Zones of Contribution for Municipal Wells in Dane County, Wisconsin

Results of Delineations from the 1997 Regional Hydrologic Modeling and Management Program

by

Kenneth R. Bradbury

Wisconsin Geological and Natural History Survey — University of Wisconsin–Extension

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INTRODUCTION

Background

This report describes the delineation of zones of contribution (ZOCs) for municipal wells in Dane County, Wisconsin, carried out in 1997 as part of the continuing Dane County Regional Hydrologic Modeling and Management Program. This report represents an update of earlier ZOC delineations by Bradbury et al. (1996), and follows methodologies described in that earlier report.

The zone of contribution (ZOC) of a well is the land surface area over which recharging precipitation enters a groundwater system and eventually flows to the well (Fig. 1). The ZOC is distinctly different from the zone of influence (ZOI) of a well, which is the area within the cone of depression created by the withdrawal of water from the well.

Delineating ZOCs for municipal wells is a critical step in establishing wellhead protection areas for the wells. A wellhead protection area (WHPA) is defined by the federal Safe Drinking Water Act as the "surface and subsurface area surrounding a water well or well field, supplying a public water system, through which contaminants are reasonably likely to move toward and reach such water or well field." In practical terms, the ZOC is a technically defined area based on groundwater hydraulics, while the WHPA is a legally defined area including all or part of the ZOC and within which zoning practices or other land-use controls can be implemented to help protect groundwater from contamination.

The Wisconsin Department of Natural Resources (WDNR) has the responsibility and authority to delineate wellhead protection areas for all public water supplies in Wisconsin. In 1992, the WDNR prepared the Wisconsin Wellhead Protection Program Plan (WDNR, 1992), which required the DNR to perform initial ZOC delineations for all existing municipal wells in the state. At the same time, the Wisconsin Administrative Code, Chapter NR 811, was revised to require that a wellhead protection program plan be submitted for each new municipal well constructed in Wisconsin after April 1, 1992.

The technical methodologies for ZOC delineation range from simple to complex, and are described in a number of publications such as Born et al. (1988), Bradbury et al. (1991), Kreitler and Senger (1991), Muldoon and Peyton (1993), and USEPA (1987), among others. Most of these authors suggest simple techniques, such as the fixed-radius methods, as a first approach, but most also recommend the use of numerical groundwater flow models as more sophisticated and reliable methods for ZOC delineation.

In 1995, the Wisconsin Geological and Natural History Survey (WGNHS) and U. S. Geological Survey (USGS) jointly developed a three-dimensional groundwater flow model for Dane County, Wisconsin (Krohelski et al, in press) as part of a countrywide groundwater study (the Dane County Regional Hydrologic Study) administered by the Dane County Regional Planning Commission (RPC). This model is based on an updated hydrogeologic database and newly completed water table and potentiometric maps for Dane County. The model directly simulates pumping from all high-capacity wells in the county, including all municipal wells. The Dane

County groundwater flow model, combined with a particle-tracking code (described below) is ideally suited for delineating ZOCs for high-capacity wells in Dane County.

Differences Between the 1996 and 1997 Delineations

Bradbury et al. (1996) delineated zones of contribution based on 1991 conditions and pumping rates in Dane County. The 1997 delineations reported here differ from the 1996 delineations in several ways, as follows:

- The 1997 delineations include additional wells proposed by each community in Dane County based on year 2020 planning scenarios.
- The 1997 delineations use travel-time criteria of 5, 50, and 100 years; the 1996 delineations used 5, 10, and 100 years.
- The 1997 delineations use two different pumping rates: expected rates based on year 2020 conditions and "maximum sustained" pumping rates, based on one-half the design capacity of each well. The 1996 delineations used current pumping rates from 1995.

The 1997 delineations are thought to be more relevant for wellhead protection planning than the 1996 delineations because they account for future new wells and projected pumping rates.

Objectives

The overall objective of 1997 modeling program was to use the Dane County regional ground-water flow model to delineate the 5-, 10-, and 100-year zones of contribution for all municipal high-capacity wells in Dane County, Wisconsin. The resulting information can be used in the development of wellhead protection plans for these wells.

Acknowledgements

This project has been a cooperative effort of the Wisconsin Geological and Natural History Survey, the U.S. Geological Survey, and the Dane County Regional Planning Commission. David Saad and Jim Krohelski of the USGS carried out modeling runs for the project. Mike Czechanski and Cristin Harris assisted with plotting and digitizing the zones of contribution. The Dane County Regional Planning Commission has provided long-term support for the development of the Dane County groundwater flow model, and has developed the Regional Hydrologic Modeling and Management Program to continue model support and development. Communities in Dane County participating in this program include:

Dane County
Madison Metropolitan Sewerage District
City of Madison
City of Fitchburg
City of Middleton
City of Sun Prairie
City of Verona
Village of Belleville
Village of Blue Mounds
Village of Cottage Grove
Village of DeForest
Village of McFarland
Village of Waunakee
Town of Westport
Town of Windsor

