Report

Delineation of capture zones for municipal wells in fractured dolomite, Sturgeon Bay, Wisconsin, USA

Todd W. Rayne · Kenneth R. Bradbury
Maureen A. Muldoon

Abstract A wellhead protection study for the city of Sturgeon Bay, Wisconsin, USA, demonstrates the necessity of combining detailed hydrostratigraphic analysis with groundwater modeling to delineate zones of contribution for municipal wells in a fractured dolomite aquifer. A numerical model (MODFLOW) was combined with a particle tracking code (MODPATH) to simulate the regional groundwater system and to delineate capture zones for municipal wells. The hydrostratigraphic model included vertical and horizontal fractures and high-permeability zones. Correlating stratigraphic interpretations with field data such as geophysical logs, packer tests, and fracture mapping resulted in the construction of a numerical model with five high-permeability zones related to bedding planes or facies changes. These zones serve as major conduits for horizontal groundwater flow. Dipping fracture zones were simulated as thin high-permeability layers. The locations of exposed bedrock and surficial karst features were used to identify areas of enhanced recharge. Model results show the vulnerability of the municipal wells to pollution. Capture zones for the wells extend several kilometers north and south from the city. Travel times from recharge areas to all wells were generally less than one year. The high seasonal variability of recharge in the study area made the use of a transient model necessary.

Résumé Une étude pour la protection d'un champ captant pour la ville de Sturgeon Bay (Wisconsin, Etats-Unis) montre qu'il est nécessaire de combiner une analyse hydrostratigraphique détaillée avec une modélisation de la nappe pour définir les zones de contribution aux puits captés pour l'alimentation en potable (AEP) dans un aquifère dolomitique fracturé. Un modèle numérique (MODFLOW) a été combiné avec un code de suivi de particules (MODPATH) pour simuler le système aquifère régional et pour délimiter les zones de prélèvements concernées par les puits de l'AEP. Le modèle hydrostratigraphique comporte des fractures verticales et horizontales et des zones à forte perméabilité. Les interprétations stratigraphiques ont été corrélées avec les données de terrain telles que les logs géophysiques, les tests entre packers et la cartographie des fractures, de manière à construire un modèle numérique avec cinq zones à forte perméabilité liées à des plans de stratification ou à des variations de faciès. Ces zones constituent des conduits majeurs de l'écoulement horizontal des eaux souterraines. Les zones de fractures qui plongent ont été simulées comme des couches minces à forte perméabilité. La localisation des roches affleurantes et les phénomènes karstiques de surface ont été utilisés pour identifier les secteurs de recharge plus importante. Les résultats du modèle montrent la vulnérabilité des puits de l'AEP à la pollution. Les zones d'alimentation des puits s'étendent à plusieurs kilomètres au nord et au sud de la ville. Les temps de parcours depuis les zones de recharge vers tous les puits sont en général inférieurs à un an. La forte variabilité saisonnière de la recharge dans la région étudiée a rendu nécessaire l'utilisation d'un modèle en régime transitoire.

Resumen Se ha elaborado un estudio de perímetros de protección en la ciudad de Sturgeon Bay (Wisconsin, Estados Unidos) que demuestra la necesidad de combinar análisis detallados hidroestratigráficos con modelos numéricos para delimitar las zonas que contribuyen a los pozos de producción municipal en un acuífero de dolomitas fracturadas. Se combinó un modelo numérico (MODFLOW) con un código de seguimiento de partículas (MODPATH) para simular el sistema regional de aguas subterráneas y para delimitar las áreas de captura de los pozos municipales. El modelo hidroestratigráfico incluía fracturas horizontales y verticales y zonas de alta permeabilidad. Mediante correlación de las interpretaciones estratigráficas con diversos datos de campo, tales como perfiles geofísicos, ensayos con obturadores y identificación de fracturas, se pudo construir

Received: 8 July 1999 / Accepted: 28 June 2001
Published online: 6 September 2001

T.W. Rayne (✉)
Department of Geology, Hamilton College,
198 College Hill Road, Clinton, NY 13323, USA
e-mail: trayne@hamilton.edu

K.R. Bradbury
Wisconsin Geological and Natural History Survey,
3817 Mineral Point Road, Madison, WI 53705, USA

M.A. Muldoon
Department of Geology, University of Wisconsin-Oshkosh,
800 Algoma Blvd, Oshkosh, Wisconsin 54901, USA

 DOI 10.1007/s100400100154

un modelo numérico que incorporaba cinco zonas de alta permeabilidad relacionadas con planos de estratificación o cambios de facies. Estas zonas actuaban como conductos principales para el flujo horizontal de las aguas subterráneas. Se simuló las zonas de buzamiento de las fracturas como capas delgadas de alta permeabilidad. Se empleó la situación de los afloramientos de la roca encajante y las características de karstificación superficial para identificar las áreas de recarga preferencial. Los resultados del modelo han mostrado la vulnerabilidad de los pozos municipales frente a la contaminación. Las áreas de captura de dichos pozos se extienden varios kilómetros hacia el norte y el sur de la ciudad. Los tiempos de tránsito desde las áreas de recarga hasta los pozos son generalmente inferiores a un año. La elevada variabilidad estacional de la recarga en la zona de estudio hizo imprescindible la aplicación de un modelo transitorio.

Keywords carbonate rocks · fractured rocks · numerical modeling · capture zones

Introduction

Background

Sturgeon Bay, Wisconsin is a city of about 9,000 residents in Door County, which occupies a peninsula bounded by Green Bay on the northwest and Lake Michigan on the southeast (Fig. 1). The city is situated on both sides of Sturgeon Bay, a funnel-shaped bay extending southeast from Green Bay, and linked to Lake Michigan by the Sturgeon Bay Ship Canal. The Door Peninsula is composed of fractured dolomite of Silurian age which dips gently to the southeast. The dolomite serves as the principal aquifer for water supply in the county (Sherrill 1975). Pleistocene glaciation has removed much of the surficial sediments in the county, and the dolomite is commonly exposed at the surface or covered by thin soils in most of the county (Sherrill 1978). The dolomite has undergone dissolution and shows numerous small karst features. The lack of thick soil to attenuate contaminants, combined with the rapid groundwater

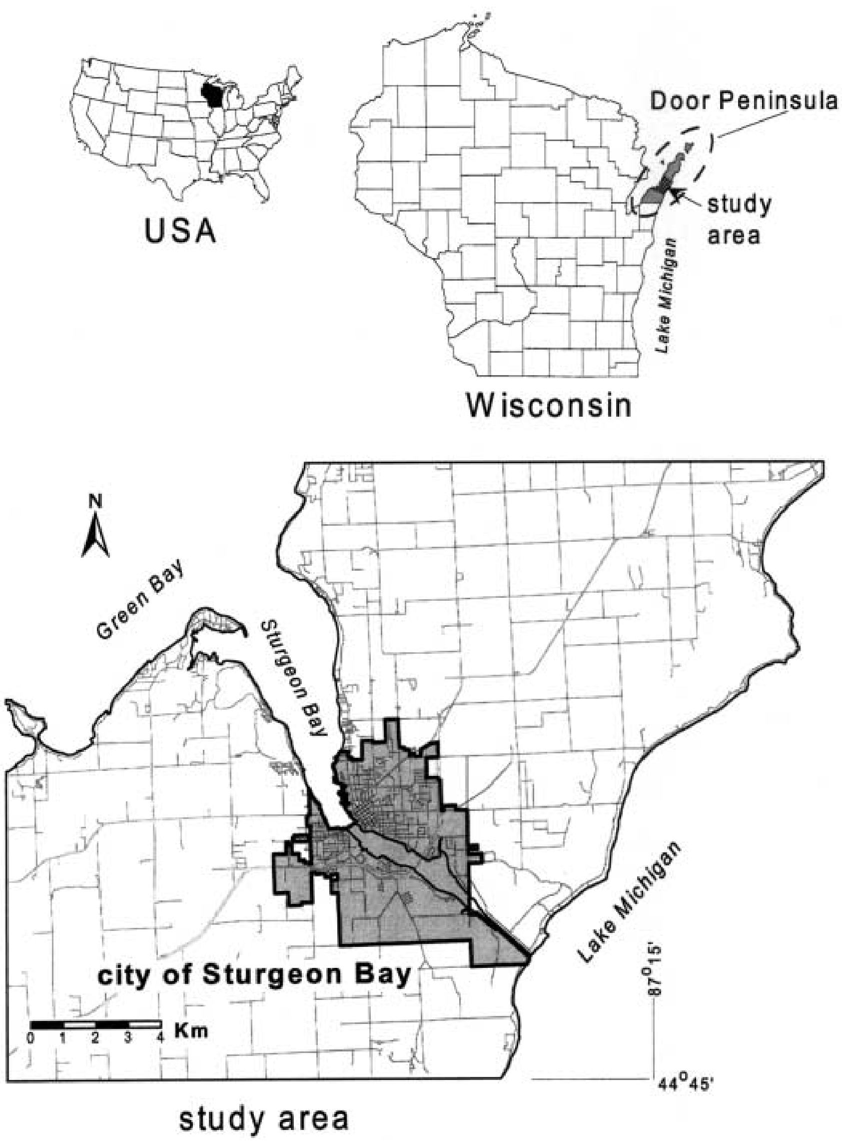


Fig. 1 Location map showing Sturgeon Bay, City of Sturgeon Bay, Green Bay, and Lake Michigan

 DOI 10.1007/s100400100154

movement through the fractured dolomite aquifer, results in frequent contamination of groundwater by bacteria, nitrate, and other pollutants (Sherrill 1975).

The city of Sturgeon Bay relies entirely on groundwater pumped from municipal wells finished in the dolomite aquifer for water supply. Since the turn of the century, the city has installed 12 municipal wells within the city limits. Water from nine of these wells has shown bacterial contamination, and seven have been shut down and abandoned. Currently (1999) the city operates five wells. Water from three of these wells is disinfected using on-site ozonation (McMahon Associates 1991).

The objective of the study was to delineate capture zones for the five remaining municipal wells in the City of Sturgeon Bay as part of a wellhead protection study. Wellhead protection programs are designed to protect groundwater used for public consumption by identifying and managing potential sources of contamination within the capture zone of the well. The capture zone is the land-surface area where recharging precipitation enters a groundwater system and eventually flows to a well. Methods for capture-zone delineation are presented in United States Environmental Protection Agency (1987), and Bradbury et al. (1991). Eckenfelder Inc. (1997) presents methods of capture-zone delineation in carbonate-rock aquifers in which open-conduit flow predominates.

Previous work in Door County indicated that vertical fractures as well as horizontal bedding planes and dissolution zones provide the primary pathways for groundwater flow in the Silurian dolomite (Sherrill 1978; Bradbury and Muldoon 1992; Gianniny et al. 1996). Development of a groundwater flow model for the Sturgeon Bay area requires characterization of vertical fractures, horizontal high-permeability zones, and matrix permeabilities at a regional scale. This study integrates surface and subsurface stratigraphic, geophysical, and hydrogeological data in order to characterize both the horizontal high-permeability zones and matrix permeabilities in the dolomite aquifer.

