Evaluation of Wellhead Protection Area Delineation Methods, Applied to the Municipal Well Field at Elmore, Ottawa County, Ohio[1]

JEFFERY K. BATES[2] AND JAMES E. EVANS[3], Department of Geology, Bowling Green State University, Bowling Green, OH 43403

ABSTRACT. This study evaluates several different delineation methods that are used for Wellhead Protection programs, as mandated by the Safe Drinking Water Act Amendments of 1986. The municipal well field for the village of Elmore utilizes the regional aquifer (Silurian Lockport Dolomite, a dense, extensively fractured carbonate) which is overlain by a leaky confining layer (glacial till). Drilling records and water surface elevations from 444 water wells within a region 330 km² surrounding the well field were used to generate maps of the potentiometric surface, bedrock elevation and surficial layer thickness. In addition, field observations were made of the aquifer from local rock quarries for porosity types, percent porosity, fracture density, and fracture orientation. The data suggest that groundwater flow is directed northward, toward Lake Erie, and that recharge occurs through the leaky confining layer.

Three groundwater flow models were used, an analytical (GPTRAC), semi-analytical (CAPZONE) and finite difference (MODFLOW) model. The three models predicted zones of influence that were generally the same size, however they differed in shape and asymmetry due either to implicit model assumptions or different model calculations for transmissivity and recharge. A sensitivity analysis identified aquifer transmissivity, porosity, and anisotropy as the critical variables in determining which model is appropriate to use in a Wellhead Protection Area delineation and in improving the accuracy of such a model.

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INTRODUCTION

Wellhead Protection Programs

The Safe Drinking Water Act Amendments of 1986 mandate a national program to protect municipal well fields from groundwater contamination. The legislation tasked the U.S. Environmental Protection Agency (US EPA) with establishing procedures and guidelines (US EPA 1987, 1989, 1991) that are to be followed by the states in establishing and implementing state Wellhead Protection (WHP) Programs. At the state level, a WHP program must designate the state and local agencies responsible for implementing and enforcing it.

At the local level, individual Wellhead Protection (WHP) areas must be designated for municipal well fields, recognizing what area around the well field is vulnerable to groundwater pollution. A complete WHP plan would show the extent of the WHP area, inventory all potential pollution sources with that WHP area, include a management plan for use of the groundwater resources within a WHP area, include a contingency plan to follow in the event of groundwater contamination, list procedures to follow for the location of future wells, and finally, demonstrate that there was public participation in the development and implementation of the WHP plan (US EPA 1987).

Many of the above criteria involve public policy decisions, but the critical *scientific* step involves the delineation of a WHP area around each municipal well field. The size and shape of a WHP area is based upon time-of-travel (TOT) zones. A one-year TOT zone is defined as the maximum distance that a groundwater contaminant could travel towards a pumping well (discharge zone) within one year. WHP programs for the State of Ohio are requested to calculate one-year and five-year TOT zones as the basis for delineating the size of a WHP area around a municipal well field. It should be noted that TOT zones are not necessarily circular in shape. A variety of hydrologic parameters could produce an elliptical shaped TOT zone, with most of the area "upstream" of the well, because that will be the portion of the flow field that is diverted toward the well.

Six different delineation methods have been proposed for determining TOT zones, each varying widely in their difficulty of application, technical sophistication, and hydrogeological accuracy (US EPA 1987, 1991). The methods include: (1) drawing a circle of arbitrary radius around each well; (2) modifying the size of such an arbitrary circle by using some basic hydrogeological data from the region; (3) using data from somewhere else, with similar geology and hydrology, to draw a variable shape radius around the well; (4) using analytical or semi-analytical methods (based upon the equations for groundwater flow, typically using certain simplifying assumptions); (5) actually measuring the flow field using dye-tracing experiments or geophysical field methods; and (6) using numerical models (computer-generated models that approximate groundwater flow).

For any given WHP program, it is not always clear which method listed above is appropriate to use. On the one hand, simplistic calculations (such as the first several methods) are rarely accurate. On the other hand, actual field measurements can be difficult or expensive to obtain, and the mathematical models require the services of trained professionals, obviously increasing the costs. For many communities, the higher expense of the more

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[2]Present Address: Environmental Department, Columbus State Community College, 550 E. Spring St., Columbus, OH 43215

[3]Address all correspondence to: James E. Evans, Department of Geology, Bowling Green State University, Bowling Green, OH 43403

sophisticated models may not be justified. An additional cost, after formulating a WHP plan, is for groundwater monitoring programs to assess the success of the plan or need for modification (Meyer 1990). These issues pose difficult decisions for communities, few having the adequate technical resources to even make an informed choice. The scale of this undertaking can be understood as there are approximately 1,200 communities in Ohio that rely on groundwater for a public water system (Ohio EPA 1992).

This project has three goals, the first was to provide assistance to local government agencies by providing the delineation of a WHP area for Elmore. The second goal is to describe the varying geology and hydrogeology often found in northwest Ohio, so as to demonstrate the varying degrees of groundwater vulnerability. The third goal is to assess the difference between the results of analytical, semi-analytical, and numerical models and to perform a sensitivity analysis. Sensitivity analysis is a method where individual variables are changed in order to assess the importance of those variables toward the outcome of the model. The goals of sensitivity analysis are to identify which variables cause the greatest change in the model outcome, hence are the critical data to obtain.

Background Geology and Hydrogeology

The village of Elmore is located on the Portage River, in southwestern Ottawa County, OH (Fig. 1). Elmore's well field includes four wells (the oldest two are used infrequently) serving approximately 1,600 people. The wells are located in the Lockport Dolomite, the regional aquifer and part of the "Ohio-Indiana carbonate bedrock and glacial regional aquifer" (Swain and Johnson 1989).