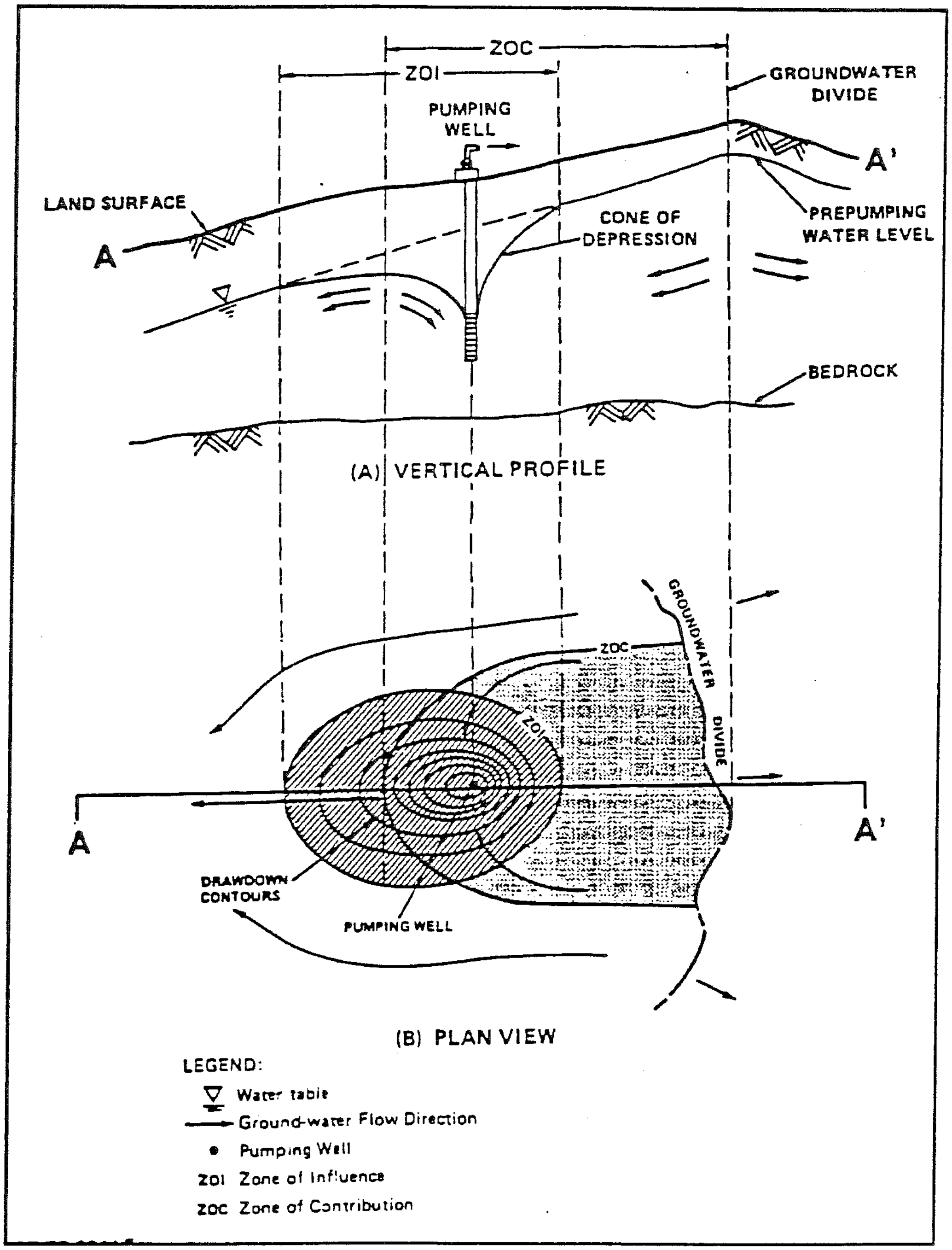


Fig. 20 Diagram and terminology for wellhead protection in a simple hypothetical groundwater flow system (from USEPA, 1987).

METHODOLOGY

Regional Groundwater Model

The Dane County regional groundwater flow model is described in detail by Krohelski and Bradbury (in press). The model uses the U.S. Geological Survey modular groundwater modeling code, commonly known as MODFLOW (McDonald & Harbaugh, 1988), one of the most commonly used groundwater modeling codes in the United States. The ZOCs were determined using the particle-tracking code PATH3D (Zheng, 1991), which uses input and output files created by MODFLOW.

The regional model, as currently implemented, simulates three-dimensional, steady-state groundwater movement through the entire groundwater system in Dane County. The model domain is discretized into a finite-difference grid consisting of rows, columns, and layers, and extends to natural hydrologic boundaries outside the political boundaries of Dane County itself. The model grid contains 200 rows and 240 columns, with a uniform grid spacing of 400 m, or about 0.25 mi. Recharge to the model occurs at the water table and is non-uniform. Swanson (1996) describes the creation of the model recharge array. The model simulates vertical groundwater flow to or from lakes and streams using the MODFLOW river package. The groundwater flow model was calibrated to existing steady-state hydraulic heads and streamflows as measured in the early 1990s. Krohelski and Bradbury (in press) describe the calibration procedure.

