Wisconsin Geological
and Natural History Survey
DIVISION OF EXTENSION
UNIVERSITY OF WISCONSIN–MADISON

Applications of the Columbia County, Wisconsin, groundwater-flow model

Companion to
Hydrogeology and simulation of groundwater flow in Columbia County, Wisconsin
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Introduction

In 2008, the Columbia County Wisconsin Departments of Health, Land and Water Conservation, and Land Information, and University of Wisconsin-Extension initiated a project with the Wisconsin Geological and Natural History Survey and the U.S. Geological Survey, to assess Columbia County's groundwater resources. This project was completed with funding from the Columbia County Board of Supervisors and the Wisconsin Department of Natural Resources Bureau of Drinking Water and Groundwater.

The county-wide groundwater assessment included compilations of existing information, additional monitoring and data collection, and the development of a computer model that simulates the regional groundwater flow system. The project resulted in a series of publications that provide technical and educational resources for managing the county's groundwater (Gotkowitz and Mauel, 2012; Gotkowitz and others, 2012; Schoephoester and Gotkowitz, 2012; Sellwood, 2012). Gotkowitz and others (2021) provide a comprehensive description of the hydrogeology and document the development and calibration of the computer model.

The regional model simulates three-dimensional, steady-state groundwater conditions across Columbia County. The hydrostratigraphy represented in the model was developed through analysis of water well records, aquifer tests, borehole geophysical logs, and correlations with conceptual and numerical models constructed for neighboring Dane (Parsen and others, 2016) and Sauk Counties (Gotkowitz and others, 2005). The model simulates pumping from high-capacity wells used for irrigation, industrial, and municipal water supply. Model results provide quantitative analysis of flow to wells and discharge of groundwater to surface water features.

One of the first uses of the Columbia County groundwater flow model was to simulate capture zones, or zones of contribution (ZOCs), for wells. A ZOC is that part of the land surface over which recharging precipitation enters a groundwater system and eventually flows to a well. Model-simulated ZOCs provide a scientific basis for identifying wellhead protection areas and assessing potential contaminant sources to a well. The model can also be used to quantify the effects of current and proposed groundwater withdrawals, assess groundwater flow patterns near land used for spreading industrial and agricultural waste, and assess connections between groundwater and surface water features.

Since its initial development in 2014, the Columbia County groundwater flow model has been used to respond to requests for information about specific groundwater and land use issues of interest to local officials, residents, and the business and agricultural communities. This report compiles results from several applications of the model and demonstrates how it can be used to support management of groundwater resources.

Methods

This section summarizes methods used to construct the groundwater flow model and methods used in applying the model to several land use and well-head protection issues. Gotkowitz and others (2021) provide detailed discussion about the hydrogeologic framework and model development and calibration.

Groundwater-flow model

The Columbia County regional groundwater flow model was developed using the U.S. Geological Survey's MODFLOW-NWT code (Niswonger and others, 2011). The flow model simulates spatially variable average annual groundwater recharge using results of a soil-water balance model (Westenbroek and others, 2010). The MODFLOW model consists of six layers with a uniform grid of 815 rows by 995 columns of 300 ft by 300 ft cells. The model layers vary in thickness across the model domain because they represent the spatial variability in the geologic formations, as described below. The model domain extends into neighboring counties, but the focus area of Columbia County is represented in greater detail. The model simulates groundwater-surface water interactions using the Streamflow Routing (SFR2) package (Niswonger and Prudic, 2005). It implements the unsaturated flow zone (UZF) package (Niswonger and others, 2006) to track "surface leakage," which is recharge to cells where the simulated water table exceeds the land surface (top of model layer 1). Pumping is represented with the multi-node well (MNW2) package (Konikow and others, 2009). This package apportions discharge to the well from each layer intersected by the well, based on the head and transmissivity of each layer.

Hydrogeology and model layers

Six model layers are used to represent the hydrostratigraphy in the county. From the top down, layers 1 and 2 simulate the unlithified aquifer. This aquifer is thin or absent in much of eastern Columbia County but is thick and prolific in major river valleys. Two model layers were used to improve simulation of vertical hydraulic gradients where they are present.

