisbon demonstration area, simulated drawdown, 1 acre lots, no return flow.

Appendix F: Raymond Demonstration Area

The Raymond demonstration area, which consists of all of the Town of Raymond and all of U.S. Public Land Survey system Township 4 North, Range 21 East, is located in north-central Racine County. The Township sits on a gently undulating plain formed on silty-clay till of the Oak Creek Formation. The landscape slopes gently toward the East and West Branches of the Root River, which flows from south to north through the Township. Much of the Root River has been ditched and channeled to form the Root River Canal, which carries treated municipal effluent from several upstream communities. The Township is primarily rural, and currently contains one municipal well operated by the North Cape Sanitary District. Local geology consists of silt, clay, sand and gravel over dolomite bedrock of Silurian age. Depth to bedrock ranges from 100 to 200 feet, and depth to the water table ranges from 15 to over 110 feet. Soils are generally silty, and recharge rates are low. Based on water-balance recharge modeling and model calibration, the best-fit groundwater model used a uniform hydraulic conductivity of 3 ft/day and variable recharge rate of 0.5 in/yr.

Simulated water-table contours show that local groundwater flows generally east (toward the Root River Canal) from a water-table divide west of the Township (fig F1). Scattered areas of planned open space are located mainly in riparian areas along the Root River and its tributaries (fig F2). Due to the wastewater inflow to the Root River Canal and the size of the Root River there were no useable surface water targets in the Township. Potential future groundwater development might occur almost anywhere in the Township. The combination of low recharge and clayey soils causes drawdowns from domestic pumping to be significant in this area. Maximum potential water-table decline based on no return of wastewater flows is nearly 30 feet in the west-central part of the Township (fig F2) and is mitigated near the river.

Table F1. Simulated hydrologic impacts for the Raymond demonstration area. Note that there were no appropriate flux targets available in the township.

	Boundary flux		Drawdown in feet		
Run	cfs	% change	center	SW	NE
Baseline - no wells	1.7	0.0	0.0	0.0	0.0
5 acre lots	2.1	27.3	4.1	5.2	1.0
3 acre lots	2.4	45.4	6.7	8.6	1.6
1 acre lots	3.9	136.3	20.2	26.0	5.0
5 acre lots w/return	1.7	2.7	0.4	0.5	0.1
3 acre lots w/return	1.7	4.5	0.7	0.9	0.2
1 acre lots w/return	1.9	13.6	2.0	2.6	0.5