The three layers of the regional groundwater flow model represent four hydrostratigraphic units. From the top layer down, the hydrostratigraphic units are: unlithified surficial material (layer 1); Paleozoic carbonates, shales, and sandstones (layer 2); the shaley facies of the Eau Claire Formation (simulated as a semiconfining bed between model layers 2 and 3); and the Mt. Simon sandstone (layer 3). The Mt. Simon sandstone is the primary aquifer unit for most of the high-capacity wells in Dane County. The regional model includes a multi-aquifer well (MAW) package, which allows the simulated wells to draw water from more than one model layer in proportion to the transmissivity of the layers. The MAW package partitions the total well discharge between the model layers open to the well based on the transmissivity and head in the layers. Wells that were open predominantly to one hydrostratigraphic unit were assigned to the model layer representing that unit. Wells open to significant portions of more than one unit were assigned input values corresponding to the multiple layers.

Well Locations and Pumping Rates

The regional groundwater flow model includes both the active and planned municipal wells known to the RPC at the time the database was updated in 1997. Appendix A lists these wells. The model also contains seven high-capacity, non-municipal wells because these wells were expected to have a noticeable impact on model calibration. All of the locations of the active municipal wells were field checked and plotted on U.S. Geological Survey topographic maps, 7.5 minute series. The locations of the wells were then digitized using a Geographic Information

System (GIS) in order to facilitate more precise estimation of their geographic coordinates (latitude/longitude) and Dane County UTM coordinates.

Runs of the MODFLOW model were conducted using two different sets of pumping rates for the municipal wells. Results (files of hydraulic head distributions and cell-by-cell flow rates) were saved to use as input to the particle tracking runs described below. One run (the 2020 run) used the projected pumping rates for the year 2020 (Appendix A), thought to be most representative of future conditions. A second run (the "maximum sustained pumping rate" or "one-half design capacity" run) used pumping rates at one-half the engineered capacity of each well. In most cases, the maximum sustained pumping rate is greater than the projected actual 2020 pumping rate (Appendix A).

The difference between the two modeled pumping rates is related to the actual operation of the wells. Municipal wells are designed to yield water at a specific rate (for example, 1000 gallons per minute), and this rate is constant as long as the well is pumped. However, few, if any, municipal wells in Dane County are pumped continually. Instead, most wells operate for only a few hours each day. In a steady-state model, this discontinuous pumping rate is averaged over an entire day to give an actual pumping rate which is less than the design capacity of the well, and typically even less than half of the design capacity. The half-capacity model run was designed to simulate larger but realistic pumping rates.

Delineation of the Zones of Contribution (ZOCs)

The particle tracking code PATH3D (Zheng, 1991) was used to model the ultimate zone of contribution for each pumping well by tracking imaginary particles backwards from the well location upgradient to points where they enter the groundwater flow system (Fig. 2). The possible points of entry represented in the regional groundwater flow model are the water table (i.e., recharge from the ground surface through the unsaturated zone) and surface water bodies, such as rivers and lakes. The velocity of the particles depends on the gradient in head, the hydraulic conductivity, and the porosity of the aquifer materials. Hydraulic conductivity values were input into the MODFLOW model along with other input parameters. The MODFLOW model then produced a distribution of head values for each layer of the model. PATH3D uses the head distribution, grid spacing and porosity values to calculate particle velocity vectors (velocity and direction of movement).