Hydrogeology

The Silurian dolomite aquifer ranges in thickness from 60 to 150 m in the study area (Sherrill 1975), and consists of the Niagaran Series and the underlying Alexandrian Series (Fig. 2). Both series are made up of gray, thinly bedded to massive dolomite with local cherty zones and shale layers. A more complete description of the dolomite stratigraphy can be found in Gianniny et al. (1996).

The Ordovician Maquoketa shale underlies the dolomite, and is a regional aquitard (Bradbury et al. 1991). Surficial deposits consist of unconsolidated Pleistocene strata (sand, gravel and lacustrine sediments), which range in thickness from zero to about 10 m in the area surrounding the city. In general, the Pleistocene deposits are less than 1 m thick on the upland areas and greater than 2 m thick in low-lying areas.

Series	Group	Formation	Member
Niagaran		Engadine	
		Manistique	Cordell
			Schoolcraft
	Burnt Bluff	Hendricks Dolomite	
		Byron Dolomite	
Alexandrian		Mayville Dolomite	
		Maquoketa	

Fig. 2 Stratigraphy of the Silurian dolomite in Door County

The dolomite has very low primary permeability but is extensively fractured. Studies by Sherrill (1978), Bradbury (1982), Bradbury et al. (1991), Bradbury and Muldoon (1992), and Roffers (1996) show vertical fracture sets with orientations of about 70 and 155°. Average fracture spacing is about 3 to 6 m (Bradbury et al. 1991). Vertical fractures decrease in aperture (width) and density (number of fractures per unit area) with depth (Sherrill 1978), and serve as conduits for vertical movement of recharge and contaminants from the surface. High-permeability horizontal features such as bedding planes are evident in quarry walls and outcrops and appear on borehole geophysical logs such as natural gamma and heat-pulse flowmeter. Although usually only a few centimeters thick, these planar discontinuities form horizontal-flow zones which can be correlated over distances of as much as several kilometers in the subsurface (Gianniny et al. 1996).

Determining the location and continuity of horizontal-flow zones in the dolomite aquifer was essential to model groundwater flow accurately in the study area. The basis for the conceptual model of the aquifer was the work described by Gianniny et al. (1996), in which they identified 14 horizontal high-permeability zones within the dolomite aquifer in the Sturgeon Bay area. All are parallel to the bedding and are most highly developed at lithologic contacts. They range in thickness from 0.3 to 11 m, and represent boundaries of contrasting lithologies, layers with high primary porosity (e.g., coquina-like packstones or vuggy zones), or lithologies containing numerous bedding-plane partings at the boundaries of depositional cycles. In the study area, there are five laterally continuous flow zones (termed C, D, E, J, and K in Gianniny et al. 1996). In this report, the intervals of the aquifer between the flow zones are considered “non-flow” zones. Although some groundwater flow occurs in these zones, the amount is relatively very small in comparison to that in the flow zones.

 DOI 10.1007/s100400100154

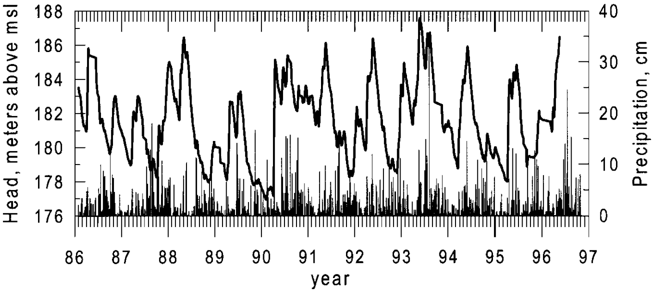


Fig. 3 Long-term water-level fluctuations in observation well DR-265 and precipitation data

Hydrogeologic Characterization

Water-Level Measurements

Water levels in the dolomite aquifer fluctuate seasonally over 30 m due to short-duration, high-intensity recharge events and low effective porosity in the fractured dolomite (Sherrill 1978). The hydrograph for US Geological Survey observation well DR-265, in the northern part of the city, shows annual water-level fluctuations of nearly 10 m in this unpumped well (Fig. 3). The annual low point typically occurs in September or October, and the annual high point typically occurs in March or April fol-

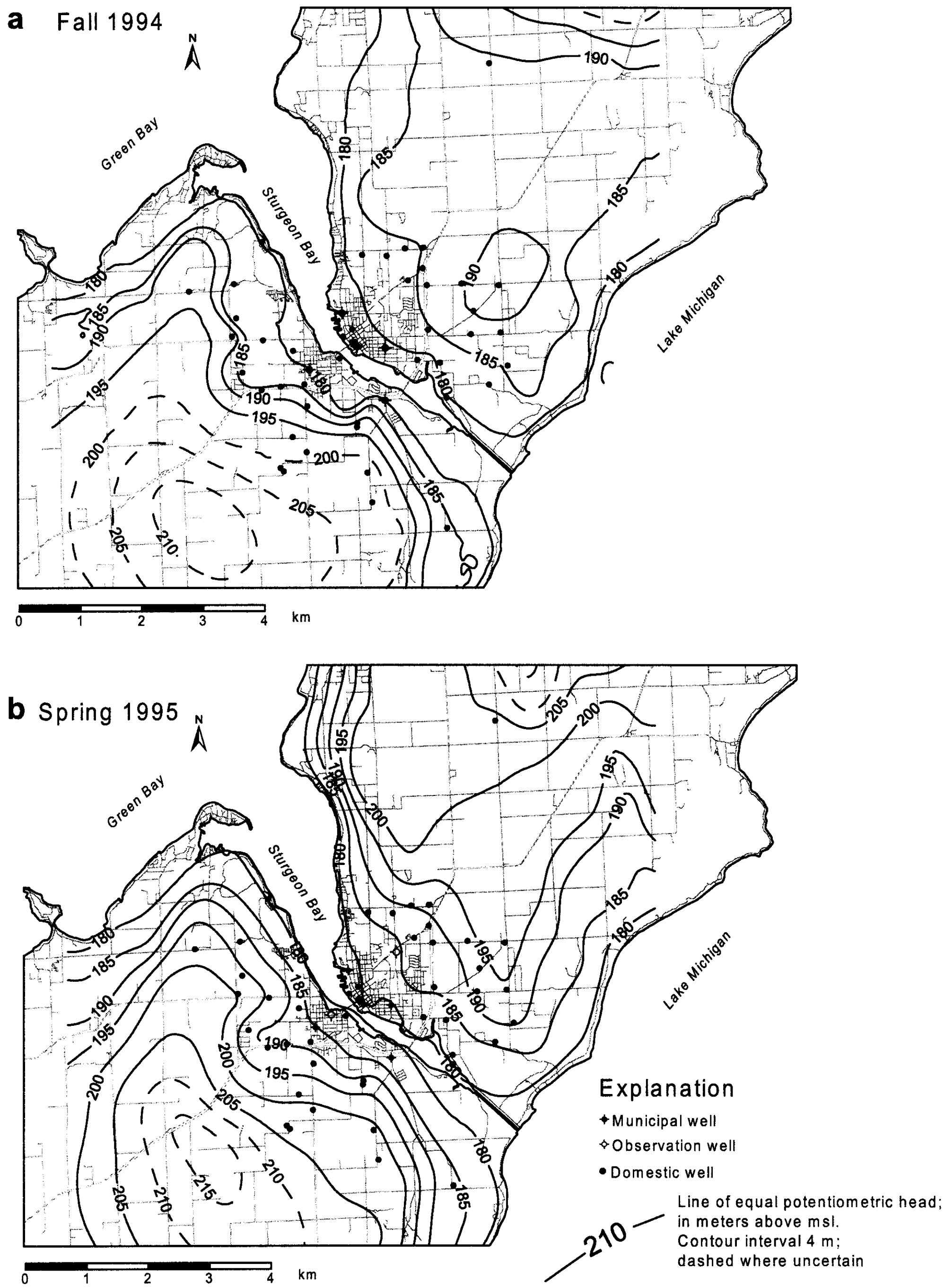


Fig. 4a, b Distribution of potentiometric head in the study area. **a** Fall 1994 (n=67). **b** Spring 1995 (n=92)

DOI 10.1007/s100400100154

lowing periods of high recharge. The dynamic fluctuations of water levels in the dolomite aquifer indicate that a single potentiometric map, which represents a “snapshot” of the heads in the aquifer, might be of limited use for delineating zones of contribution to municipal wells.

In order to capture the range of water-level fluctuations near Sturgeon Bay, water-level data from domestic and monitoring wells were collected in November 1994 and April 1995 for use in the construction and calibration of the flow models and to provide insight into groundwater-flow directions. The measured hydraulic head is a composite value over the open interval of the borehole, which commonly extends for 50 to 100 m.

The two potentiometric surfaces for the fall and spring, shown in Fig. 4, show the seasonal transience of groundwater levels near Sturgeon Bay. Groundwater elevations are highest near the crest of the peninsula, and slope east and west toward Lake Michigan and Green Bay, respectively. The potentiometric surface also slopes toward Sturgeon Bay and the Sturgeon Bay ship canal from the north and south. During spring, measured potentiometric levels exceed 204 m north and south of Sturgeon Bay. During fall, potentiometric levels are several meters lower.

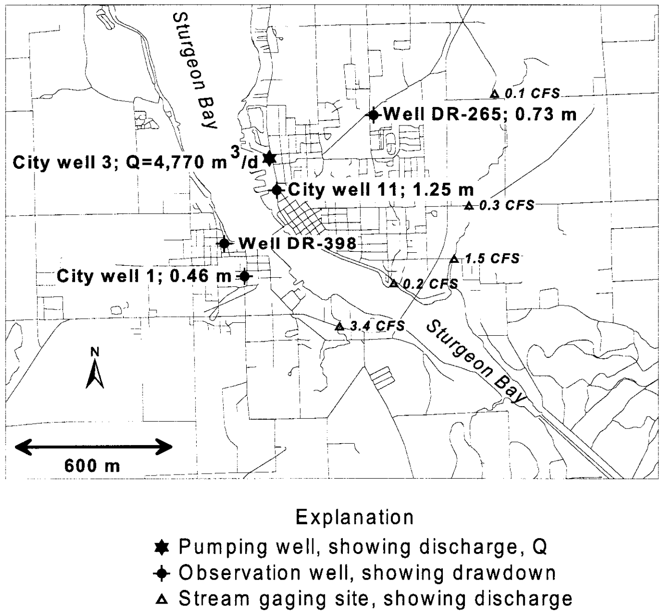


Fig. 5 Map of the City of Sturgeon Bay, showing observation wells for city well pumping test with drawdowns after 4 h of pumping and stream-measurement points with stream-flow values

Estimation of Recharge Rates

Soil characteristics, topography, the presence of karst features and fractures, and the spatial and temporal distribution of annual precipitation work together to control groundwater recharge rates in the study area. A soil-water mass-balance analysis (Swanson 1996; Bradbury et al. 1998) was used to provide initial estimates of recharge rates. This method uses precipitation measurements, estimates of runoff and evapotranspiration, and soil-moisture storage capacity to estimate groundwater recharge.