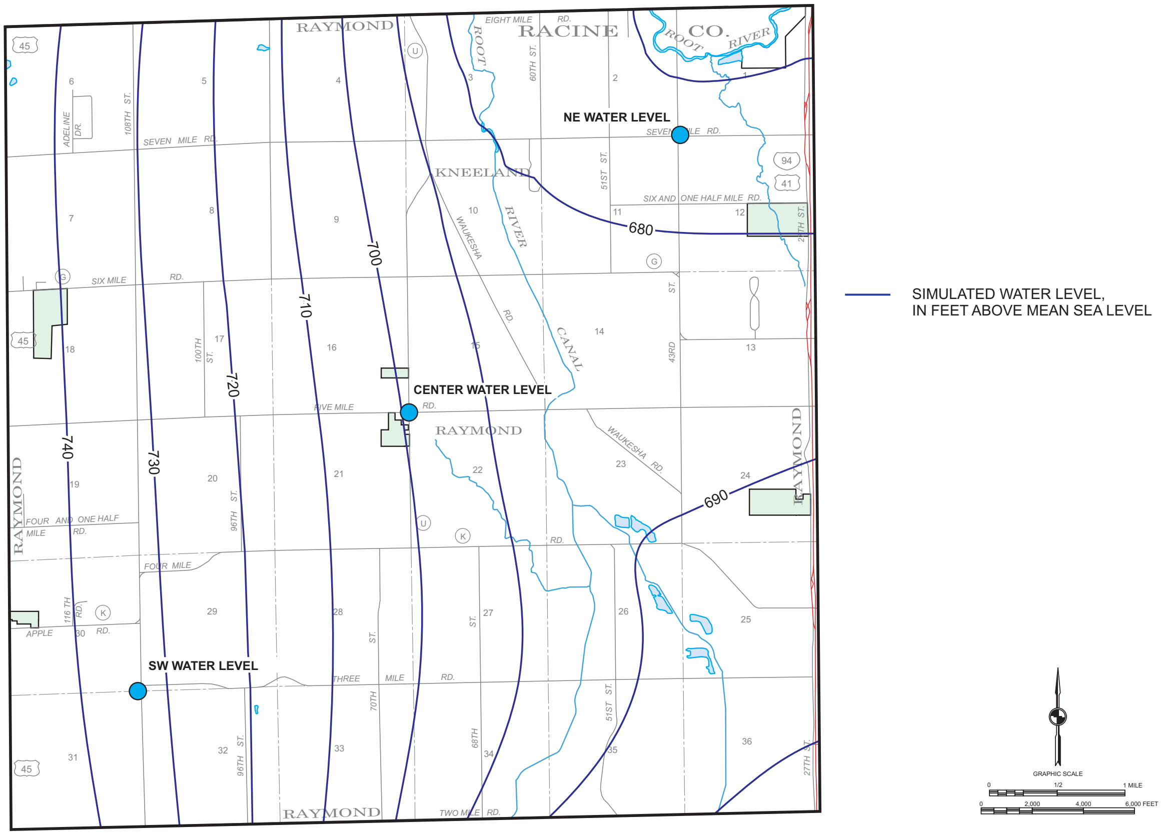

Figure F1. Raymond demonstration area, showing simulated water table and locations of water-level test points.

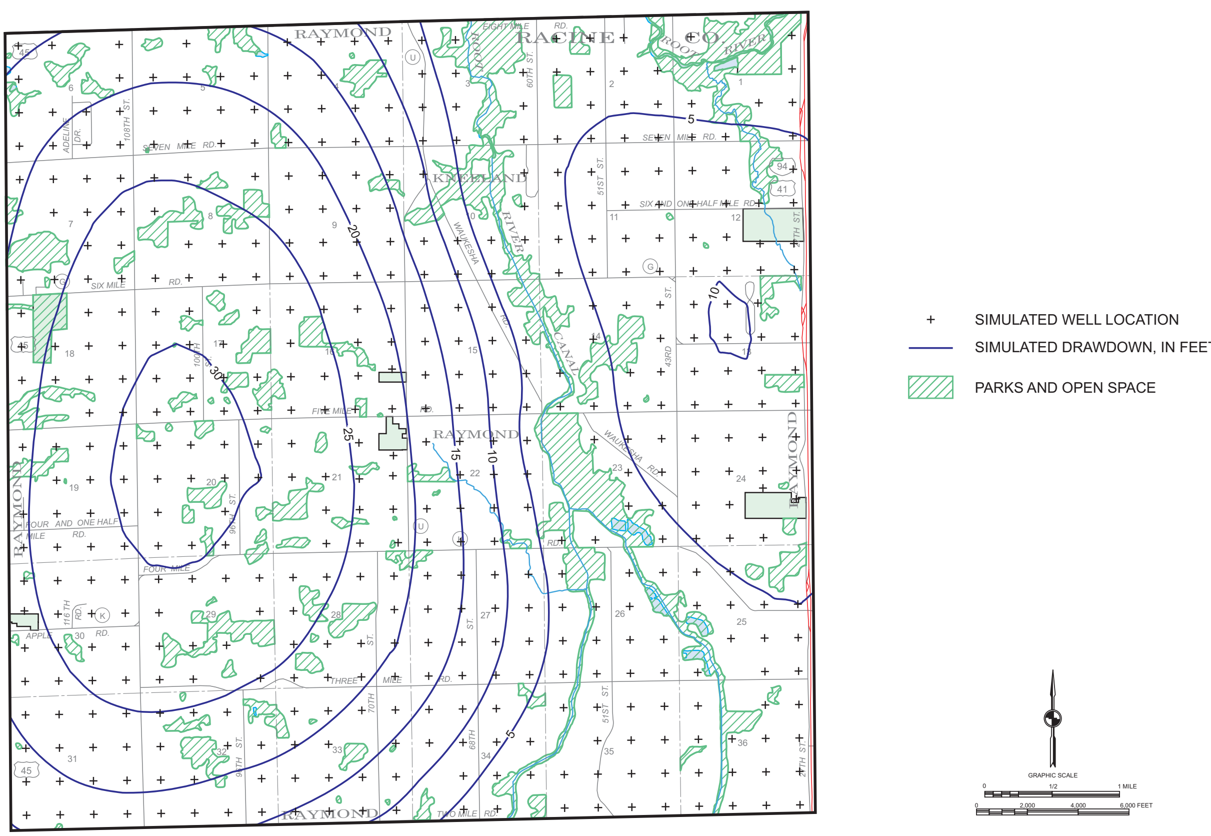

Figure F2. Raymond demonstration area simulated drawdown, 1 acre lots, no return flow.