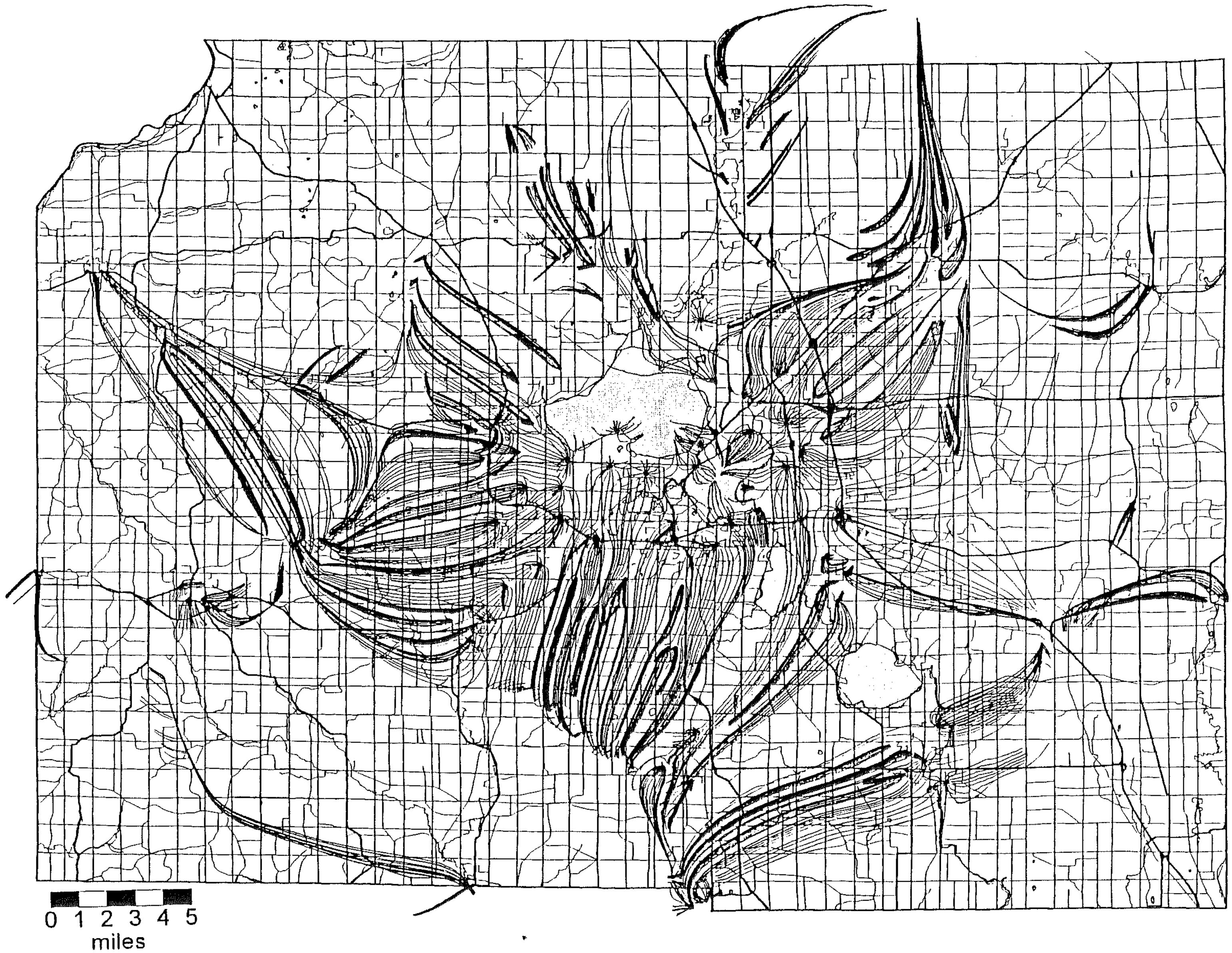
To initiate particle tracking, particles were entered in rings at the top and bottom of the open interval of each well, thus bracketing the actual zone where water could enter the well. The PATH3D code tracked the particles as they were moved upgradient away from the well. The particle front positions at 5, 10, and 100 years were written to an output file and then processed to produce coordinates that could be plotted on a digital basemap using the Dane County UTM coordinate system. The entire paths of all particles from the well to the points of entry into the groundwater system were recorded in a separate output file.

Creation of Maps Showing ZOCs

This report summarizes the results of the ZOC delineations. Figure 2 is a map of the entire county, showing all well locations and the steady-state particle traces for each well. This figure is useful for gaining an overall sense of groundwater movement to municipal wells in Dane County.

The final graphical output showing the ZOC delineations was created by digitizing the areas outlined by each set of particle paths and storing the resulting polygons in ArcInfo geographic information system (GIS) coverages. Line files of county and municipal boundaries, section lines, roads, and surface water bodies were overlaid to create a base map for plotting the municipal well locations and ZOCs. The ZOCs are displayed by creating polygons representing each of the three plotted particle front positions (5, 10, and 100 years). Each of the three polygons is given a different fill pattern to distinguish the limits of the three zones. In many cases the particle fronts were different for the upper and lower sets of particles. The upper particles generally encounter the water table fairly rapidly, whereas the lower particles may travel great distances in the deep sandstone aquifer before they reach the surface. The gradients in the water table and deep sandstone aquifers may also be different so that the upper particles move in a different direction than the lower particles. In cases where the horizontal positions of the upper and lower particles were not coincident, the time-front positions farthest from the well were selected for the boundaries of the time-front polygon, resulting in the most conservative estimate for the zone of contribution.

Fig. 2
Ultimate Zones of Contribution for Municipalities in Dane County, WI.



RESULTS

Zones of Contribution

The composite map of particle traces for all municipal wells in Dane County (Fig. 2) illustrates the complexity of the groundwater flow systems in the county and also demonstrates that the source of groundwater for local wells originates relatively near the well locations. Each traceline on Figure 2 represents the three-dimensional path of a single hypothetical "particle" of water from the water table to a particular well. The collection of particle pathlines for each well outlines the ultimate ZOC for that well. In Figure 2, these three-dimensional traces are projected onto a two-dimensional map, resulting in some apparent angular refractions of the particle tracks where the particles are moving vertically from one model layer to the next. All traces on Figure 2 are *steady-state* particle paths, meaning that these are the paths that groundwater would take assuming that the groundwater system is steady (i.e., recharge is constant, pumping rates and water levels are unchanging) for an infinitely long period of time. Therefore, the length of a particular pathline is not necessarily related to the velocity of the particle, although in general the longer paths are associated with longer travel times. Steady-state travel times for many wells from recharge to entry into the well are on the order of several thousand years.