The soil-water mass-balance analysis tends to underestimate groundwater recharge because it does not account for water lost to runoff from each soil unit (Swanson 1996). However, because most runoff in Door County enters the subsurface in adjacent soil units or through small karst features (Bradbury and Muldoon 1992), the estimated recharge values provide a reasonable starting point for developing the model recharge rates. Annual recharge rates from the soil-water mass-balance method range from 0.14 to 0.24 m/year (5.7 to 9.3 in/year), with an average of 0.2 m/year (7.9 in/year). For comparison, a previous study in northern Door County determined an annual recharge rate of 0.32 m/year (12.9 in/year; Bradbury 1982), and Bradbury and Muldoon (1992) estimated an annual recharge rate of 0.20 m/year (7.8 in/year) in central Door County using well-hydrograph analysis.

The results from the soil-infiltration model indicate that all groundwater recharge during an average year occurs in March, April, October, and November. During the winter (December through February) the ground is frozen and precipitation accumulates as snow. A major recharge event occurs in March and April as the soil thaws, the snowpack melts, and spring rains occur. From May through September, the weather is warm, and evapotranspiration generally exceeds precipitation. During October and November, evapotranspiration decreases and fall rains occur. Using both steady-state and transient models to determine seasonal recharge, Bradbury (1982) determined spring recharge rates in northern Door County of 0.33 to 0.72 m/year (13.1 to 28.3 in/year), and fall recharge rates of 0.07 m/year (2.8 in/year).

Recharge-rate estimates based on the soil-infiltration model do not account for the presence of shallow bedrock, sinkholes, closed depressions, and other karst and fracture features which may act to focus groundwater recharge. Maps of surface-solution features from Stieglitz and Dueppen (1994), and Stieglitz and Johnson (1996), soil maps showing areas of thin or no soil, and fracture density maps at several scales (Roffers 1996) were used to locate areas where recharge may be focused. Areas of exposed dolomite, thin soils, and solution features or intense vertical fracturing were assigned the highest recharge rates. Areas with no solution features or low fracture density or thick soils were given the lowest rates.

Determination of Hydraulic Conductivity

City well pumping test

Water-level fluctuations in nearby wells in response to pumping from municipal supply wells show that the dolomite aquifer is laterally well connected in the subsurface. A pumping test in which city well 3 (Fig. 5) was pumped for four hours caused 0.46 m (1.5 ft.) of drawdown in city well 1, which is on the opposite side of the

 DOI 10.1007/s100400100154

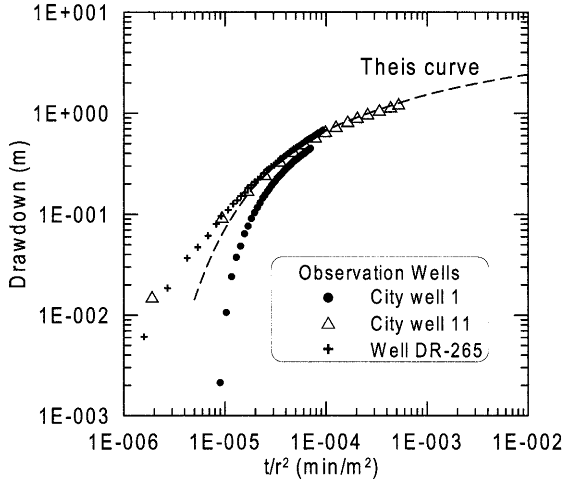


Fig. 6 Relation between drawdown and t/r^2 for the city well pumping test, showing comparison with the Theis-type curve

Sturgeon Bay channel from the pumping well. The rapid response of well 1 indicates that the Sturgeon Bay channel does not act as a significant boundary to lateral groundwater movement beneath it. Results of this test, analyzed using the Theis (1935) artesian non-leaky model, yielded an average transmissivity of 980 m^2/day, and a storage coefficient of 3×10^{-5}.

Drawdown data from wells DR-265 and city well 11 during the city well 3 pumping test are very similar, and drawdown data from city well 1 approach these at late times (Fig. 6). All three data sets approximate the Theis curve at late times, showing that at a large (100- to 1,000-m) scale, the dolomite aquifer responds as an equivalent porous medium. However, this assumption breaks down at the smaller scales needed for wellhead-protection and transport studies.

Hydraulic conductivity tests using straddle packers

A series of pumping tests in two deep wells (DR-265 and DR-398) using straddle packers demonstrated the importance of near-horizontal fracture zones in controlling groundwater flow in the study area. The tests, described in detail in Bradbury et al. (1998), were designed to measure the hydraulic conductivity of specific fractured and non-fractured zones identified on borehole logs by isolating the intervals with inflatable packers. The tests also provided reliable measurements of the vertical distribution of hydraulic head at the two sites.

Hydraulic conductivity values, vertically averaged over the packer interval of 2.9 m in well DR-265, are shown in Fig. 7. The values range over six orders of magnitude in one well, from 0.0006 to 70 m/day (2×10^{-8} to 3×10^{-3} ft/s). Most of the highest values of hydraulic conductivity, generally above 0.1 m/day, are clearly associated with fracture zones (test zones 1, 4, 5, 6, and 10 on Fig. 7). The conductivity of unfractured dolomite, measured at this scale, is about 1.5×10^{-2} m/day, as shown by test zones 3 and 7. The base of the well penetrates shale of the Maquoketa Formation. This material has a hydraulic conductivity of less than 10^{-3} m/day (zone 12 on Fig. 7).

The hydraulic conductivity of these intervals is interpreted to be almost entirely due to near-horizontal fractures, while the rock matrix yields little water. Therefore, the packer-test estimates are probably lower than the hydraulic conductivity of individual fractures. However, the test-zone thickness is consistent with the vertical discretization scale of the numerical model.

Hydraulic heads measured prior to pumping during the packer tests show that significant vertical hydraulic gradients exist in the dolomite. The total hydraulic head (right-hand curve) in well DR-265 decreases from about 182 m above sea level at test zone 1, at 135-m elevation, to less than 180 m at test zone 4, at 108-m elevation (Fig. 7). Below test zone 4 the head increases steadily to zone 11 (elevation 58 m) at the top of the Maquoketa Formation. The vertical hydraulic gradient is thus downward in the upper part of the aquifer, and upward in the lower part of the aquifer. Note that the lowest total head coincides with the position of highest hydraulic conductivity, a large conductive fracture at elevation 108 m.

Specific capacity estimates

Specific capacity tests in private domestic wells provide additional information on the distribution of hydraulic conductivity in the study area. Well contractors commonly measure the specific capacity of private wells, defined as the sustainable pumping rate divided by the drawdown in the well at a quasi steady state, as a guide to predicting well performance. We used the TGUESS code of Bradbury and Rothschild (1985) to estimate hydraulic conductivity of 350 wells in the Sturgeon Bay area. These estimates are based on many simplifying assumptions and are only approximate, but the results can be used to identify regional averages and spatial trends in areas where more rigorous aquifer tests are not abundant.

The specific-capacity estimates yield a geometric mean hydraulic conductivity of 0.3 m/day (1×10^{-5} ft/s) for the Sturgeon Bay area, and represent a composite average over the entire thickness of the dolomite aquifer. Table 1 summarizes the test results and Fig. 8 shows the location of high K estimates in the study area.

Although no clear spatial trends are apparent in the composite hydraulic conductivity across the study area

Table 1 Results of hydraulic-conductivity estimates based on specific-capacity tests

Statistic	Hydraulic conductivity (m/day)
Number of tests	350
Minimum	0.011
Maximum	210
Mean	2.5
Geometric mean	0.27

 DOI 10.1007/s100400100154

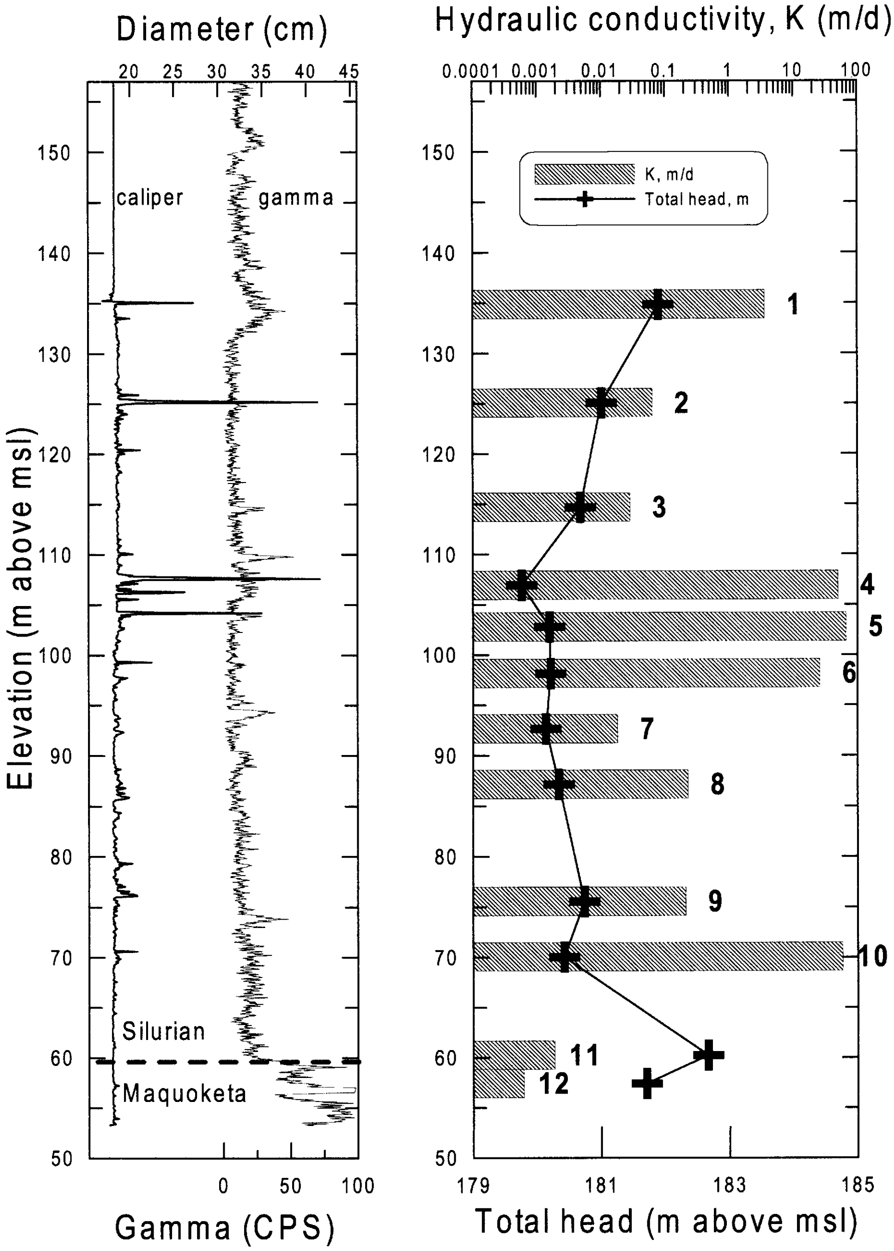


Fig. 7 Results of borehole geophysical logging and packer testing in well DR-265. Head values were measured prior to pumping

(Fig. 8), a small number of relatively high hydraulic-conductivity values occur northeast and southwest of the Sturgeon Bay city limits.