The Lockport Dolomite is a massively bedded, gray-white, finely- to coarsely-crystalline, fossiliferous, porous, biostromal and biohermal dolomite, with interstratified nodular chert near the base (Sparling 1965, 1971). The unit is about 110 m thick in the Elmore area, thinning both to the east and west. The Lockport Dolomite is conformably underlain by undifferentiated strata (mostly gray shales with interbedded dolomite) of Silurian age (Janssens 1977) and is unconformably overlain by the Silurian Salina Group (gray-brown dolomites and argillaceous dolomites). Within the study area, the Lockport Dolomite is the only fractured carbonate unit of sufficient thickness to serve as an aquifer (Ohio DNR 1970).

In this region, the Lockport Dolomite was deposited as a platform carbonate on the east flank of the Findlay Arch, which is a northern extension of the Cincinnati Arch (Fig. 1). The Findlay Arch served as a topographic high that influenced the formation and position of carbonate build-ups during Silurian time (Sparling 1965, Janssens 1977, Stout 1941). The resulting carbonate build-ups have been interpreted as reefs and associated deposits (Lowenstrom 1950). The unconformity at the top of the unit has been interpreted as the result of Silurian regression and subaerial exposure (Riley 1980).

Most of the porosity and permeability in the Lockport Dolomite is secondary, or a consequence of diagenesis (dissolution of calcite and replacement by dolomite), which was enhanced by dissolution along joints and fractures. Estimates for secondary porosity in the Lockport Dolomite range from zero to 25% (Andersen 1980, Requarth 1978). Individual pore sizes range from less than 1.0 mm to cavern-sized holes, as observed in quarry walls (Requarth 1978, Kahle 1988). Some secondary porosity appears to be fabric selective, for example reef zones typically have porosity up to one-third higher than adjacent inter-reef rock (Andersen 1980). Other important hydrogeologic features include karstification features within the dolomite (Kahle 1988), and the formation of bedrock valleys due to the erosion of overlying units by streams and by Late Cenozoic glaciation (Breen and Dumochelle 1991). Buried bedrock valleys were then formed when the valleys were subsequently filled by glacial deposits (Ohio DNR 1970). Finally, most of the bedrock surface was covered by glacial deposits.

Dissolution-enhanced joints and fractures within the Lockport Dolomite are extremely important as pathways for recharge or discharge for the aquifer, and as potential pathways for groundwater contamination. Fracture trace analysis (e.g., Lattman and Parizek 1964) in the study area has revealed a dominant set of fractures and joints with a northeast-southwest trend, and a secondary orthogonal set with northwest-southeast trend (Armstrong 1976, Kihn 1988, Dean et al. 1991). At bedrock quarries in this region, individual fractures range from a few centimeters to a few tens of meters in length (Motamedi 1982), up to 30 cm in width, and form sub-horizontal

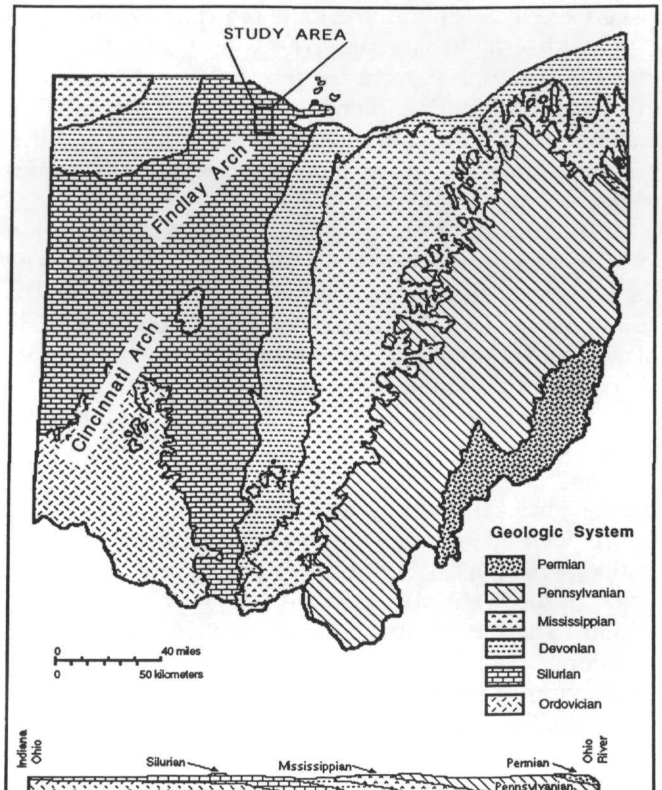


FIGURE 1. Bedrock geology map of the state of Ohio, with study area indicated (modified from Ohio DNR 1983).

sets that are interconnected by sub-vertical sets (Lanz 1979, Andersen 1980, Requarth 1978). The effective porosity (the proportion of porosity available for fluid flow) is estimated to be 0.6 to 6.2% for fractured carbonate aquifers in the region (Roadcap 1990).

The surficial materials are predominantly tills, ranging in thickness from zero (exposed bedrock) to about 7.0 m in the study area (Goldthwait et al. 1971, Forsyth 1971). The hydrogeological properties of these tills are difficult to characterize, due to calcium carbonate cementation and fracturing. Slug tests on similar tills in the region suggest hydraulic conductivities of about 10^{-7} to 10^{-8} cm/sec (McKay et al. 1993, Steen 1993). There are localities where the till is covered by glacial-lacustrine silts and clays up to several meters thick. Soils in the region include the Lenawee-Kibee-Colwood association, Hoytville-Nappanee association, and Castalia-Milton association. These are all typically silty-clay loams with relatively low permeability, and are often drained when used for farming (Ohio DNR 1981).