Appendix G: Wheatland Demonstration Area

The Wheatland demonstration area, which consists of all of the Town of Wheatland and Sections 1 through 12 of U.S. Public Land Survey system Township 1 North, Range 19 East and Sections 25 through 36 of Township 2 North, Range 19 East, is located in western Kenosha County, within the Fox River drainage basin. The Town is primarily rural, and currently contains no municipal wells. Primary surface-water features in the Town include the Fox River, flowing from north to south through the eastern third of the Town, and Munster and Palmer Creeks, which flow into the Fox River from the west. Local geology consists of sand and gravel over dolomite bedrock of Silurian age. Depth to bedrock ranges from 50 to 200 feet, and depth to the water table ranges from 0 to 50 feet. Based on water-balance recharge modeling and model calibration, the best-fit groundwater model used a uniform hydraulic conductivity of 14.2 ft/day and recharge rate of 7.9 in/yr.

Simulated water-table contours show that local groundwater flows generally east and west across the county to discharge into the Fox River, which is the primary hydraulic control in the Township (fig G1). Major areas of planned open space correspond mostly to wetlands and riparian areas along the surface water features (fig G2). Due to the locations of the planned open space, potential future groundwater development might occur mostly in the south-central and northwest parts of the Town. Maximum potential water-table decline based on no return of wastewater flows is slightly more than 2 feet in these areas (fig G2).

Table G1. Simulated hydrologic impacts for the Wheatland demonstration area

	Boundary flux		Drawdown in feet			New Munster Creek		Palmer Creek	
Run	cfs	% change	center	SW	NE	cfs	% change	cfs	% change
Baseline - no wells	0.6	0.0	0.0	0.0	0.0	3.7	0.0	2.5	0.0
5 acre lots	0.7	18.5	0.2	0.2	0.1	3.5	-4.1	2.5	-1.7
3 acre lots	0.7	31.1	0.3	0.4	0.1	3.4	-6.8	2.4	-2.9
1 acre lots	1.1	95.1	1.0	1.0	0.5	2.9	-20.2	2.3	-8.6
5 acre lots w/return	0.6	1.8	0.0	0.1	0.0	3.7	-0.4	2.5	-0.2
3 acre lots w/return	0.6	3.0	0.0	0.1	0.0	3.7	-0.7	2.5	-0.3
1 acre lots w/return	0.6	9.1	0.1	0.1	0.0	3.6	-2.0	2.5	-0.9