Groundwater Geochemistry

The geochemistry and isotopic signature of water in the study area were examined to provide information on flow-path length and groundwater age, which was used to help validate the numerical model. The major-ion geochemistry of water samples from the city wells is rather uniform and indicates that the water is at near-equilibrium with dolomite (Bradbury et al. 1998). Surface water in Sturgeon Bay has lower values of total dissolved solids than local groundwater (Bradbury et al. 1998).

Tritium concentrations in the Sturgeon Bay municipal wells range from about 9 to 16 TU (Table 2), within the range of current precipitation. Tritium data indicate that the water is young and suggest that travel times from recharge areas to the wells are relatively short (<35 years). A plot of $\delta^{18}O$ versus $\delta^{2}H$ concentrations shows that groundwater samples from municipal wells and upgradient observation wells fall near the local meteoric water line, whereas local surface water plots significantly to the right of the line (Fig. 9). These results show a lack of significant groundwater-surface water mixing in the dolomite aquifer near Sturgeon Bay, and indicate that the Sturgeon Bay municipal wells do not produce significant quantities of local surface water.

DOI 10.1007/s100400100154

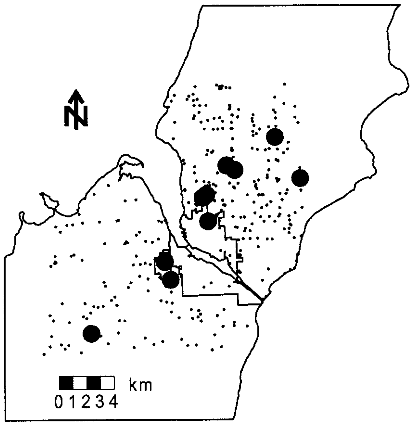


Fig. 8 Locations of hydraulic-conductivity estimates based on specific-capacity data. *Large circles* represent hydraulic-conductivity estimates greater than 10 m/day

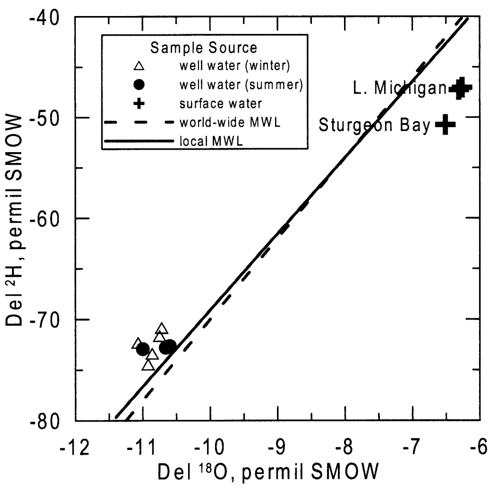


Fig. 9 Relations between $\delta^{18}O$ versus $\delta^{2}H$ for Sturgeon Bay groundwater and surface water

Groundwater Modeling

Approach

The modeling component of this study was done in three phases. In phase one, a two-dimensional particle-tracking code was used to approximate the shapes of the capture zones (Bradbury et al. 1998). In phase two, a transient, three-dimensional code (MODFLOW, McDonald and Harbaugh 1988) was applied to more completely simulate the aquifer and to delineate capture zones with more accuracy. In the third modeling phase, a simple, two-dimensional fracture network model (Rouleau 1988) was used to study the lateral spreading of water in the fractured unsaturated zone above the water table.

Conceptual Model

The basis of the conceptual model for the Sturgeon Bay study is derived from the stratigraphic and hydrogeologic studies of Gianniny et al. (1996), and previous work by Bradbury and Muldoon (1992), and Sherrill (1978). The aquifer is composed of multiple dipping layers of dolomite, with an uppermost layer of unconsolidated sand and gravel and lacustrine deposits.

Hydraulically, the dolomite aquifer near Sturgeon Bay is conceived to behave as a dual-porosity system. The horizontal-flow zones control lateral groundwater movement and are responsible for almost all of the aquifer's transmissivity. The unfractured dolomite matrix contributes little transmissivity to the system but is important to groundwater storage. Vertical fractures control the flow between near-horizontal flow zones.

The recharge rate is spatially variable, related to areas where fractured dolomite is exposed and has undergone solution, or where soils are thin or absent.

Boundary conditions include specified head boundaries in Lake Michigan and Green Bay (177 m; the long-term average lake elevation), head-dependent flux boundaries in Sturgeon Bay and streams in the model area, and no-flow boundaries at groundwater divides. The locations of groundwater divides were determined from the potentiometric-surface maps. Pumping rates for City of Sturgeon Bay municipal wells were averaged over a

Table 2 Isotopic contents of water from Sturgeon Bay municipal wells and local surface waters

Sample location	Sample date	$\delta^{18}O$ (per mil SMOW)	$\delta^{2}H$ (per mil SMOW)	^{3}H (tritium units)	Tritium error (tritium units)
Green Bay – Big Quarry	6 Nov 1994	–6.31	–47.26	19.6	1.4
Sturgeon Bay – downtown	6 Nov 1994	–6.51	–50.73	19.4	1.4
Lake Michigan at Coast Guard Station	6 Nov 1994	–6.26	–47.03	21.4	1.6
City well 3	3 Jan 1995	–11.07	–72.30	14.3	1.1
City well 3	5 July 1995	–11.00	–72.92	16.2	1.2
City well 6	3 Jan 1995	–10.75	–71.62	14.0	1.0
City well 7	3 Jan 1995	–10.86	–73.37	13.0	1.0
City well 7	5 July 1995	–10.66	–72.78	14.2	1.1
City well 8	3 Jan 1995	–10.92	–74.44	10.4	0.8
City well 10	3 Jan 1995	–10.72	–70.83	8.8	0.7
City well 10	5 July 1995	–10.60	–72.63	11.2	0.9

 DOI 10.1007/s100400100154

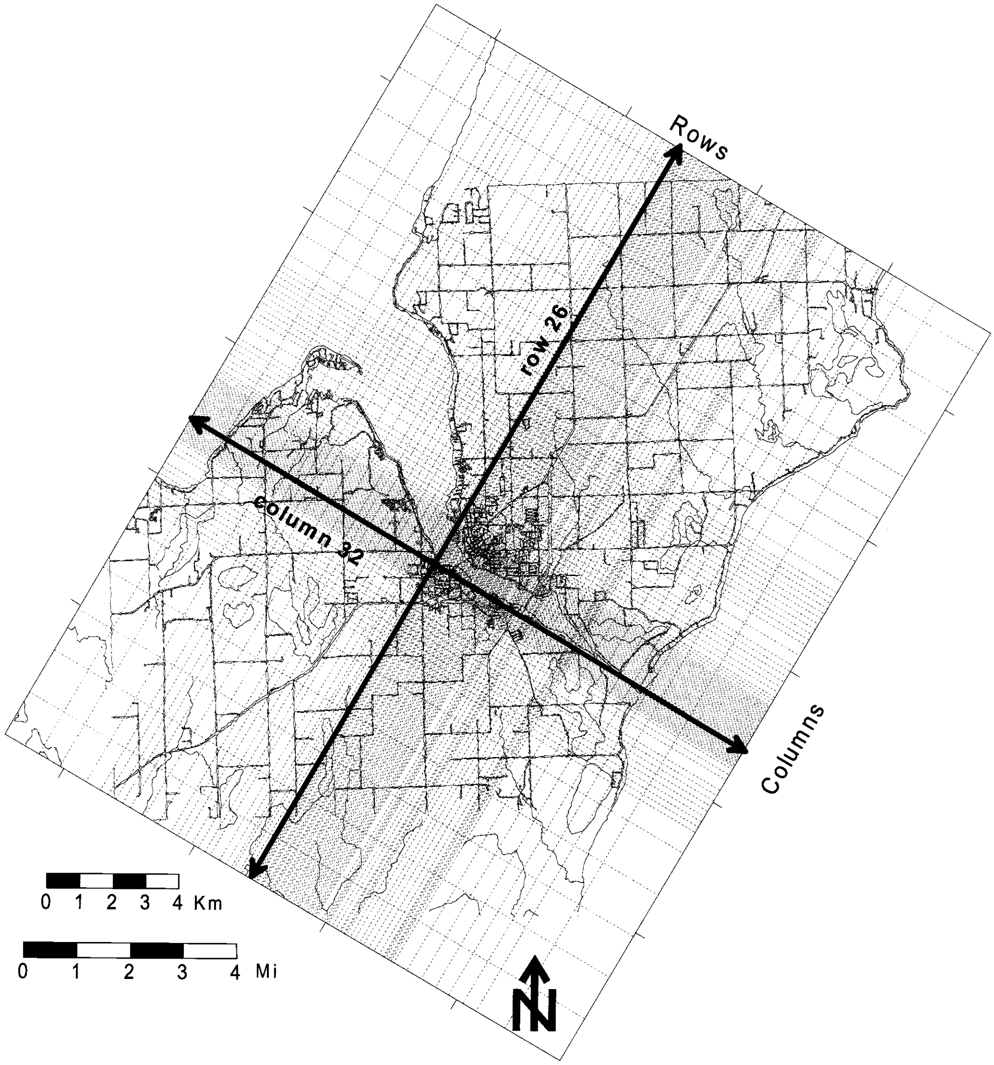


Fig. 10 MODFLOW model grid

year to give temporally uniform withdrawal rates for each well.

MODFLOW Model

The goal of the modeling was to construct a groundwater model which would simulate the aquifer as realistically as possible. This required a three-dimensional transient model with spatial and temporal variability of recharge rates, simulation of near-horizontal flow zones, and reasonable representation of boundary conditions. The aquifer was modeled using MODFLOW (McDonald and Harbaugh 1988), a modular, three-dimensional, transient finite-difference model, and Groundwater Vistas (Environmental Simulations Inc. 1996), a graphical user interface for model input, output, and data visualization. At this stage, both steady-state and transient models were developed. A transient model most accurately reflects aquifer behavior because of the dynamic seasonal water-level fluctuations seen in wells.