Model layer 3 simulates the upper bedrock aquifer, which generally consists of alternating layers of sandstone, dolomite, and siltstone. Although not present in parts of western and northern portions of the model domain, this aquifer is laterally continuous across the eastern and southern areas of Columbia County. Model layer 3 varies in thickness to simulate this thinning of the upper bedrock to the west and north. A shaly facies at the base of the Tunnel City Group forms an aquitard between the upper bedrock aquifer and the underlying Elk Mound aquifer. Field measurements and observations suggest the upper bedrock aquifer is anisotropic, with higher lateral conductivity compared to vertical hydraulic conductivity. This implies that groundwater flows readily through the formation in horizontal directions but vertical groundwater flow is restricted. Vertical hydraulic conductivity varies laterally within model layer 3, representing this anisotropy and the effects of the aquitard at the base of the Tunnel City.

Layers 4, 5, and 6 represent the Elk Mound aquifer, which extends across the model domain. The aquifer includes sandstone of the Eau Claire Formation. The Eau Claire Formation is referred to as the Eau Claire aquitard in areas where it contains laterally extensive shale layers on the order of 5 to 10 feet in thickness. The aquitard is well-defined south and west of Columbia County, but sandstone dominates the composition of the Eau Claire Formation within Columbia County. Precambrian crystalline rock forms the lower boundary to the groundwater system.

Well locations and pumping rates

The model was calibrated to a large data set that was generally representative of conditions between 1970 and 2010. Over 250 high-capacity wells (those permitted to withdraw more than 100,000 gallons per day (gpd)) were simulated in the calibrated model. Historical pumping rates at each well were averaged to obtain the pumping rates used in calibration.

Applications of the model typically required changes to the pumping rates used in the calibrated model to reflect current conditions. The pumping rates assigned to wells for the ZOC delineations were based on the volume of water pumped during 2011 and 2012, as reported by municipalities to the Wisconsin Department of Natural Resources (personal communication, R. Smail). The annual volume of water pumped from each well was converted to an average daily pumping rate for use in this steady-state model (table 1). Wells that were included in the calibrated model but had subsequently been taken out of routine use were assigned pumping rates of zero in these simulations. Wells were added to the model as needed to complete various scenarios.

Advective particle tracking and zones of contribution

Particle tracking is a technique used with groundwater flow models to mathematically identify the path a particle of groundwater would take along flow lines. This technique was implemented with the MODPATH code (Pollock, 1994) to identify the ZOCs for wells of interest in Columbia County. Particles were started at the top, middle, and bottom of each model layer intersected by the open interval of a well and tracked backwards for travel times of 5 and 50 years. This ensured that each ZOC included multiple flow paths and resulted in delineation of conservatively large areas. Forward particle tracking was performed to verify the results of the backward method. The particle traces were brought into a geographic information system (GIS) software package (ArcGIS) and converted to polygons. In MODFLOW, wells are simulated at the center of each cell regardless of the well's actual location within the cell. The polygon locations were adjusted slightly in ArcGIS to reflect the correct well location.

Although the ZOC is a defined area based on groundwater hydraulics, in some cases the results include a larger area of the land surface than that over which recharging precipitation flows to the well. This occurs because the flow paths, which define an irregularly shaped three-dimensional volume, are projected onto a two-dimensional map. Where wells are constructed with casings set deep below land surface, the recharge area for the well may be physically distant from the well itself (Franke and others, 1998). For the purposes of this report, the ZOCs include the land surface where precipitation infiltrates and eventually flows to the well and the surface projection of the area between these flow paths and the well. This makes the ZOC conservatively larger, and is appropriate to include in developing a well-head protection area.

Table 1. Pumping rates used to simulate zones of contribution at municipal wells.

Community	**Wisconsin Unique Well Number**	**Pumping rate,** gallons per minute
Arlington	FH500	32
Arlington	SO618	22
Arlington, off-line	BF357	NA
Cambria, abandoned	BF358	NA
Cambria, abandoned	BF359	NA
Cambria, reconstructed	RG680	79
Cambria	OU123*/YG115**	40
Columbus	DR434	4
Columbus	BF360	57
Columbus	BF361	57
Columbus	EJ755	184
Fall River	BF362	73
Fall River	BF363	74
Friesland	AW120	12
Friesland	BF364	1
Lodi	OH446	76
Lodi	BF365	61
Lodi	BF366*/NY856**	98
Pardeeville	BF368	49
Pardeeville	BF369	NA
Pardeeville	EP384	58
Portage	EQ935	275
Portage	BF371	152
Portage	BF372	86

Table 1. Pumping rates used to simulate zones of contribution at municipal wells.