Maps of the ZOCs for each individual well in Dane County were developed which provide more detail and also constrain the ultimate ZOC to 5-, 10-, and 100-year flow boundaries (Figs. 3 and 4). Participating Dane County communities received local maps plotted at a scale of 1:24,000. Such boundaries should be more useful for WHPA delineation in real human terms. Various pumping rates and travel times were modeled as the basis for delineating ZOCs, offering each community a range of protection alternatives. Alternative ZOCs are based on 5-, 50- and 100-year travel times for each of two different pumping rates:

1. 2020 Pumping (Fig. 3)—projected 2020 average daily water use distributed evenly among existing and future wells for each community;

2. Maximum Sustained Pumping (Fig. 4)—50% of the pumping capacity for both existing and proposed new wells.

For each of these wells, the ZOC is best viewed in a three-dimensional sense as an ellipse with a cross-section represented by the shaded area of the ZOC and extending from the water table to the bottom of the deep sandstone aquifer. It is interesting to note that many of the time-constrained ZOCs are rather small, and that even the travel paths for the 100-year flow boundaries are only on the order of one or two miles long.

Comparison of Figures 3 and 4 shows the effect of pumping rate on the size of the ZOCs. The effect is slightly different for each well, but in general the maximum sustained pumping rate produces a zone of contribution about 10 to 30 percent larger than the 2020 pumping rate.

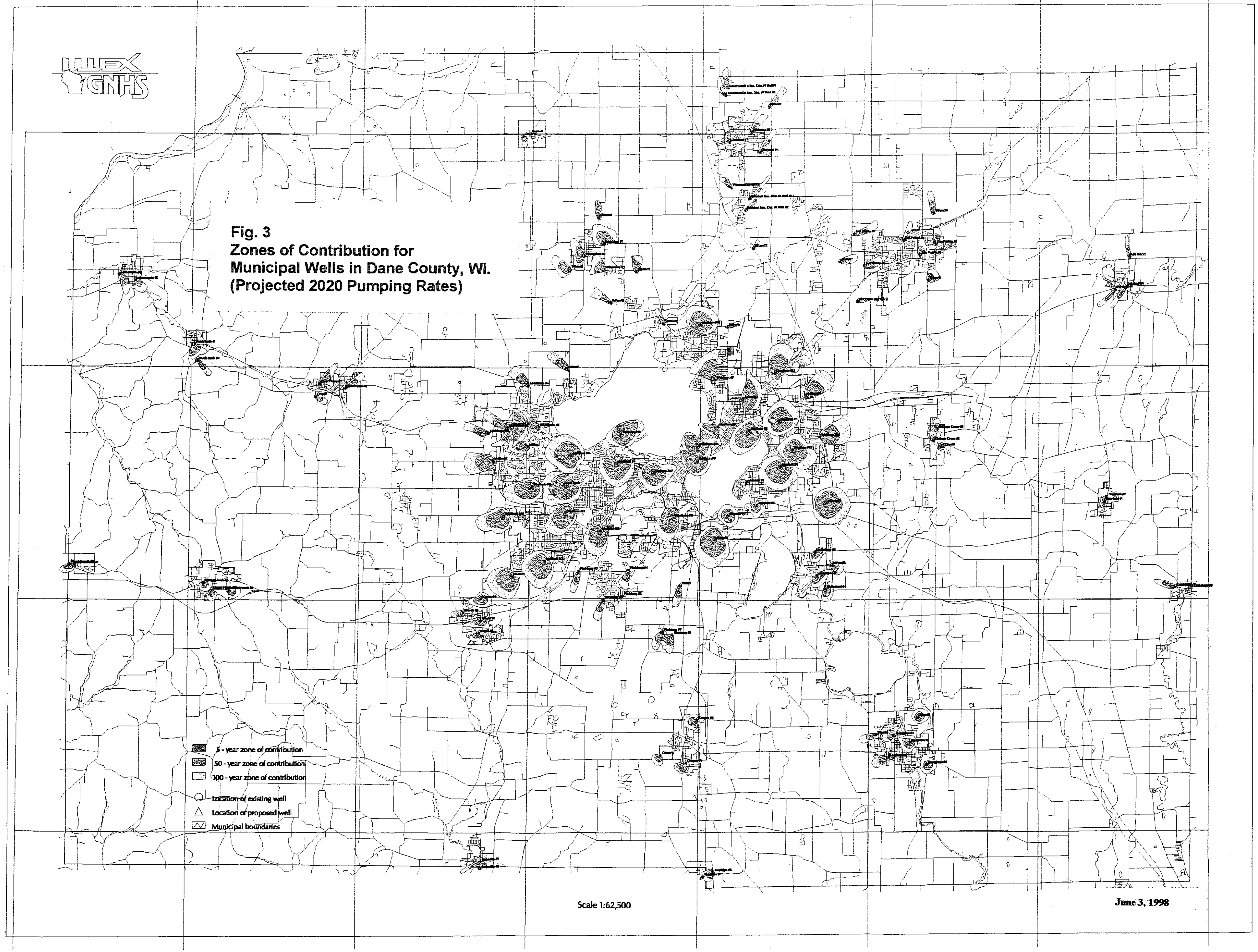


Fig. 3
Zones of Contribution for Municipal Wells in Dane County, WI.
(Projected 2020 Pumping Rates)