Spatial and temporal discretization

The MODFLOW model consists of 99 rows, 97 columns, and 12 layers, for a total of 115,236 finite-difference cells, of which 90,560 are active. The model grid (Fig. 10) is aligned 60° from north in order to match the average orientation of vertical fracture sets. The grid is irregularly spaced, with node spacing ranging from 50 m in the City of Sturgeon Bay to 1,000 m at the edges of the model. Grid spacing was also finer near areas known to contain abundant small karst features or exposed fractures in order to simulate spatial variability of recharge more accurately. The uppermost layer (layer 1) in two cross-sectional views of the model represents unlithified material at the surface (Fig. 11). Layers 2–12 represent dipping bedrock, and are arranged to discretely simulate the five continuous flow zones and related non-flow zones identified by Gianniny et al. (1996) in the study area. The model simulates the flow zones as thin, continuous, highly permeable layers. The intervals between the flow zones were modeled as thicker layers with lower horizontal and vertical hydraulic conductivity. The 11 bedrock layers dip approximately one degree to the

 DOI 10.1007/s100400100154

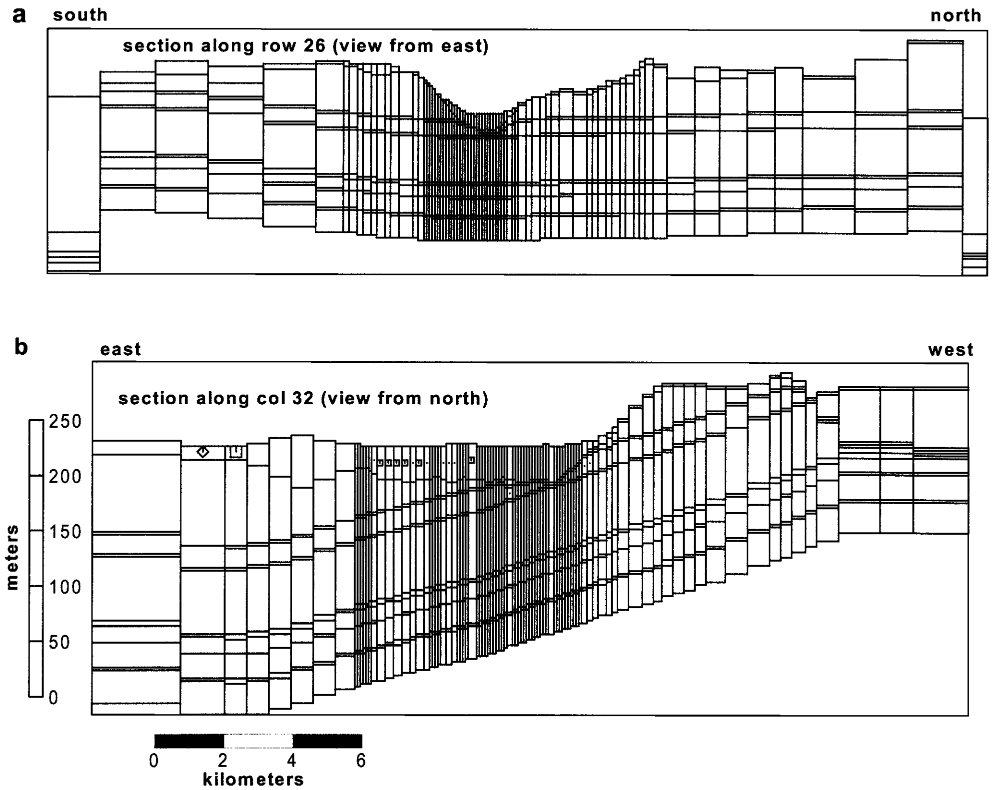


Fig. 11a, b Sections along rows and columns of the model grid. **a** South-north along row 26. **b** East-west along column 32

Table 3 Values of hydraulic conductivity used in the model

Layer number	Horizontal K (m/day)	Vertical K (m/day)
1	0.1	0.1
2	1	0.1
3	45	4.5
4	4.5	0.6
5[a]	45, 350	4.5, 35
6[a]	1, 55	0.1, 5.5
7[a]	0.5, 350	0.01, 3.5
8[a]	2.5, 55	0.3, 5.5
9[a]	45, 350	4.5
10[a]	0.95, 55	0.01, 5.5
11	45	4.5
12[a]	0.2, 55	0.05, 5.5

[a] Layers with two conductivity zones (see Fig. 12)

southeast. The top layer, representing surficial unlithified material, truncates the bedrock layers unconformably, and has variable thickness. The thickness of each remaining bedrock layer is uniform throughout the model domain, but thickness varies between layers. Thickness of layers ranges from less than 1 to 40 m. Vertical fractures were not modeled discretely. It is assumed that vertical fractures are dense enough that their effects can be lumped into the vertical hydraulic-conductivity term for each layer (Table 3).

The transient model was constructed to simulate the groundwater system through one water year, from October through September. The model uses six stress periods which range in length from 30 to 150 days. Each stress period has different recharge rates, as shown in Table 4. Initial head conditions for the transient runs were taken from the calibrated steady-state model. Values of hydraulic conductivity and river-node parameters from the steady-state model were used in the transient model.

In the transient model the initial starting heads, thought to represent fall conditions, were not replicated after one model cycle (six stress periods which represent seasonal and subseasonal periods of high and low recharge rates; Table 4). The model did not achieve transient stability (the ability to replicate one "model" year with the next model year) until at least two cycles of the model were complete. The final model then consisted of 12 stress periods, representing two identical years.

Boundary conditions

All boundary conditions which were identified in the conceptual model were used in the numerical model. Submarine outcrop areas of the dolomite in Green Bay and Lake Michigan were modeled as specified head boundaries. Head-dependent flux boundaries were used under parts of Green Bay, parts of Lake Michigan, Sturgeon Bay, and in the major streams using the MODFLOW river package. This type of boundary allows the model to compute the flux into or out of the aquifer depending on the head difference between the stream (or bay) and the aquifer. The groundwater divides were identified from the spring and fall potentiometric

 DOI 10.1007/s100400100154

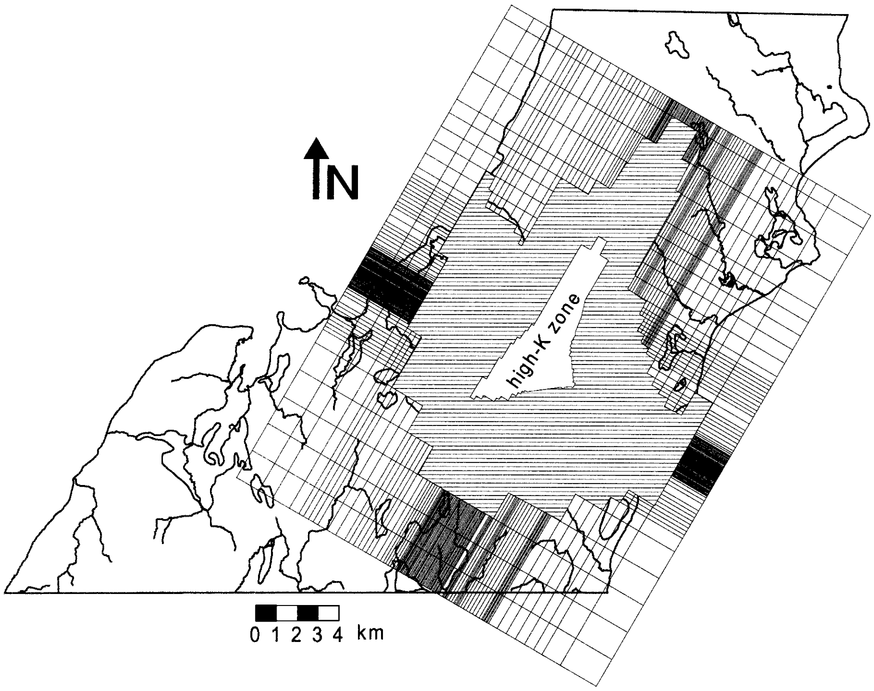


Fig. 12 High hydraulic-conductivity (K) zone in the MODFLOW model

Table 4 Lengths of recharge periods and recharge rates in the four recharge zones for steady-state and transient model runs

Recharge period	Length of period (no. days, month)	Recharge zone	Recharge rate (m/day)
Steady state	–	1	1.2E-03
	–	2	1.1E-03
	–	3	6.0E-04
	–	4	5.0E-04
1	31, October	1	4.0E-05
		2	3.0E-05
		3	8.0E-06
		4	5.0E-06
2	30, November	1	4.9E-03
		2	5.1E-03
		3	3.2E-03
		4	2.2E-03
3	91, December–February	1	0.00
		2	0.00
		3	0.00
		4	0.00
4	31, March	1	6.1E-03
		2	6.3E-03
		3	5.0E-03
		4	4.2E-03
5	30, April	1	1.5E-03
		2	1.2E-03
		3	9.2E-04
		4	8.5E-04
6	153, May–September	1	2.5E-04
		2	1.5E-04
		3	1.2E-04
		4	3.0E-05

maps (Fig. 4) and they were treated as no-flow boundaries in all layers.

Municipal wells for the City of Sturgeon Bay were modeled by removing water from the model at the location of each well. The average pumping rates were calculated by summing monthly pumping rates over a 1-year period for each well and converting the rate to units of m^3/day. Pumping rates were apportioned to each flow layer in each well by weighting the total pumping rate by the transmissivity of each flow layer using the method of McDonald and Harbaugh (1988).

Parameter values

Parameters required for the MODFLOW model include hydraulic conductivity, storage coefficient, specific yield, porosity, and recharge. Hydraulic-conductivity values were assigned based on the results of pumping tests and packer tests conducted as part of this study. In addition, results from pumping tests conducted by Sherrill (1975) were used. Vertical hydraulic conductivity was calculated using an estimated anisotropy ratio (K_h/K_v) of 10 based on the work of Bradbury (1982). Values of hydraulic conductivity used in the model are shown in Table 3.

A high hydraulic-conductivity (K) zone in the central area of the model domain was used in layers 5 through 10 (Fig. 12). The high-K zone was delineated on the basis of transmissivity estimates from specific-capacity tests using TGUESS (Bradbury and Rothschild 1985). This large area is topographically low, which suggests the occurrence of more intensively fractured and thus more easily eroded rock. Furthermore, head values in this area were unacceptably high in early model runs with the high-K zone not present.