The aquifer has an average annual recharge rate of 8 to 13 cm/yr (Norris 1959). Water levels in observation wells fluctuate about 1.0 to 1.5 m annually (Ohio DNR 1970, US Geological Survey 1990). Natural flow is northward toward Lake Erie, with minor amounts of natural discharge at springs and to surface waters. The baseflow component of the flow of the Portage River is 0.26 m^3/sec, which is exceeded 83% of the time (Ohio DNR 1966).

Wells in the region are situated above buried bedrock valleys, or at intersecting joint and fracture sets. Groundwater flow can be highly variable—wells having high yields from fracture zones are juxtaposed with wells having low yields from unfractured and impermeable rock (Breen and Dumochelle 1991). High-yield wells in the region have a specific capacity of 29 liters/min/m of drawdown (Norris and Fidler 1971).

Pump tests on wells within a 20 km radius of Elmore indicates transmissivity ranges from 22 to 297 m^2/day (Ohio DNR 1970) and storativity ranges from 2.0×10^{-3} (Winegardner 1971) to 1.5×10^{-5} (Dunbar Drilling 1988). This range of values was used in initial runs of the groundwater flow models, but in calibrating the results to pump test data from Elmore's wells, it was found that lower transmissivity values were applicable.

METHODS

Field Studies

Aquifer properties were evaluated at surface outcrops of the Lockport Dolomite at the GenLime Group Quarry in Genoa (Clay Township, Ottawa County) and at the Ohio Lime Company Quarry in Woodville (Woodville Township, Sandusky County). Both quarries are within 5.0 km of the well field at Elmore. The data that was obtained included percent porosity, porosity types, pore size dimensions, fracture width, fracture orientation, and fracture density. These values were used in the groundwater flow models.

Geological Maps

A data base of over 700 well logs from the region were evaluated for location, date drilled, static water level, and depth to bedrock. Many wells were eliminated due to incomplete information, location outside the study area, or steep hydraulic gradients resulting from adjacent pumping wells or quarry dewatering operations. A final data base of 444 wells (Fig. 2) were used and digitized using a Geographical Information System (GIS). Detailed data descriptions are given in Bates (1994).

A base topographic contour map was created from portions of nine adjacent U.S. Geological Survey topographic quadrangle maps, and an arbitrary x- and y-coordinate grid established with a grid spacing of 305 m (1,000 ft). Digitized data included the latitude and longitude of each well, water surface elevation, surficial layer thickness, and bedrock elevation. Maps for water surface elevation, elevation of bedrock, and surficial layer thickness were generated from the digitized data base using the contouring program SURFER (Golden Graphics 1989). Portions of these maps were used to construct the groundwater flow models. For model calculations, the grid was rotated 25° counter-clockwise, to parallel the dominant orientation of fractures and joints.

Pumping Well Data

Historical pumping data for the Elmore municipal well field were obtained and evaluated. The oldest two wells are maintained on standby as emergency sources. The two newer wells are 30 cm diameter wells drilled to 123 m depth, with the upper 12 m cased, through the surficial layer. The average daily pumping rates are 170 m^3/day and 290 m^3/day, respectively, from the two wells. The wells are sufficiently close together (within 120 m) to be treated as a single point of discharge for the simpler models, and as separate discharge points for the more complex models.

Delineation Methods

For comparison purposes, the arbitrary fixed radius and calculated fixed radius methods were determined. The analytical method used in this study is the General Particle Tracking (GPTRAC) method. The aquifer is considered to be unconfined, with "best-guess" estimates of a transmissivity of 70 m^2/day, porosity of 2%, and a hydraulic gradient of 0.015 toward the NNE.

The semianalytical method used in this study is CAPZONE (Bair et al. 1991), which computes drawdown at wells and then superimposes this drawdown on a potentiometric surface map created from the SURFER file. An advantage of using CAPZONE in this study is the availability of dealing with leaky confining layers using a Hantush-Jacob approach. TOT zones are created from the endpoints of a reverse particle tracking program (Schafer 1987), in this case a model called GWPATH was used. Initial steps toward using this model involved demonstrating that other pumping wells in the region do not affect the zone of influence around Elmore's well field. The same model parameters were used as with the analytical model above, in addition the storativity was set as 1.0×10^{-3}, the aquifer conductivity was set as 7.0×10^{-4} cm/sec, the hydraulic conductivity of the semi-confining layer was set as 2.0×10^{-7} cm/sec, and the average thickness of the semi-confining layer