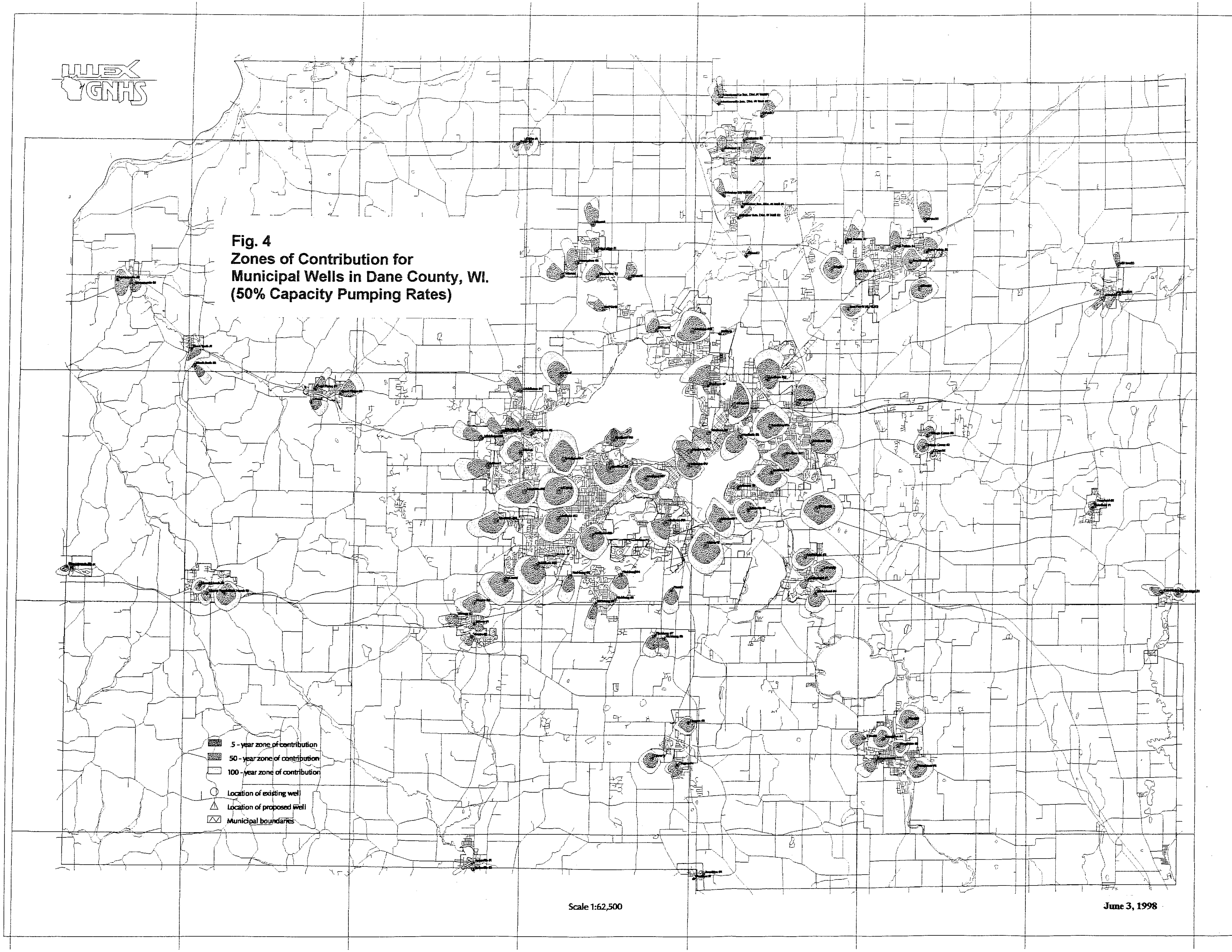


Fig. 4
Zones of Contribution for Municipal Wells in Dane County, WI.
(50% Capacity Pumping Rates)

Accuracy of the ZOC Delineations

The accuracy of the locations of the ZOCs depends on the accuracy of the groundwater flow model and of the field data and data interpretations used to construct it. The MODFLOW and PATH3D codes themselves are mathematically very precise, and numerical errors associated with these codes are probably insignificant. However, the calibration of the groundwater flow model (the "fit" of the model to observed field data) is not perfect, although it is considered good from a groundwater modeling standpoint (Krohelski et al., in press). In general, the model results are probably most precise in areas where hydrogeologic data are abundant, such as in the Madison metropolitan area. The model is less accurate in areas where hydrogeologic data are sparse, such as in western Dane County, where very few deep water wells exist. Also, the precision of the ZOC delineations decreases with increasing travel time. Therefore, the time-constrained ZOCs shown in Figures 3 and 4 are much more precise than are the long tails of the particle paths shown in Figure 2.