 DOI 10.1007/s100400100154

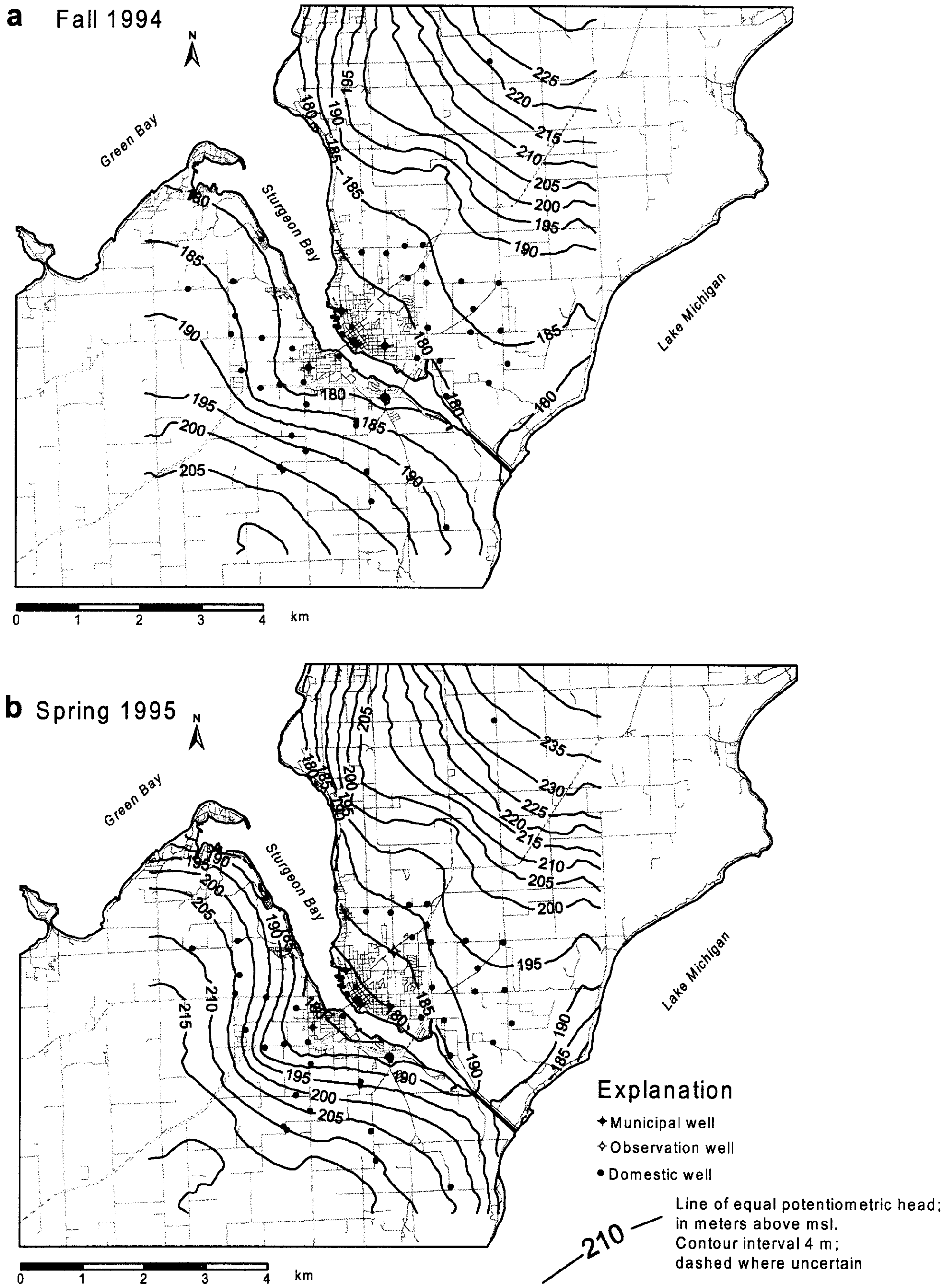


Fig. 13a, b Model-simulated hydraulic head at calibration targets. **a** Fall. **b** Spring

Values of storativity for the transient model, determined from pumping tests and packer tests, range from 0.0005 to 0.001. The storativity values were varied to assist in the calibration; a uniform value of 0.0006 was used in the calibrated model. Storativity in the unconfined layers is approximated by the specific yield, estimated at 0.01, a value typical for fractured aquifers (Bradbury et al. 1998).

Effective porosity is used in the particle-tracking model for velocity calculations. A uniform effective porosity value of 0.0005 was used in the numerical model. This seemingly low value is similar to a value from Bradbury and Muldoon (1994) who used effective porosity as a calibration parameter in a discrete-fracture model in central Door County. In addition, Muldoon and Bradbury (1998) used an effective porosity value of 0.0003 to successfully model tracer experiments conducted in a quarry four kilometers south of Sturgeon Bay. Furthermore, porosity values ranging from 0.0003 to 0.002 were calculated using fracture-density measurements from Bradbury and Muldoon (1994).

The areal distribution of recharge was assigned based on the presence of karst landforms and fractures (closed depressions, known sinkholes, exposed fractured rock).

 DOI 10.1007/s100400100154

Model cells overlying such features were initially assigned a recharge rate double the estimate obtained from the soil-infiltration model. These values were varied slightly during model calibration. Recharge rates were also varied in the transient model to reflect seasonal variability of recharge (i.e., very little in mid-winter and summer, high in November, March, and April). Six recharge periods were used in the final transient model (Table 4).

Model Calibration

Calibration of the steady-state model involved adjusting values of hydraulic conductivity and recharge within a reasonable range (i.e., within measured and estimated values) until the best match between measured heads (from the potentiometric maps) and modeled heads was attained. The hydraulic conductivity and thickness of stream sediments were also adjusted to calibrate modeled fluxes to measured base-flow values. The transient model was also calibrated by adjusting values of the hydraulic conductivity and thickness of stream sediments. The range of vertical hydraulic conductivity values for stream and lake sediments (0.005–1.5 m/day) were based on work by Bradbury (1982). Stream-sediment thickness was measured and estimated from fieldwork. Streamflows were measured in four locations on two streams in August 1995 (Fig. 5).

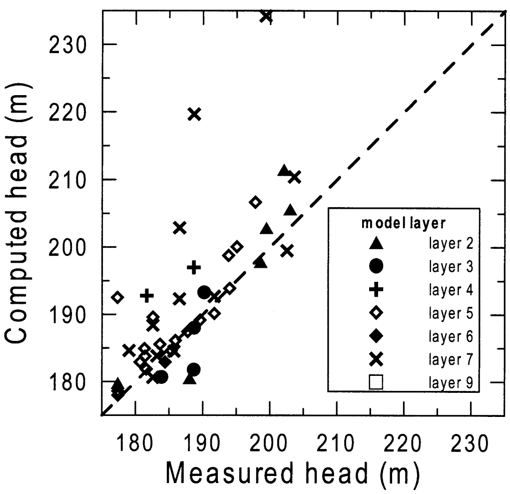
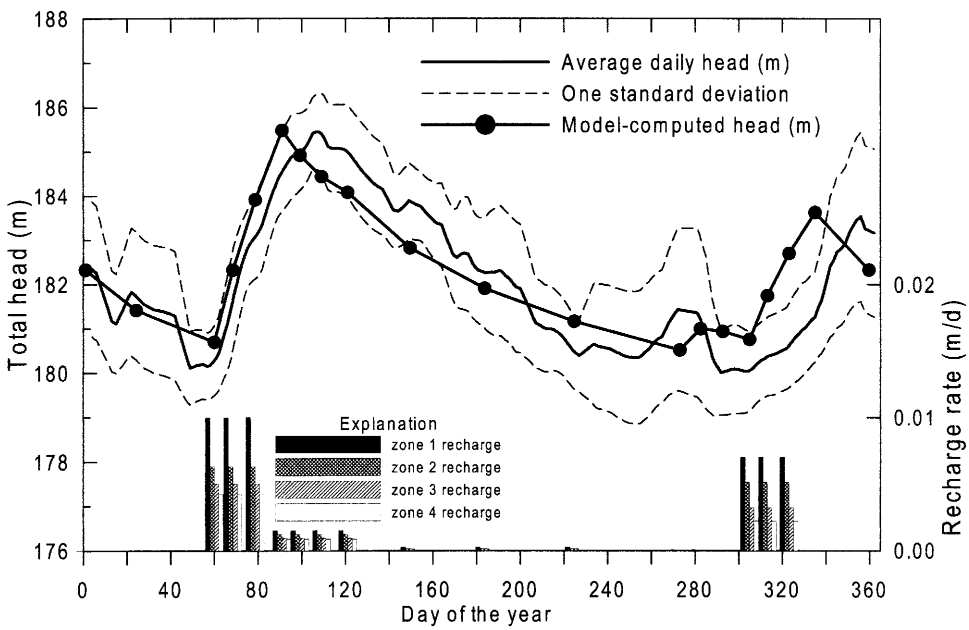


Fig. 14 Relation between measured and computed hydraulic heads at calibration targets

Steady-state model calibration consisted of repeated model runs attempting to match hydraulic heads in 75 calibration targets distributed among nine of the 12 model layers. The calibration targets were water levels in domestic wells measured during 1994 and 1995, and the vertical distribution of hydraulic head measured during the packer tests on monitoring wells DR-265 and DR-398 (Fig. 7). In addition, the long-term daily average water levels measured in well DR-265 were used to constrain the transient calibration. Calibration of the transient model was accomplished by adjusting recharge rates in each zone and in each period until the modeled heads matched measured heads in well DR-265.

The distribution of hydraulic head in model layer 7 (representing flow zone E; Gianniny et al. 1996) at transient time steps representing fall and spring conditions shows an acceptable reproduction of water levels at the calibration targets (Fig. 13; cf. Fig. 4). Model residuals range from –34.8 to +7.5 m, with a mean residual of –0.19 m (Fig. 14). Most of the data fall near the ideal 45° line of perfect calibration, but some outliers also occur. These outliers could be due to measurement error as well as model error or to problems of well construction in the target wells. The transient model acceptably reproduces the hydrograph from well DR-265 (Fig. 15). The computed heads are within one standard deviation of the

Fig. 15 Computed and measured long-term hydrograph of well DR-265, showing recharge in transient model



 DOI 10.1007/s100400100154

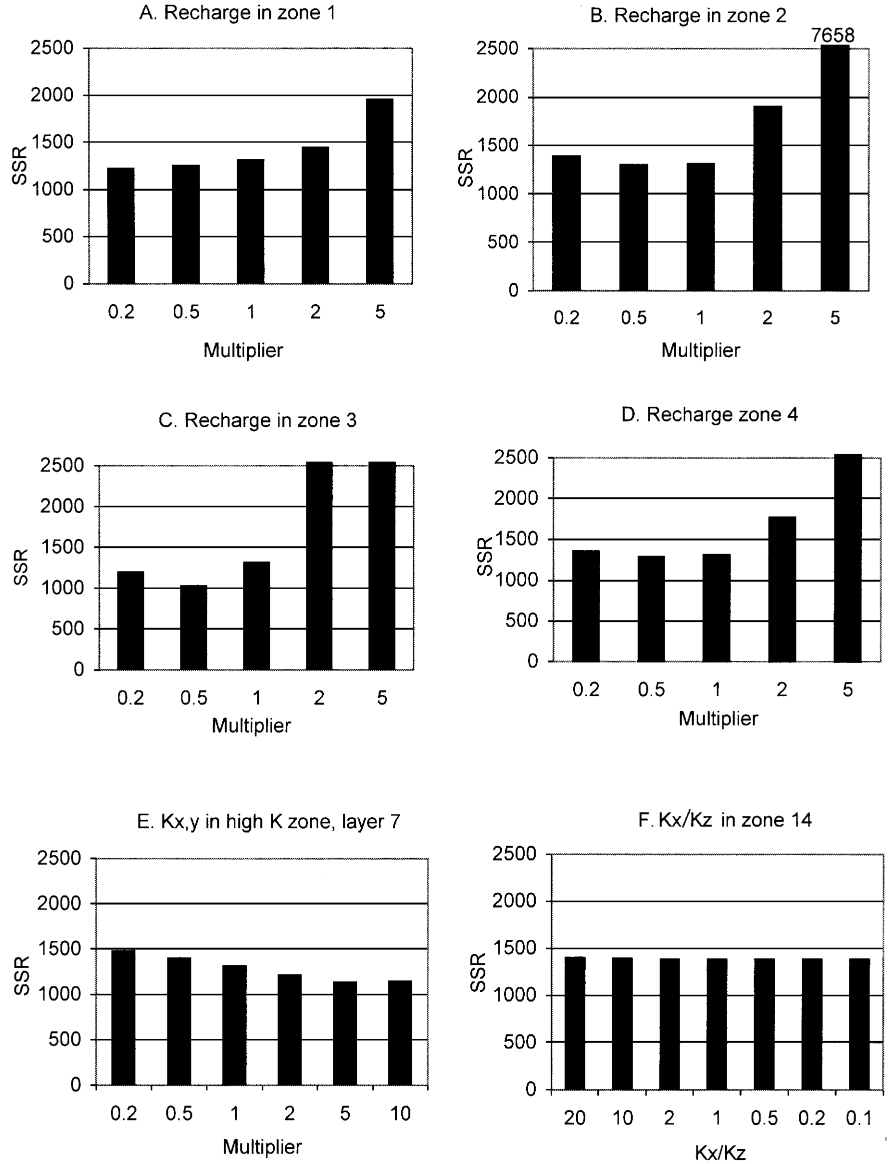


Fig. 16 Sensitivity analysis for selected model parameters. *SSR* is sum of squared residuals of head

nine-year mean water level for most of the simulation period.