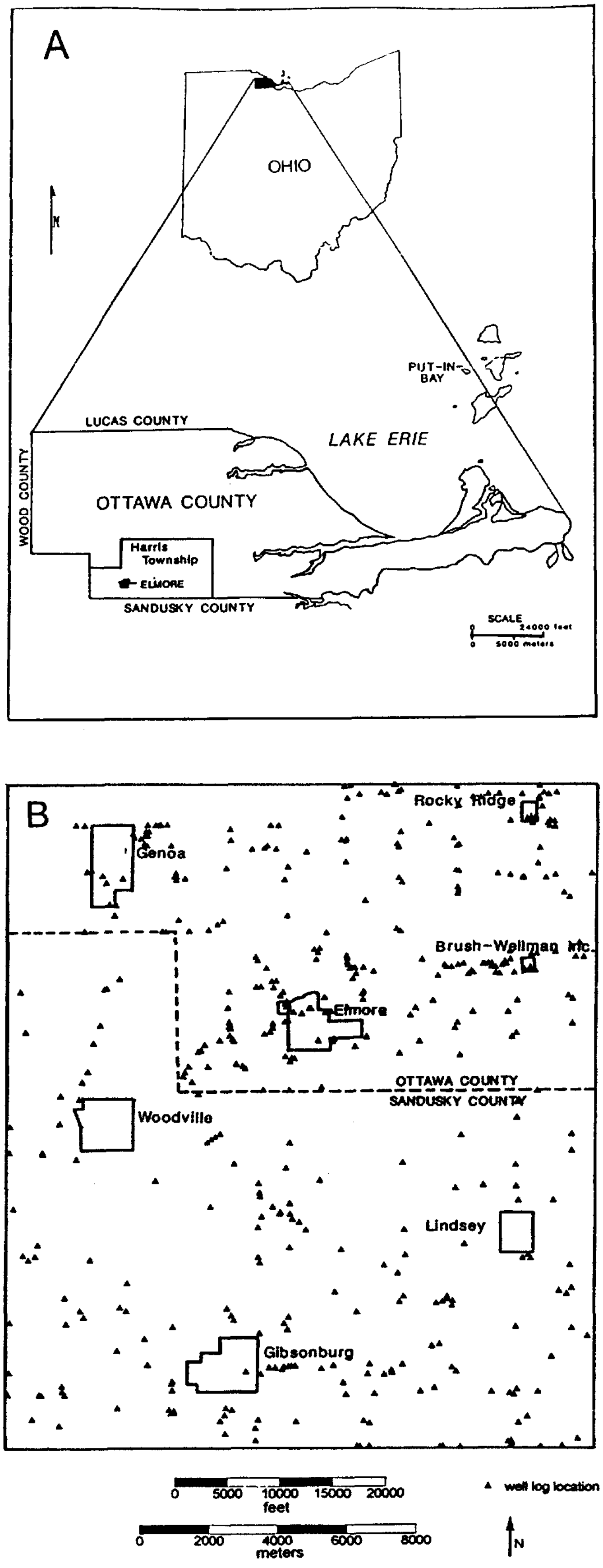


FIGURE 2. Maps showing (A) location of the study area around the town of Elmore, Ottawa County, in northwestern Ohio; and (B) locations of the 444 wells used for construction of geological and hydrologic maps in this study.

was set as 7.0 m. Calibration of the model was accomplished by comparison to the results of a pump test performed on Elmore's well no. 3 in 1987. These results indicated that model parameters needed to be adjusted to an aquifer hydraulic conductivity of 1.6×10^{-4} cm/sec, transmissivity of 15.0 m^2/day, and storativity of 4.0×10^{-4} in order to duplicate the observed drawdown and response time.

The numerical model used in this study was MODFLOW (McDonald and Harbaugh 1988), which includes a reverse particle tracking method called MODPATH. MODFLOW is a modular, three-dimensional, finite-differences model which accounts for information not included in the other models, including surface water-groundwater interactions, aquifer heterogeneity, and various boundary conditions. The block matrix used for MODFLOW was virtually identical as the one used for CAPZONE. Discretization of the model area was performed by breaking it into variable grid sizes, with a finer-scale grid around wells and natural recharge or discharge areas. A three-layer configuration was used in MODFLOW, with the surficial layer, Lockport Dolomite, and underlying strata designated as layers 1, 2, and 3. Appropriate boundary conditions were assigned (for example, layer 3 represented "no flow" cells to account for the impermeable lithologic contact). Initial runs of MODFLOW used the values determined from the calibrated CAPZONE model (see above), but these were changed slightly to calibrate MODFLOW results to the 1987 pump test results. A best-fit calibration determined that the surficial layer had a hydraulic conductivity of 2.0×10^{-7} cm/sec and a vertical leakage rate of 1.1×10^{-5} m/day, and that the aquifer transmissivity was 7.0 m^2/day. The aquifer recharge rate was then estimated to be 0.05 m/yr, and the Portage River then found to have a vertical leakage of 3.0×10^{-4} m/day. Additional details can be found in Bates (1994).

RESULTS

Field Studies

Fracture size, orientation, and density were described from quarry outcrops. The dominant orientations are NW-trending, with a secondary orthogonal set, which is consistent with the results of previous workers (Armstrong 1976, Kessler 1986). Porosity descriptions and estimates were also made at quarry outcrops. The porosity values ranged from zero (in unfractured carbonate) to 0.30 (in fracture zones), and the average porosity for the entire aquifer was estimated as 0.02.

Geological and Hydrogeological Maps

Data from 444 wells was used to construct a bedrock elevation map (Fig. 3), an isopach map of surficial layer thickness (Fig. 4), and a potentiometric surface map (Fig. 5). Bedrock relief in the study area is about 37 m. Local bedrock highs are typically reef bioherms, and many of these are actively quarried. Surficial thickness ranged from zero to 17 m, with an average thickness of about 7 m. In this study area, surficial layer thickness is inversely related to elevation of the bedrock surface. The potentiometric surface ranges from 168 m to 207 m,