Community	Wisconsin Unique Well Number	Pumping rate, gallons per minute
Portage	TQ310	444
Poynette	BF375*/YG586**	128
Poynette	BN481	128
Randolph	NY646	86
Randolph	YI080	44
Rio	BF377*/WK859**	28
Rio	BF376	28
Wyocena	BF381	25
Wyocena	BF382	12
Harmony Grove	BF367	48
Harmony Grove	CC036	48
Wisconsin Dells	BF379	NA
Wisconsin Dells	SO619	75
Wisconsin Dells	BF380	135
Wisconsin Dells	BF378	65
Wisconsin Dells	AC717	95
Wisconsin Dells	BG952	69
Wisconsin Dells	BG953	75

NA not analyzed, well may be abandoned or off-line.
*/** indicates original well (*) and reconstructed well (**)

Effective porosity

Groundwater velocity and travel times are based in part on effective porosity. The effective porosity of sediment or bedrock represents the amount of interconnected pore space; it is a measure of the volume of open space within the aquifer available for groundwater flow. During model development, values of porosity were assigned to model cells to facilitate advective particle tracking simulations. Effective porosity assigned to model layers 1 and 2 (table 2) are based on a map of Quaternary materials (Hooyer and others, 2015). Porosities of 0.05 and 0.15 are assigned to the upper bedrock aquifer (layer 3) and the Elk Mound aquifer (layers 4, 5, and 6), respectively.

Table 2. Effective porosity assigned to unlithified sediment in model layers 1 and 2.

Unlithified material	Porosity
Windblown sand	0.30
Sand and gravel stream sediment	0.25
Silty, sandy stream sediment	0.20
Hillslope sediment, primarily sand	0.20
Till, clayey silt, sand	0.15
Fill	0.15
Peat overlying stream sediment	0.15
Peat overlying lake sediment	0.05
Lake sediment with sand	0.10
Lake sediment with silt and clay	0.05