In both the steady-state and transient models, the main source of inflow is recharge, whereas outflow is through river cells and wells. In the transient model, inflow is also derived from storage. Water-balance calculations for the steady-state and transient models have errors of less than 0.1%.

Model Sensitivity

Estimates of all parameters in the model have associated uncertainty. To examine uncertainty, sensitivity analyses were performed by systematically changing the value of one parameter within a plausible range and examining the effect on the sum of squared head residuals in the calibrated steady-state model. Sensitivity of recharge rates and K in selected zones in the steady-state model, plotted as the value of the sum of squared head residuals (SSR) versus the multiplier of the parameter, are shown in Fig. 16. The modeled heads are most sensitive to recharge rates, particularly in zone 3 which covers the highest percentage of the model area. Compared to recharge rates, modeled heads are insensitive to hydraulic conductivity (Fig. 16E), and the anisotropy ratio (K_x/K_z) in non-flow zones (Fig. 16F).

Some of the sensitivity graphs in Fig. 16 show that a multiplier other than 1.0 produces a slightly lower sum of squared head residuals. The parameter values which produced a lower SSR were not used because they were either outside of the plausible range of measured values or they produced unacceptable results in the transient model.

Particle Tracking

Particle tracking was performed using the MODPATH-3 code (Pollock 1994), chosen for its capability to do

 DOI 10.1007/s100400100154

Fig. 17 MODPATH-generated particle paths for the five city wells

reverse particle tracking in transient groundwater flow. MODPATH operates as a post-processor to the MODFLOW model, and uses the MODFLOW cell-by-cell mass-balance files to calculate flow velocities throughout the aquifer. MODPATH then tracks particles through the calculated flow field. Particles were initialized in rings of ten particles placed around the five municipal wells in flow zones open in each well. MODPATH then tracked these particles backwards in time through the transient-flow field until the particles reached the water table. The outline of the resulting paths delineates the zone of contribution for the well.

Particle-tracking simulations were done with steady-state and transient versions of the model, but only transient simulations were used for delineation of the final capture zones. To test the results of reverse particle tracking in a transient model, forward simulations were performed with the particles starting at ending locations determined by the reverse runs. The results were different from the reverse runs, implying that simple reverse particle tracking may not be appropriate in transient models. This is probably due to the temporal changes in the configuration of the water table and potentiometric surfaces in a transient-model run. To resolve this problem with reverse particle tracking in a transient model, an approach suggested by Zheng and Bennett (1995) was adapted, in which particles are started from wells at each time step in the transient model. Particles were started at the beginning of each of the 12 stress periods in the two-year model run. The resulting collection of particle paths outlines the transient-capture zone for each well.

In order to generate a conservative capture-zone analysis, the simulated pumping rates of the city wells were increased to the maximum pump capacity for each well before running the final transient particle-path simulations. For most of the wells, this pumping rate is about double the actual rate of use. Using the higher pumping rates produces slightly larger capture zones, and is considered appropriate for future planning scenarios in which water use in Sturgeon Bay might increase or one or more wells have to be taken off line for repairs.

The wells on the northern side of the city have capture zones extending nearly 10 km to the northeast, whereas capture zones for the wells on the south side of the city extend nearly 7 km to the southwest (Fig. 17). Groundwater travel times from the water table to the municipal wells vary with depth in the well but in all cases are quite short. The average travel time from the water

 DOI 10.1007/s100400100154

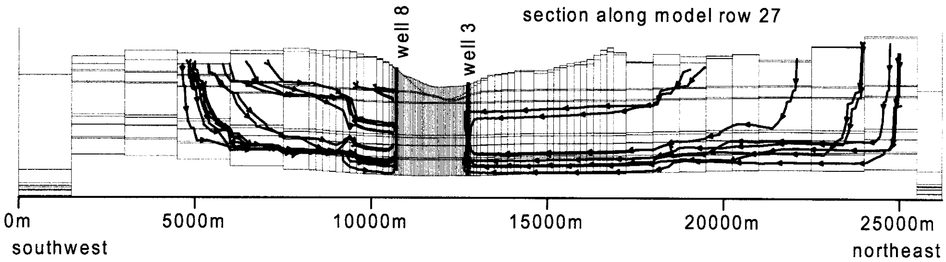


Fig. 18 Section along row 27, showing vertical particle movement

table to the wells was 152 days. The minimum and maximum travel times were 14 and 729 days, respectively. Several of the particles had paths originating in Sturgeon Bay, indicating that some municipal wells may be inducing the flow of surface water from the bay into the aquifer. All particles reached the water table or the bay within the two-year simulation time.

Effective porosity (n_e) is the only parameter used by MODPATH which is independent of the calibrated flow model. In order to examine the sensitivity of the particle travel times to effective porosity, particle-tracking runs were performed with n_e values ranging between 0.0003 and 0.002. Even with the higher value of n_e, particle travel times remained short. Using an effective porosity of 0.002, average travel time to a well was 416 days, with 90% of the particles traveling from the water table to the wells within two years. Average travel time to a well was 127 days using an effective porosity of 0.0003.

The near-horizontal flow zones clearly control groundwater movement to the municipal wells. Figure 18 is a section along model row 27 showing the vertical sense of particle movement to city wells 8 and 3. Particle movement is largely vertical from the water table to the first major flow zone. Upon entering a flow zone, particle movement is mostly horizontal.

Two-Dimensional Fracture Network Model

The saturated-zone particle tracking using the MODFLOW and MODPATH models delineates well capture zones for the saturated zone only. This procedure could underestimate the lateral extent of the capture zones because it does not account for lateral spreading in the unsaturated zone above the water table. The unsaturated zone in the Sturgeon Bay area, particularly in areas north and south of the city limits, can be up to 30 m thick. Recharging water moves through the shallow fracture network above the water table, and the complex fracture pathways might lead to significant lateral movement of water.

A stochastic, two-dimensional, discrete fracture-flow model (Rouleau 1988; modified by Bradbury and Muldoon 1994) was used to test the amount of lateral spreading which might occur in the unsaturated zone between the land surface and the water table. The model creates realizations of fracture networks based on statistical properties of fractures measured in the field, simulates saturated groundwater flow, and tracks hypothetical particles of water through the domain. The use of a saturated-flow model in the unsaturated zone is acceptable

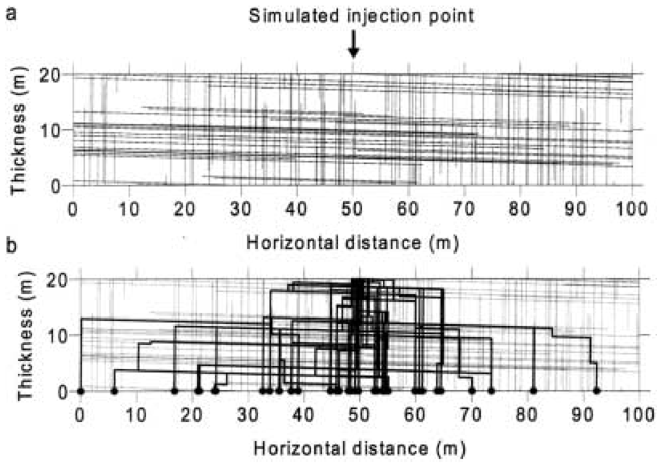


Fig. 19a, b Problem domain for the fracture-network model. **a** Simulated fractures. **b** Particle-tracking results. *Thick lines* are particle paths

because, during recharge events, the fracture network becomes saturated for short periods of time, whereas the rock matrix remains unsaturated. This model does not consider flow in the rock matrix.

The spreading analysis uses a hypothetical problem domain of a cross section 100 m long and 20 m thick. The heads at the top and bottom boundaries are constant, with a 5-m head loss across the section from top to bottom. The sides of the model domain are no-flow boundaries. Particles are injected along a 2-m-wide strip centered along the upper boundary. Simulated particles were initiated at 0.1-m increments across this distance (i.e., 21 particles). Three sets of fractures were simulated in the model, with statistical properties based on measurements from Bradbury and Muldoon (1994), and Roffers (1996). Set 1 represents near-horizontal bedding-plane fractures. Sets 2 and 3 represent near-vertical fractures (Fig. 19).