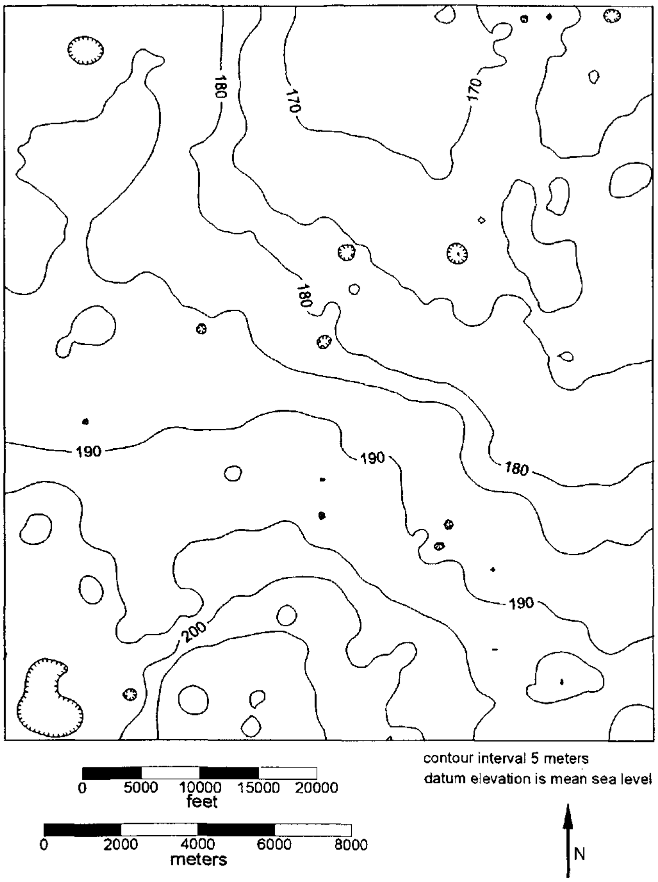


FIGURE 3. Map of the elevation of the bedrock surface, generated from well data, surface outcrops, and data from rock quarries.

increasing generally from north to south. Local depressions in the potentiometric surface correlate to pumping wells, quarry dewatering operations, and bedrock lows.

Arbitrary Radius Method

For comparison purposes only, the arbitrary radius method is shown in Fig. 6A. Various states use different values, including the Illinois minimum of 122 m (400 ft) and maximum of 305 m (1,000 ft), Nebraska (same diameter), and Massachusetts (762 m or 2,500 ft). These circular TOT zones do not account for numerous variables.

Analytical Method

The analytical method, model GPTRAC, is based upon simplifications of the groundwater flow equations. The 1, 5, and 10 year TOT zones are shown in Fig. 6B. In comparison to the arbitrary radius method, these TOT zones are strongly asymmetrical, and demonstrate how the capture zones are directed up gradient of the wellfield. While the analytical method accounts for a greater number of the hydrogeological variables, it does not account for the effects of drawdown of the potentiometric surface due to pumping.

Semianalytical Method

Prior to calculating the TOT zones, CAPZONE was used to calculate the drawdown of the potentiometric surface. A preliminary calculation was made to show that other pumping wells within the region did not affect the well field at Elmore (Bates 1994). CAPZONE was then used to calculate drawdown in the zone of influence around Elmore's well field, using hydrologic variables from the 1987 pump test. The drawdown results were 14 m and 23 m at the two wells, respectively, and the radius for the zone of influence was about 600 m (Bates 1994).

The 1, 5, and 10 year TOT zones were then calculated, using the hydrologic data, as calibrated from the 1987 pump test, and with the modifications of the flow field required by drawdown in the zone of influence (Fig. 7A). The results show asymmetrical shaped TOT zones somewhat intermediate in size and shape to the arbitrary radius and analytical methods. A sensitivity test was run, using the 5-year TOT zone as a comparison standard. Changing transmissivity from 94 m^2/day to 15 m^2/day to 4 m^2/day reduced the 5-year TOT zone by approximately two-thirds (Fig. 7B). A change in porosity values from 0.2% to 2% to 10% greatly affected the size and asymmetry of the 5-year TOT zone (Fig. 7C). Finally, changes in the rate of pumping had minimal effects on the size and shape of the 5-year TOT zone (Fig. 7D).

Numerical Methods

The MODFLOW model shows that drawdown in the leaky confining layer was about 2.5 m. Drawdown in the aquifer was 14 m and 24 m for the wells, and the

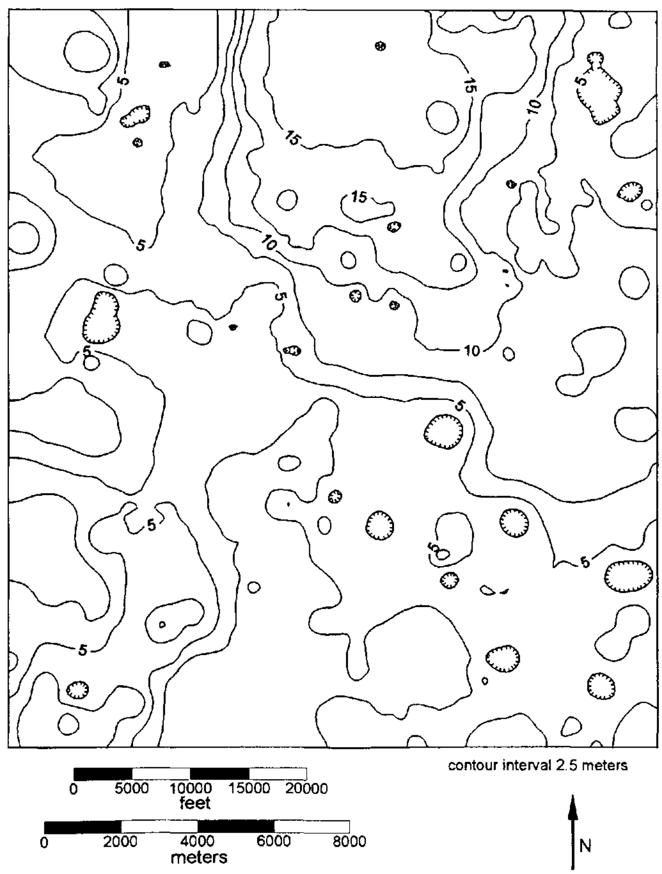


FIGURE 4. Isopach map of the thickness of the surficial layer (glacial till) in the study area, generated from well data and surface exposures.