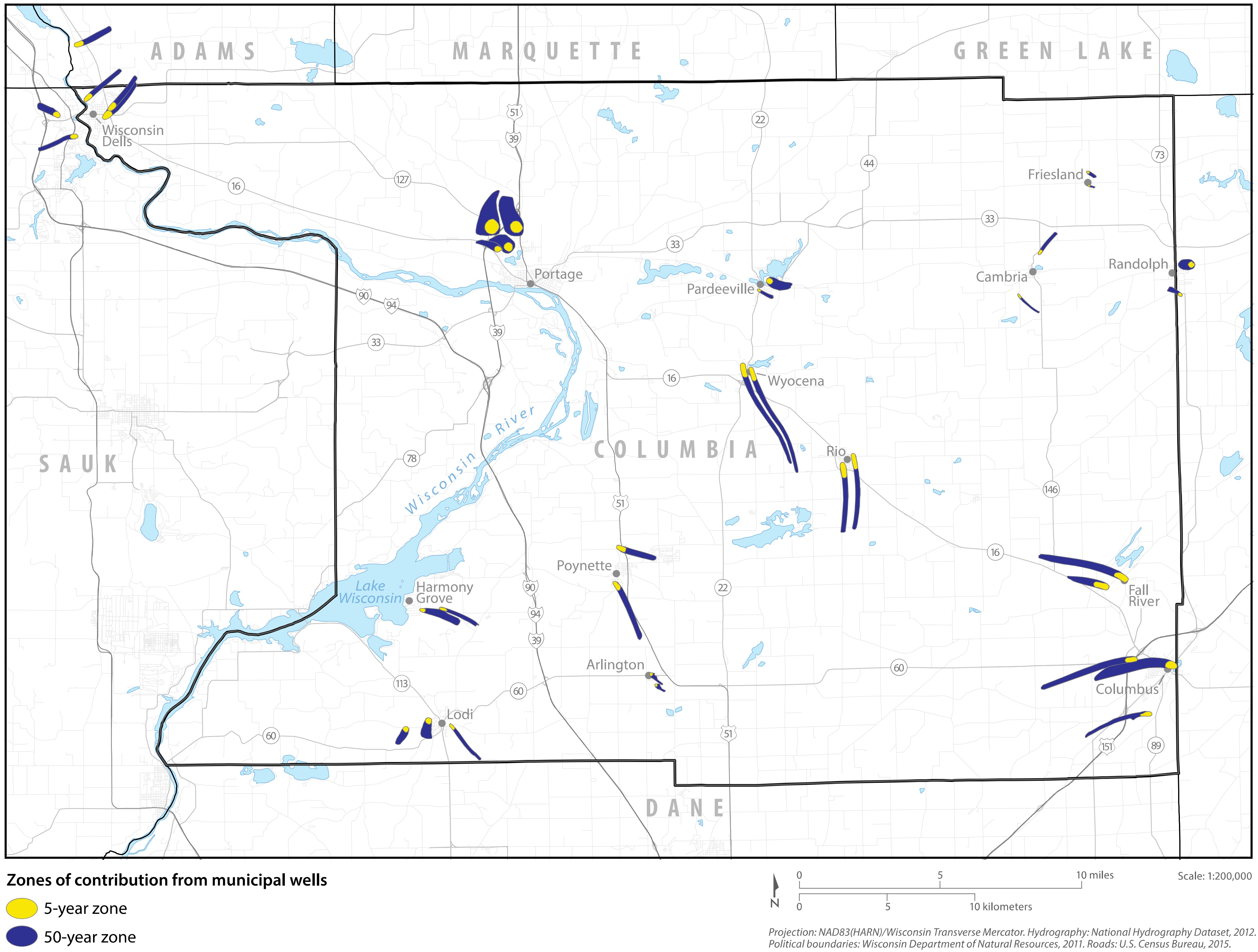
Applications

Zones of contribution for municipal wells

ZOCs developed for municipal wells in Columbia County show the areas over which recharging precipitation reaches the water table and eventually discharges to the well. In these simulations, pumping rates at each well were based on water use at the wells in 2011 and 2012 (table 1). As shown in figure 1, the travel times of 5 and 50 years illustrate that the source of water to these wells generally originates close to the well. ZOCs are of various shapes and lengths, and reflect the magnitude and direction of hydraulic gradients near the well. For example, contributing areas for municipal wells in the Wisconsin Dells illustrate the effect of the Wisconsin River, which is a major regional groundwater discharge feature. Wells located east of the river, in Columbia County, pump groundwater that was recharged to the northeast and flows west, towards the river. Wells located west of the river, in Sauk County, pump groundwater that recharged to the west and flows east, towards the river.

Maps of ZOCs presented at a more refined scale show details that support well-head protection efforts. In figure 2, the contributing areas shown for two municipal wells in Lodi, Wisconsin, illustrate how these model simulations can support land-use activities consistent with preserving well water quality. Wells are identified by their Wisconsin Unique Well Number to avoid confusion with local naming conventions. In general, well OH446 pumps groundwater that recharged through agricultural fields, while the contributing area to well NY856 encompasses a greater proportion of residential areas.

Figure 1: *Zones of contribution from municipal wells for 5- and 50-year time of travel.*



Once wells are constructed, new activities proposed within the contributing areas that could affect groundwater quality (for example, land spreading of industrial waste or manure, or construction of unlined salt-storage facilities) may warrant an increased level of safeguards and monitoring. The groundwater flow model can be used to evaluate locations proposed for new drinking water wells, to simulate the likely contributing area, and anticipate how existing land use might affect groundwater quality.