All ZOCs shown in this report assume steady-state conditions, meaning that groundwater levels and recharge rates do not change with time. In areas where this assumption is not met the ZOCs may differ slightly from those shown in the report.

In two municipalities, the Village of Brooklyn and City of Verona, the potential for error in the ZOC delineations is larger than in other areas. In both these municipalities the wells are located on or very near the regional potentiometric divide between the Yahara River basin and the Sugar River basin. At these locations, the position of the divide is critical in controlling the direction of groundwater flow and thus the configuration of the zones of contribution. Field data in these areas are too sparse to allow a precise delineation of the position of the divide or to confirm the groundwater flow model. Therefore, the ZOCs for wells in these municipalities, while consistent with the groundwater flow model, are currently unconfirmed by field data, and should be used with caution.

Other Significant Findings

In addition to delineating ZOCs for municipal wells, this project has emphasized several facts about groundwater flow in Dane County which should be of interest to local water managers and county residents. The overall picture provided by Figures 2, 3 and 4 illustrates the following points:

- The source for groundwater produced by municipal wells in Dane County is local, and for almost every well the ultimate zone of contribution lies entirely within the county itself.
- Much of the recharge for the City of Madison wells (the largest municipality in Dane County) originates within or very near the Madison city limits.
- Wells located near the Yahara Lakes may be deriving significant quantities of water from downward leakage from the lakes themselves. Any particle path on Figure 2 which

terminates in a lake or wetland indicates that lake is supplying some water to the well. Madison well 19 (Picnic Point) is an example.

- There is significant interference between wells, particularly in the Madison metropolitan area, that results in complex ZOCs. Simpler ZOC delineation methods, such as the fixed-radius techniques or even simple two-dimensional numerical models would fail to capture these interference effects and so would probably give inaccurate ZOC estimates.

- There is frequently a difference in groundwater flow direction between the shallow water table aquifer and the deeper sandstone aquifer, as illustrated by wells having sets of particles radiating in two different directions (Waunakee wells 1, 2, and 3 are examples). These wells are usually open to both the shallow Paleozoic dolomites and sandstones (model layer 2) and deeper Mt. Simon sandstone (model layer 3), and produce water from both units.

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Appendix A
Municipal Wells in Dane County and Associated Pumping Rates

Municipality	Pump Capacity (gpm)	1995 Reported Avg. Daily Pumping Rate (mgd)	2020 Projected Avg. Daily Water Use (mgd)	Max. Sustained Pumping Rate (1/2 pump cap., mgd)
Belleville #1	350	.079	.125	.252
Belleville #2	500	.107	.125	.360
Black Earth #1	500	.025	.065	.360
Black Earth #2	500	.087	.065	.360
Blooming Grove SD #8	—	.070	—[1]	—
Blue Mounds #1	350	.031	.023	.252
Blue Mounds #2	40	0	.024	.029
Brooklyn #1	270	.019	.040	.195
Brooklyn #2	470	.034	.040	.339
Burke #1 (nw22)	750	.027	.012	.540
Burke nw19	250	planned well	.013	.180
Cambridge #2	400	.147	.080	.288
Cambridge #3	450	0	.080	.324
Cottage Grove #1	150	.032	.113	.108
Cottage Grove #2	320	.057	.113	.230
Cottage Grove #3 (nw32)	750	.152	.113	.540
Cross Plains #1	425	.104	.133	.306
Cross Plains #2	650	.179	.133	.468
Cross Plains nw2	650	planned well	.133	.468
Dane #1	200	.023	.033	.144
Dane #2	300	.030	.033	.216
Deerfield #1	330	.162	.120	.237
Deerfield #2	525	.009	.120	.378
DeForest #2	350	.097	.270	.252
DeForest #3	850	.206	.270	.612
DeForest #4	1,200	.317	.270	.864
DeForest nw17	1,200	planned well	.270	.864
Fitchburg #2	500	0	.328	.360
Fitchburg #4	1,200	.614	.327	.864
Fitchburg #5	1,250	.726	.328	.900
Fitchburg #7	1,200[2]	.010	.327	.864
Fitchburg #8	1,200[2]	.011	.328	.864
Fitchburg #9	850	.337	.327	.612
Fitchburg nw15	1,200	planned well	.327	.864
Madison #3	1,847	.266	1.298	1.330
Madison #5	1,300	1.191	—	—

[1] Projected 0.08 mgd, annexed by City of Madison in 1995; well to be abandoned as a potable water source.
[2] New well (1,200 gpm) to replace #7 (350 gpm) or #8 (250 gpm), whichever fails first.