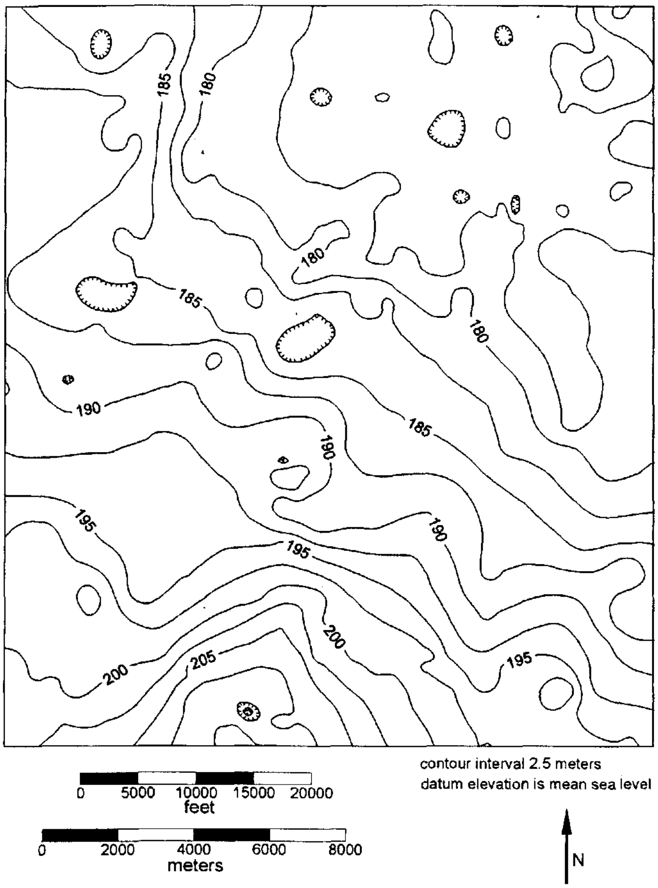


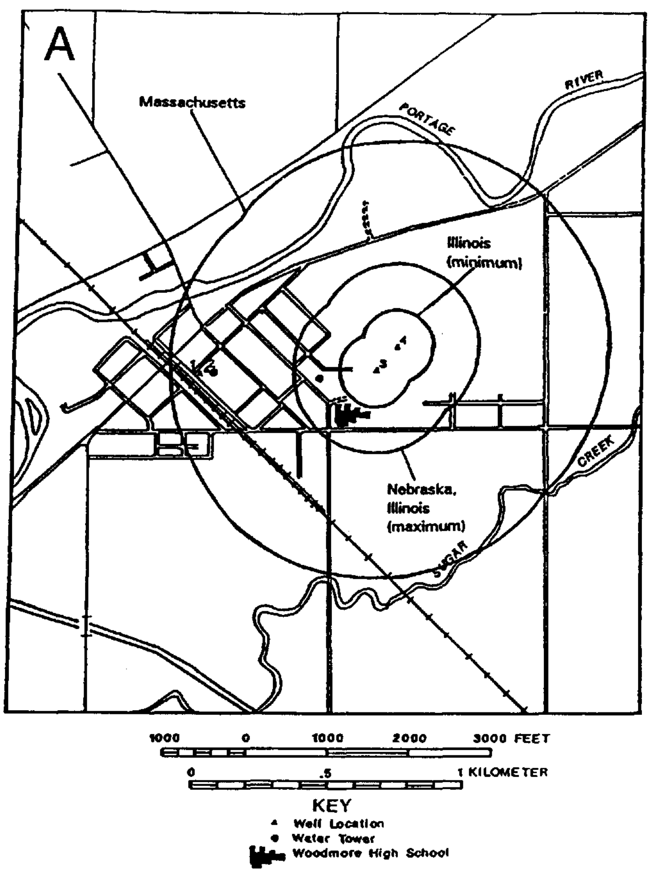
FIGURE 5. Map of the elevation of the potentiometric surface, as interpreted from water surface elevations in wells.

zone of influence had a radius of 760 m from the pumping wells. MODFLOW allows for calculation of a volumetric water budget for the well field, showing that most of the discharge from the well field is due to stimulated recharge (Table 1).

The 1, 5, and 10 year TOT zones were determined using the reverse particle tracking method MODPATH (Fig. 8A). A sensitivity test was done, using the 5-year TOT zones as a comparison standard. A range of transmissivity values, from 37 m^2/day to 7 m^2/day to 2 m^2/day produced smaller capture zones (Fig. 8B). Changing the pumping rate had a relatively minor effect on the size and shape of the capture zone (Fig. 8C). Finally, changing the aquifer anisotropy ratio (horizontal to vertical ratios of hydraulic conductivity) from 1:1 to 3:1 to 10:1 had an effect on the asymmetry of the capture zone, showing the importance of the dominant fracture trends in the bedrock (Fig. 8D).

DISCUSSION

The major difficulty in determining the size of a WHP zone for these types of aquifers is dealing with aquifer anisotropy, especially the effect of dissolution-enhanced fractures and joints. One general assumption is that the minimum size of a WHP zone should be 100 times the average fracture spacing (U.S. EPA 1991), which held generally true in this study (fracture spacings of 0.5 to 2.0 m, versus the radius of TOT zones from 120 m to 900 m). This does not account for the effect that fractures have on the asymmetry of the TOT zone. Such general rules also do not account for the effect of horizontal