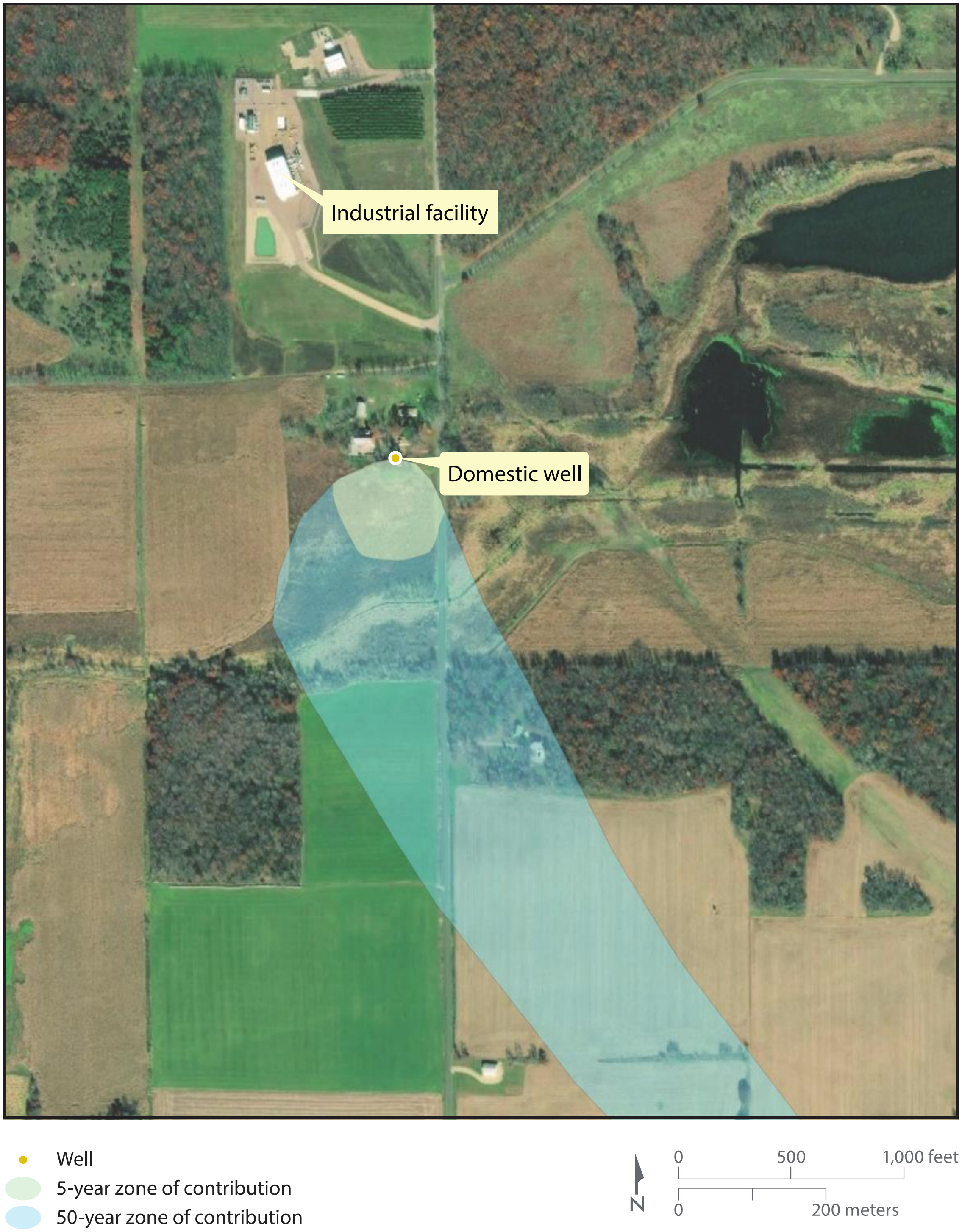
Projection: NAD83(HARN)/Wisconsin Transverse Mercator. Imagery: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

Figure 2: *Municipal wells zones of contribution, Lodi, Wisconsin. Groundwater flows from the south to the north in this area. The groundwater flow model simulates precipitation that infiltrates to the water table within the shaded areas ultimately discharges to these municipal wells.*

Zones of contribution at domestic wells

ZOCs were developed for several domestic wells within Columbia County at the request of the Land and Water Conservation Department. Figure 3 illustrates one such exercise, in which a homeowner became concerned about potential effects on groundwater quality from an industrial facility located about 1,500 from the residence. This concern developed following a storm water runoff event in which water from the facility discharged near the home. The domestic well is completed in unlithified material and was simulated in model layer 1 with a pumping rate of 24 gallons per minute. Results show that groundwater flows from south to north in this area, and the contributing area to the well extends to the south. This suggests that groundwater quality at the well is unlikely to be affected by activities to the north.