Appendix A
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Municipality	Pump Capacity (gpm)	1995 Reported Avg. Daily Pumping Rate (mgd)	2020 Projected Avg. Daily Water Use (mgd)	Max. Sustained Pumping Rate (1/2 pump cap., mgd)
Madison #6	2,575	.157	1.298	1.854
Madison #7	2,076	1.450	1.298	1.494
Madison #8	1,653	.559	1.298	1.190
Madison #9	1,400	.802	1.298	1.008
Madison #10	2,100	1.584	1.298	1.512
Madison #11	2,100	1.994	1.298	1.512
Madison #12	2,100	.161	1.298	1.512
Madison #13	2,100	2.088	1.298	1.512
Madison #14	2,100	2.525	1.298	1.512
Madison #15	2,100	2.771	1.298	1.512
Madison #16	2,100	.419	1.298	1.512
Madison #17	2,100	1.940	1.298	1.512
Madison #18	2,100	2.066	1.298	1.512
Madison #19	2,100	1.917	1.298	1.512
Madison #20	2,100	1.369	1.298	1.512
Madison #23	2,100	.197	1.298	1.512
Madison #24	2,100	1.058	1.298	1.512
Madison #25	2,100	2.593	1.298	1.512
Madison #26	2,100	2.769	1.298	1.512
Madison #27	2,100	1.914	1.298	1.512
Madison nw3	2,100	planned well	1.298	1.512
Madison nw4	2,100	planned well	1.298	1.512
Madison nw6	2,100	planned well	1.298	1.512
Madison nw18	2,100	planned well	1.298	1.512
Madison nw21	2,100	planned well	1.298	1.512
Madison nw24	2,100	planned well	1.298	1.512
Madison nw25	2,100	planned well	1.298	1.512
Marshall #1	343	.124	.117	.247
Marshall #2	500	.115	.117	.360
Marshall nw33	500	planned well	.117	.360
Mazomanie #2	500	0	.075	.360
Mazomanie #3	600	.136	.075	.432
McFarland #1	600	.189	.280	.432
McFarland #3	1,020	.146	.280	.734
McFarland #4	1,150	.391	.280	.828
McFarland nw26	1,100	planned well	.280	.792
Middleton #2	350	.104	.404	.252
Middleton #3	1,060	.312	.404	.763
Middleton #4	1,200	.440	.404	.864
Middleton #5	1,325	.518	.404	.954
Middleton #6	1,550	.751	.404	1.116
Middleton nw5	1,200	planned well	.404	.864
Middleton nw7	1,200	planned well	.404	.864
Monona #1	800	.356	.400	.576

Appendix A
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Municipality	Pump Capacity (gpm)	1995 Reported Avg. Daily Pumping Rate (mgd)	2020 Projected Avg. Daily Water Use (mgd)	Max. Sustained Pumping Rate (1/2 pump cap., mgd)
Monona #2	1,400	.404	.400	1.008
Monona #3	1,200	.491	.400	.864
Morrisonville #1	350	.027	.140	.252
Morrisonville #2	500	0	.140	.360
Mt. Horeb #3	450	.160	.165	.324
Mt. Horeb #4	500	.160	.165	.360
Mt. Horeb #5	750	.157	.165	.540
Mt. Horeb nw1	1,000	planned well	.165	.720
Oregon #2	—	.015	—	—
Oregon #3	900	.006	.300	.648
Oregon #4	850	.583	.300	.612
Oregon nw13	850	planned well	.300	.612
Stoughton #3	525	.149	.310	.378
Stoughton #4	1,140	.450	.310	.821
Stoughton #5	1,025	.298	.310	.738
Stoughton #6	1,010	.522	.310	.727
Stoughton nw28	1,100	planned well	.310	.792
Stoughton nw29	1,100	planned well	.310	.792
Sun Prairie #3	1,200	.460	.356	.864
Sun Prairie #4	1,200	.753	.355	.864
Sun Prairie #5	1,200	.182	.356	.864
Sun Prairie #6	1,200	.801	.355	.864
Sun Prairie #7	1,400	.152	.356	1.008
Sun Prairie nw23	1,200	planned well	.355	.864
Sun Prairie nw27	1,200	planned well	.356	.864
Sun Prairie nw30	1,200	planned well	.355	.864
Sun Prairie nw31	1,200	planned well	.356	.864
Verona #1	500	.114	.323	.360
Verona #2	1,000	0	.322	.720
Verona #3	950	.348	.323	.684
Verona #4	1,500	.318	.322	1.080
Waunakee #1	600	0	.327	.432
Waunakee #2	1,000	.600	.327	.720
Waunakee #3	1,000	.652	.327	.720
Waunakee nw8	1,000	planned well	.327	.720
Waunakee nw9	1,000	planned well	.327	.720
Waunakee nw11	1,000	planned well	.327	.720
Westport #1 (nw10)	500	.012	.150	.360
Westport nw12	700	planned well	.150	.504
Windsor #1	500	.100	.100	.360
Windsor #2	500	.101	.100	.360
Windsor nw16	1,000	planned well	.100	.720