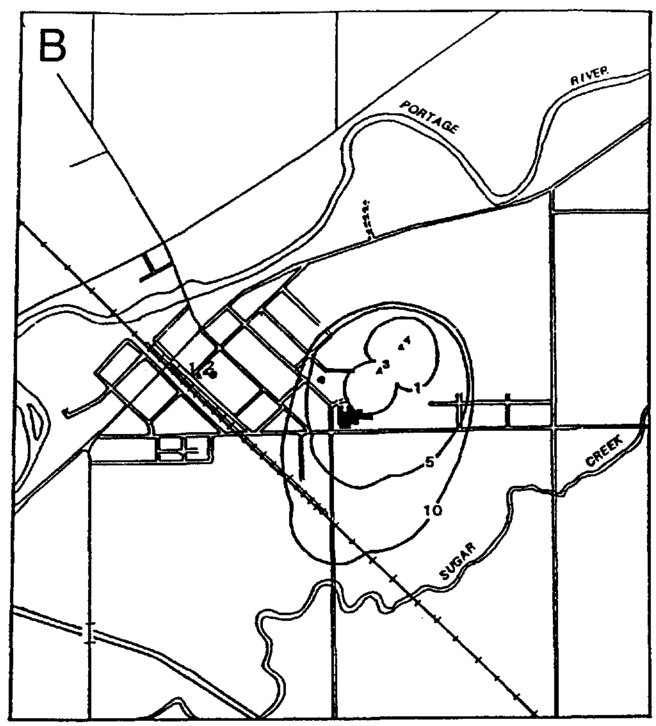
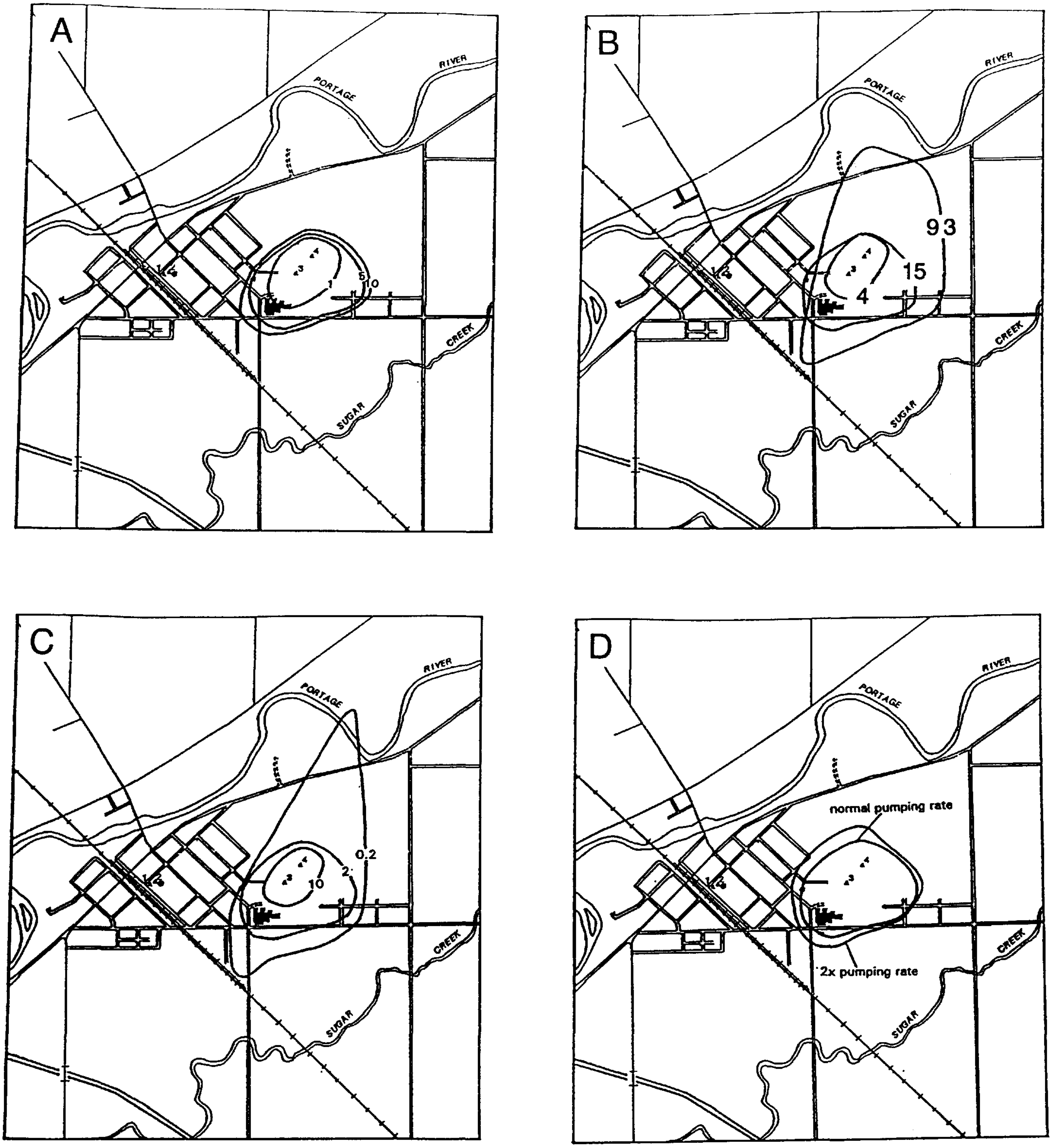


FIGURE 6. Maps showing (A) delineation of WHP area around the well field at Elmore, using the arbitrary fixed radius method (see text for details); and (B) delineation of 1, 5, and 10 year TOT zones using analytical methods (program GPTRAC).

(bedding plane) fractures sets. These considerations made the estimation of "average aquifer porosity" very difficult.

In a similar fashion, these types of aquifers pose difficulties for calculating potentiometric surface maps, which appear smooth as an artifact of plotting methods, thus they mimic a porous media. In reality, detailed field studies may document numerous changes in hydraulic gradient, and local variations in the potentiometric surface.