The ZOC shown in figure 3 demonstrates the potential to use model results as an educational tool. In this example, the homeowner may have control over a large part of the 5-year time of travel contributing area to the well. If the land owner views this area as part of a well-head protection area, they may avoid certain activities on this part of the property, such as manure storage, or applications of fertilizer or herbicide.

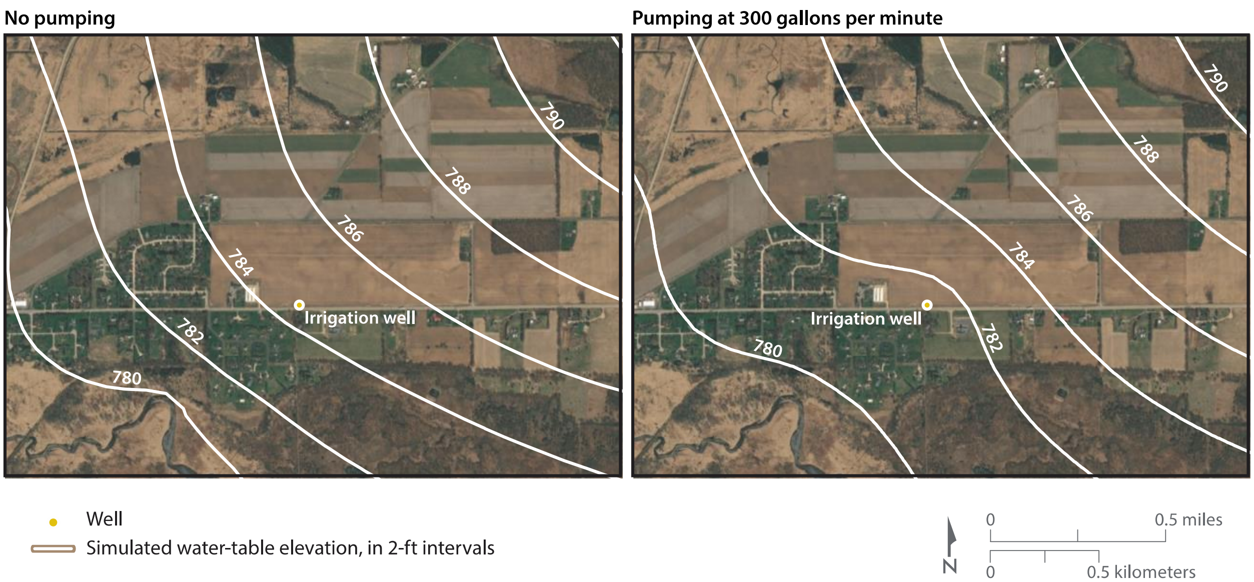


Projection: NAD83(HARN)/Wisconsin Transverse Mercator. Imagery: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

Figure 3. *Domestic well zone of contribution for 5- and 50-year time of travel. Results from the groundwater flow model show that the domestic well pumps groundwater that recharged to the south and is unlikely to be affected by activities at the nearby industrial facility to the north.*

Estimates of drawdown related to pumping

In 2014, the Columbia County groundwater flow model was used to simulate potential effects of pumping from a new high-capacity irrigation well drilled near a residential subdivision near Portage, Wisconsin. At that time, residents were concerned that pumping from this irrigation well might lower the water table, and diminish the quantity of groundwater available from domestic wells that supply potable water to nearby homes. The groundwater flow model was used to simulate the irrigation well located immediately east of the subdivision, cased to the top of the bedrock and open to the Elk Mound aquifer (model layers 4, 5, and 6). Figure 4 shows the simulated water table without pumping from the irrigation well compared to pumping at a rate of 300 gallons per minute, which is a typical high-capacity pumping rate in Columbia County (Appendix 1, Gotkowitz and others, 2021). These results indicate that the water table may drop by about 2 feet, from about 783 to 781 feet above sea level, at homes close to the well. This example demonstrates the utility of the model to address concerns about groundwater quantity and effects of new or proposed high-capacity wells.