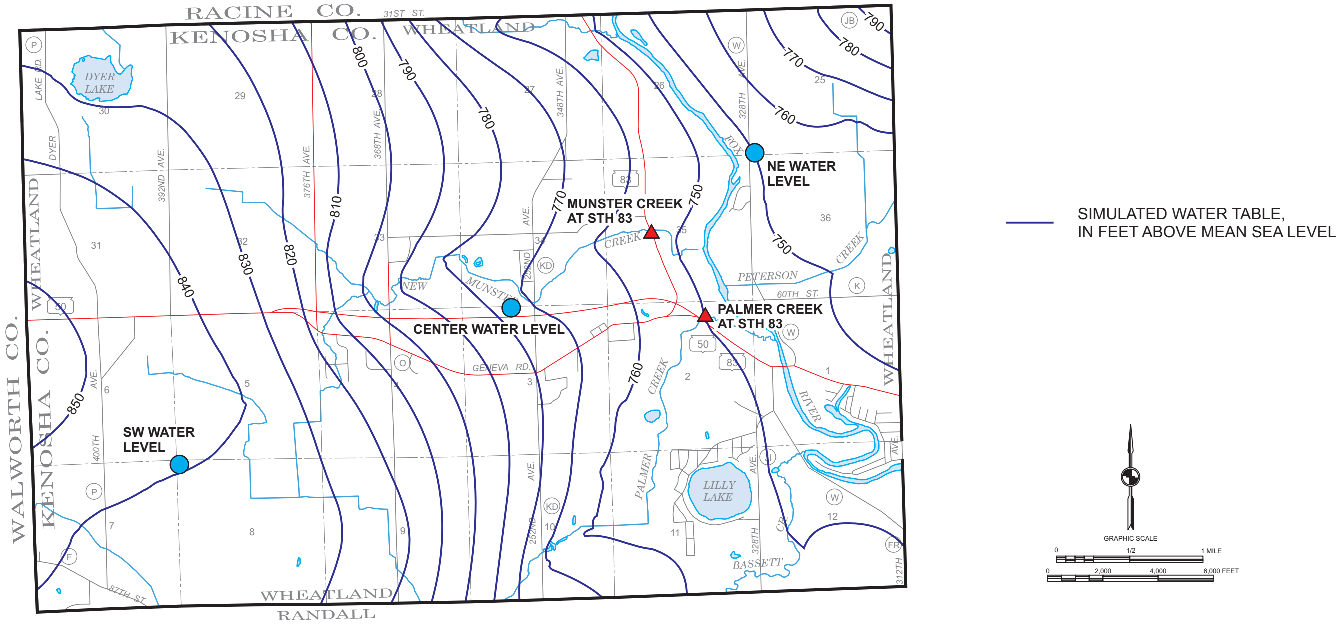

Figure G1. Wheatland demonstration area, showing simulated water table and locations of water-level and streamflow test points.

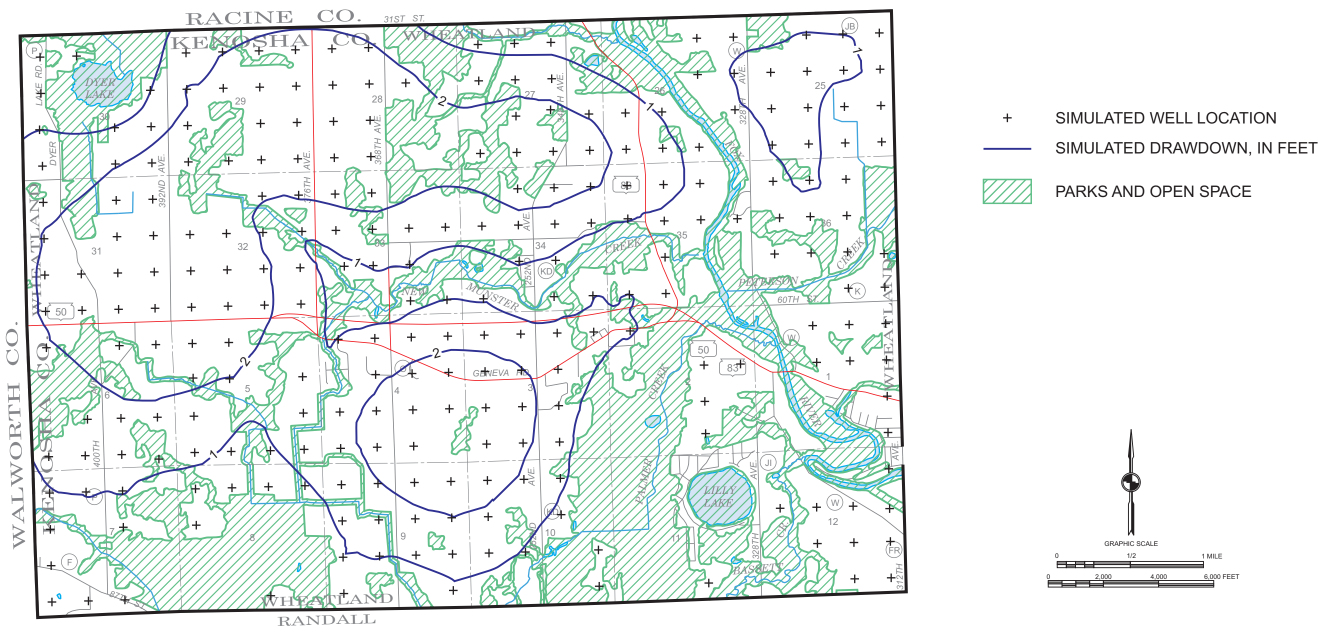

Figure G2. Wheatland demonstration area, simulated drawdown, 1 acre lots, no return flow.