Based on 10 stochastic realizations of the fracture network, the lateral spreading at the 20-m boundary is centered 5.5 m down dip, with a standard deviation of 15.2 m (Fig. 19b). Assuming this trend is linear with depth, and that the average depth to groundwater beneath the capture zone boundaries is 40 m, the model analysis gives a horizontal spreading distance of about 26 m. However, this analysis contains many uncertainties, including local variations in fracture characteristics, water-table depth, and recharge rates. For the purpose of a wellhead protection study, a conservative lateral spread-

 DOI 10.1007/s100400100154

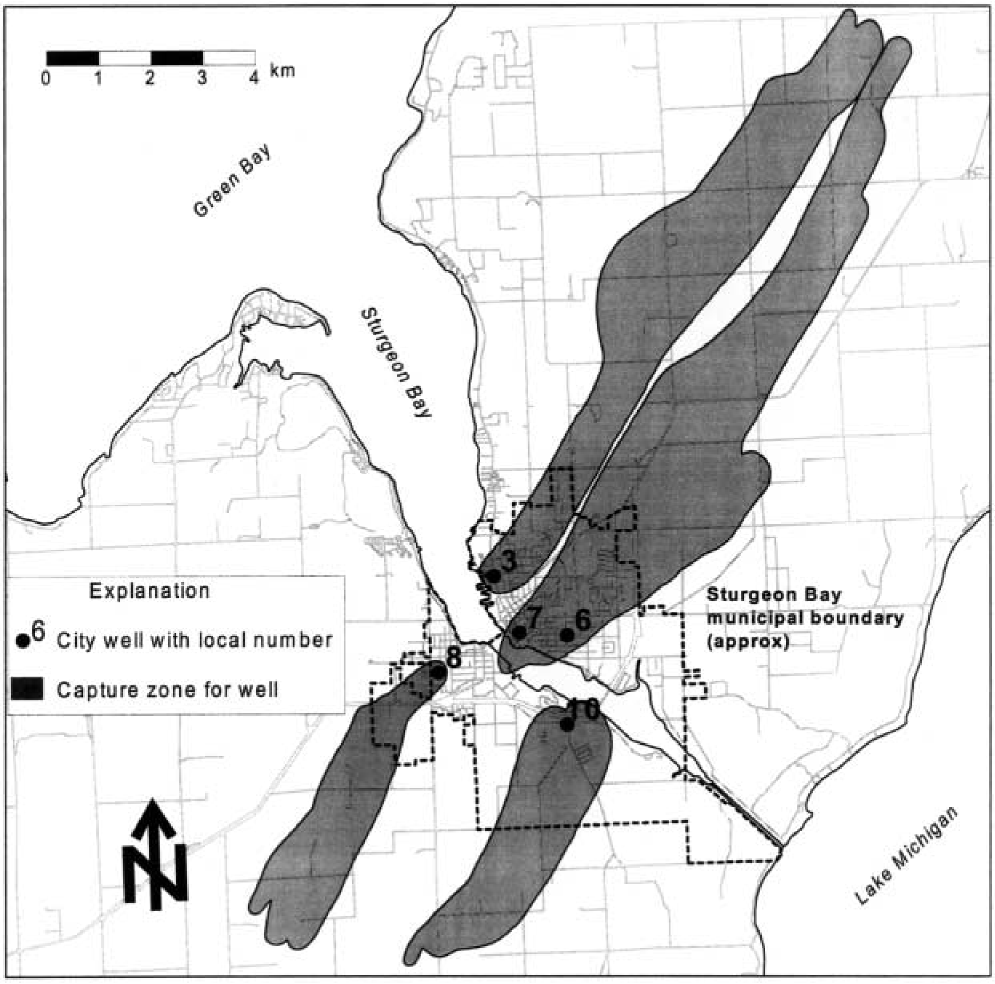


Fig. 20 Final extent of capture zones for the Sturgeon Bay municipal wells

ing distance of 100 m beyond the capture zones delineated in the three-dimensional model was chosen. The final capture zones were extended horizontally 100 m in every direction to account for this potential spreading. Although the results of the lateral spreading analysis for this study did not add a substantial amount of area to the capture zones, this process could be important in studies where capture zones are small or where the unsaturated zone is thick.

Results and Discussion

Results

Areal extent of capture zones

The capture zones for the Sturgeon Bay wells extend up to 10 km to the north and up to 7 km to the south of the city, as shown in Fig. 20. They were delineated by digitizing the boundaries of the collection of transient particle paths for each well (Fig. 17) and then extending the capture zones outward by 100 m to account for spreading in the unsaturated zone. Using this procedure, the capture zones for two wells (city wells 6 and 7) overlap, and are shown as one zone (Fig. 20). The transient particle paths also indicate that two wells (city wells 6 and 7) can potentially draw surface water from Sturgeon Bay. However, isotope data from water in city wells suggest that the amount of surface water is small.

Travel times to the Sturgeon Bay wells

Travel times from the land surface to the Sturgeon Bay wells are probably less than one year from anywhere in the capture zones. Longer travel times are also possible, given the complexity of the fractured groundwater system. However, it is unlikely that travel times ever exceed three years. The short travel times are a result of the combination of laterally continuous, high-K horizontal-flow zones and the extensive vertical fractures and karst features.

Such rapid travel times are far more rapid than in most other aquifers and are directly related to the hydrogeology of the fractured dolomite in the area. For comparison, travel times to municipal wells in a sandstone aquifer in Dane County, Wisconsin range from hundreds to thousands of years (Bradbury et al. 1996).

 DOI 10.1007/s100400100154

Discussion

Reliability of models and results

Questions always arise about the reliability and validity of capture zones generated by numerical models, and these concerns are clearly warranted given the complex hydrogeology of the study area. Although errors and alternative interpretations of the data are always possible, the analyses presented in this study are internally consistent and are also consistent with other work in Door County.

For example, the geochemical and isotopic analyses of groundwater in the study area are consistent with our model of rapid groundwater flow. All water samples are isotopically young and have been isolated from the atmosphere for less than 35 years. In addition, although this study did not include tracer experiments, the rapid groundwater velocities predicted by the model (average of 65 m/day) are consistent with reported groundwater velocities of 17 and 115 m/day from tracer experiments and contaminant monitoring in central Door County (Bradbury and Muldoon 1992). Furthermore, Muldoon and Bradbury (1998) observed groundwater velocities of up to 90 m/day in carefully controlled tracer experiments at a quarry four kilometers south of Sturgeon Bay.

Implications for other wellhead protection studies

The results of this study have significant implications for other wellhead protection studies in fractured carbonate-rock aquifers. A sufficiently detailed hydrostratigraphic model was critical to understanding the hydrogeology of the Sturgeon Bay area, and is a necessity for any serious hydrogeologic analyses in carbonate-rock aquifers. The work of Gianniny et al. (1996) was the basis for the conceptual model of the aquifer and allowed the use of a porous-media model to simulate groundwater flow and delineate zones of capture for the wells. This was desirable because the porous media model (MODFLOW) has features, such as the capability to simulate complex boundary conditions, which are not currently available in fracture models. The porous-medium approach to modeling can be used with success in large-scale studies of fractured carbonate rock if the detailed hydrostratigraphy is understood.

In fractured carbonate-rock aquifers, the groundwater flow velocities can be so high, and the resulting travel times so short, that the usual wellhead protection time-of-travel criteria (2, 5, 10 years, etc.) recommended by most wellhead protection manuals (e.g., United States Environmental Protection Agency 1987) have little meaning. In particular, it may be impossible to prioritize areas within the ultimate zone of capture based on time of travel to a well. For example, in this study some areas farther from the municipal wells are probably more critical than areas nearer to the wells because of the presence of the horizontal-flow zones which can rapidly conduct water to the wells from great distances.

Given a well-defined hydrostratigraphic model, the porous-media model MODFLOW is adequate for simulating flow in the dolomite aquifer as long as individual horizontal-flow zones are recognized and modeled as discrete layers. MODFLOW's lack of capability to explicitly simulate fracture flow is balanced by its flexibility in simulating the complex boundary conditions found in this real-world problem.

References

Bradbury KR (1982) Hydrogeologic relationships between Green Bay of Lake Michigan and onshore aquifers in Door County, Wisconsin. PhD Thesis, University of Wisconsin, Madison

Bradbury KR, Muldoon MA (1992) Hydrogeology and groundwater monitoring of fractured dolomite in the Upper Door Priority Watershed, Door County, Wisconsin. Wisconsin Geol Nat Hist Surv Open File Rep 92-2

Bradbury KR, Muldoon MA (1994) Effects of fracture density and anisotropy on wellhead protection area delineation in fractured-rock aquifers. Appl Hydrol 2:17–23

Bradbury KR, Rothschild ER (1985) A computerized technique for estimating the hydraulic conductivity of aquifers from specific capacity data. Ground Water 23:240–246

Bradbury KR, Muldoon MA, Zaporozec A, Levy J (1991) Delineation of wellhead protection areas in fractured rocks. US Environ Prot Agency, Office of Water, EPA 570/9-91-009

Bradbury KR, Swanson SW, Oelkers E (1996) Delineation of groundwater capture zones for municipal wells in Dane County, Wisconsin. Final Report to Wisconsin Dept Nat Resources

Bradbury KR, Rayne TW, Muldoon MA, Roffers PD (1998) Application of a discrete fracture flow model for wellhead protection at Sturgeon Bay, Wisconsin. Wisconsin Geol Nat Hist Surv Open File Rep 98-04

Eckenfelder Inc. (1997) Guidelines for wellhead and springhead protection area delineation in carbonate rocks. US Environ Prot Agency Publ EPA 904-B-97-003, Groundwater Prot Branch, US Environ Prot Agency

Environmental Simulations Inc. (1996) Groundwater Vistas, advanced model design and analysis software. Environmental Simulations Inc, Herndon, Virginia, USA

Gianniny GL, Muldoon MA, Simo JA, Bradbury KR (1996) Correlation of high permeability zones with stratigraphic features in the Silurian Dolomite, Sturgeon Bay, Wisconsin. Wisconsin Geol Nat Hist Surv Open File Rep 96-07

McDonald MG, Harbaugh AW (1988) A modular three-dimensional finite-difference ground-water flow model. US Geol Surv Techniques of Water-Resources Investigations 06-A1

McMahon Associates Inc. (1991) Evaluation of water supply, distribution and storage systems for the Sturgeon Bay utilities, Sturgeon Bay, Wisconsin. McMahon Rep No 1907-88470

Muldoon MA, Bradbury KR (1998) Tracer study for characterization of groundwater movement and contaminant transport in fractured dolomite. Wisconsin Geol Nat Hist Surv Open File Rep 98-02

Pollock DW (1994) User's guide to MODPATH/MODPATH – PLOT, Version 3. A particle-tracking post-processing package for MODFLOW, the U.S. Geological Survey finite difference ground-water flow model. US Geol Surv Open File Rep 94-464

Roffers P (1996) Multiscale analysis of vertical bedrock fractures in Door County, Wisconsin. MSc Thesis, University of Wisconsin, Madison

Rouleau A (1988) A numerical simulator for flow and transport in stochastic discrete fracture networks. Natl Hydrol Res Inst NHRI Paper 39, Saskatoon, Saskatchewan, Canada

Sherrill MG (1975) Ground-water contamination in the Silurian dolomite of Door County Wisconsin. Ground Water 13:209–213

Sherrill MG (1978) Geology and ground water in Door County, Wisconsin, with emphasis on contamination potential in the Silurian dolomite. US Geol Surv Water Supply Paper 2047

DOI 10.1007/s100400100154

Stieglitz RD, Dueppen TJ (1994) Mapping and inventorying of geologic features in the Sturgeon Bay-Red River Priority Watershed. Tech Rep University of Wisconsin, Green Bay

Stieglitz RD, Johnson SB (1996) Mapping and inventorying of geologic features in the Upper Door Priority Watershed. Tech Rep University of Wisconsin, Green Bay

Swanson SK (1996) A comparison of two methods used to estimate groundwater recharge in Dane County, Wisconsin. MSc Thesis, University of Wisconsin, Madison

Theis CV (1935) The lowering of the piezometer surface and the rate and discharge of a well using ground-water storage. Trans Am Geophys Union 16:519–524

United States Environmental Protection Agency (1987) Guidelines for delineation of wellhead protection areas. US Environ Prot Agency, Office of Ground-Water Prot, Washington, DC, USA

Zheng C, Bennett GD (1995) Applied contaminant transport modeling. Van Nostrand Reinhold, New York, NY, USA

 DOI 10.1007/s100400100154