Projection: NAD83(HARN)/Wisconsin Transverse Mercator. Imagery: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community.

Figure 4. *Simulated water-table elevation under conditions of no pumping (left) and pumping at 300 gallons per minute (right) from an irrigation well. These model results show a decrease of about 2 feet in the water table when the irrigation well pumps at 300 gallons per minute.*

Limitations

The Columbia County groundwater model is based upon results of field investigations and interpretation of data from across the county. The model simplifies complex and varied geologic and hydrogeologic conditions, and it represents average conditions in what is a seasonally dynamic system. Each model cell represents an area of 90,000 square feet, and up to several hundred feet of aquifer thickness. These simplifications limit the accuracy of the model and introduce uncertainty to model results. Gotkowitz and others (2021) provide additional discussion of uncertainty and error inherent in the modeling approach and limitations of the calibration, and call out specific aspects of the natural system, such as fracture flow, that are poorly represented in the model.

Of particular concern to interpreting model results presented in this report is application of the regional scale model to local-scale problems. Although beyond the scope of this report, uncertainty analysis can be performed for each application. For example, model users can examine the density of data used for model calibration from the local area of interest. Areas within the domain with more supporting data, such as water levels or borehole records, are better constrained than areas with sparse data. Similarly, model users may evaluate the model calibration in a specific area of interest to assess differences between observations (referred to as calibration “targets”) and model results. Another technique useful to characterize uncertainty involves re-running the model with changes made to key parameters. For example, the time of travel reflected in the ZOCs is affected by the porosity assigned to each type of aquifer sediment. The ZOCs can be re-run using other, geologically reasonable values of porosity to provide several ZOC delineations and illustrate a range of reasonable results. Monte Carlo techniques provide a formal and structured approach to evaluating uncertainty in model results. This method allows several model input parameters (for example, hydraulic conductivity, porosity, or recharge) to vary within a range of reasonable values for each parameter. The model is run tens, hundreds, or thousands of times, with each run or “realization” based on a random selection of parameter values. Results from the realizations are compiled and assigned a probability. The ZOC is presented with a certain probability of including all of the actual ZOC. Gaffield and others (2002) demonstrate this technique applied to a regional model developed for Rock County, Wisconsin.

Summary

Applications of the Columbia County groundwater flow model simulate conditions of interest to a variety of stakeholders, including residents, local officials, the agricultural community, and other groups interested in the county’s water resources. Although subject to uncertainty, model results quantify effects of pumping and illustrate directions and rates of groundwater flow. The ZOCs simulated for municipal supply wells support establishment of well-head protection areas. ZOCs simulated for domestic wells can support education for landowners, who in turn can protect areas at their homes and farms that are important to preserving groundwater quality.

The ZOCs illustrated in this report demonstrate that the source of groundwater produced by municipal wells in the county is local. There appears to be little well interference, as wells within villages and cities are located at sufficient distances from each other.

Columbia County is underlain by hundreds of feet of conductive sandstone aquifer. Applications of the model demonstrate the productivity of the groundwater system. Simulation of pumping from an irrigation well showed that drawdown related to high-capacity wells may be limited to a few feet at nearby wells.

The model-simulated ZOCs for municipal wells listed in table 1 were provided to the Columbia County Land Information Department in ArcMap GIS files. The flow model is archived and publicly available from the U.S. Geological Survey (Leaf and others, 2021).

Acknowledgments

The author thanks the Columbia County Board of Supervisors and the Bureau of Drinking Water and Groundwater, Wisconsin Department of Natural Resources (WDNR) for their support of the county groundwater flow model. Andy Leaf, U.S. Geological Survey, provided expertise in model calibration and in techniques for simulating groundwater–surface water interactions. Ken Bradbury, Wisconsin Geological and Natural History Survey, provided technical assistance with the graphical user interface for the model. Kurt Calkins, Director of Land and Water Conservation Department, identified land use and groundwater quality issues in the county that were well-suited for model analysis. This report was greatly improved by constructive technical and editorial reviews provided by Ken Bradbury, Anna Fehling, Linda Deith, and Ian Orland, from the Wisconsin Geological and Natural History Survey.

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