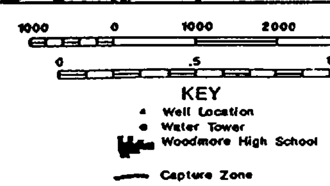
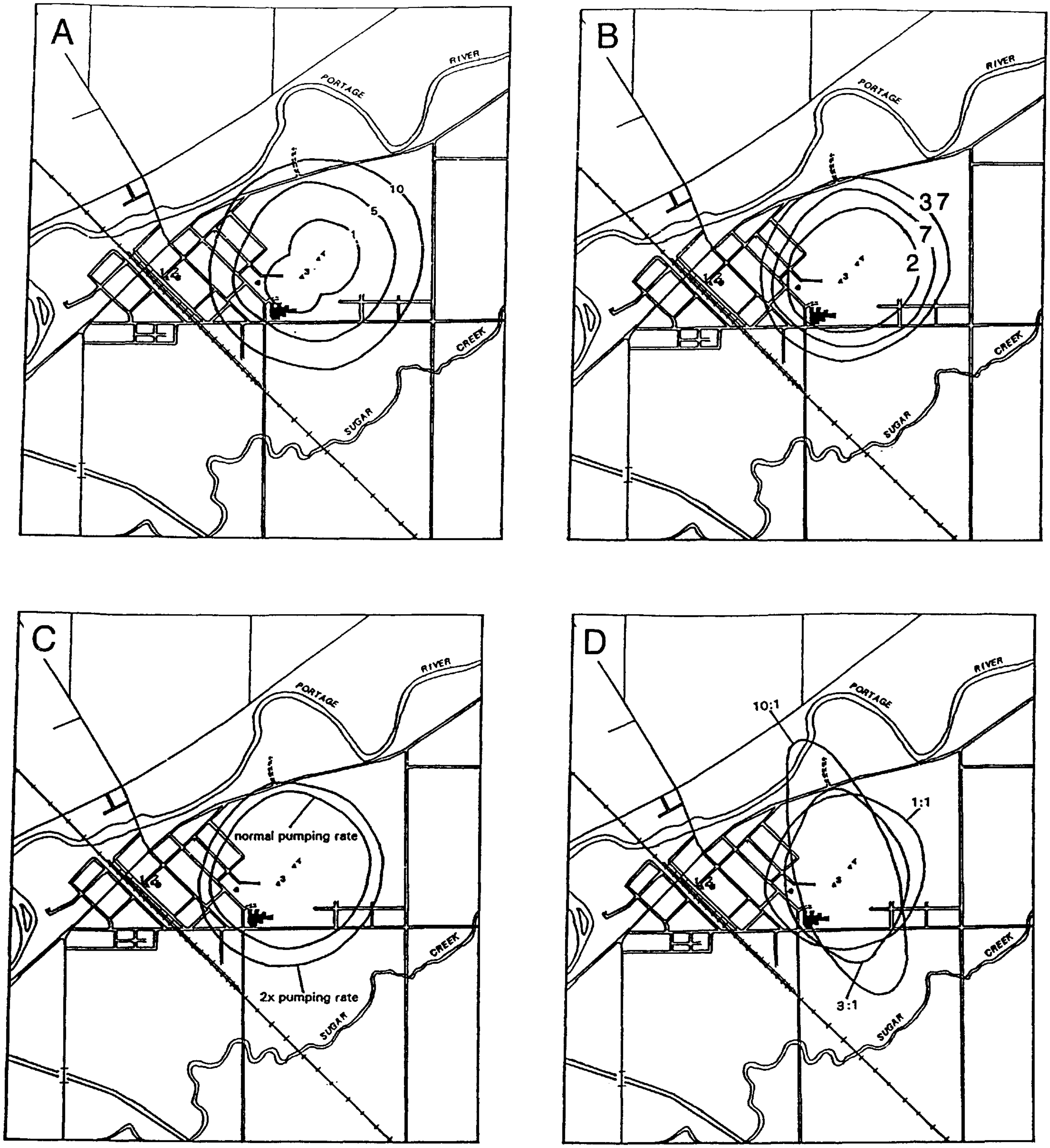


FIGURE 7. Maps showing (A) delineation of 1, 5, and 10 year TOT zones using semi-analytical methods (program CAPZONE); (B) results of the sensitivity analysis using variable transmissivity (values in m²/day); (C) results of the sensitivity analysis using variable porosity values (in percent); and (D) results of the sensitivity analysis using variable pumping rates.

A comparison of 5-year TOT zones as calculated by the various methods shows that the sizes of the zones are roughly similar, but there are marked differences in asymmetry and the importance of the flow field up gradient to the wells (Fig. 9). The more complex and time-consuming models (CAPZONE, MODFLOW) allowed for calibration of the model with pump test results, adjustment of the flow field to account for drawdown,



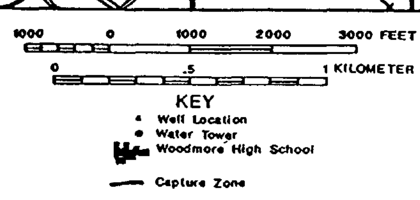


FIGURE 8. Maps showing (A) delineation of 1, 5, and 10 year TOT zones using numerical methods (program MODFLOW); (B) results of the sensitivity analysis using variable transmissivity (values in m^2/day); (C) results of the sensitivity analysis using variable pumping rates; and (D) results of the sensitivity analysis using variable anisotropy values (different ratios of horizontal hydraulic conductivity to vertical hydraulic conductivity).

TABLE 1

Volumetric flow budget calculated from MODFLOW.

	m^3/day	ft^3/day	percent
input			
vertical recharge	544	19,194	72.9%
boundary flow in	203	7,152	27.1%
(total)	(747)	(26,346)	(100.0%)
output			
discharge to wells	459	16,177	61.4%
boundary flow out	288	10,169	38.6%
discharge to river	8.0×10^{-4}	3.0×10^{-5}	0.0%
(total)	(747)	(26,346)	(100.0%)

and, for MODFLOW, calculation of the effect of the leaky confining layer on recharge.

Other differences between the semianalytical and numerical models can be attributed to different model assumptions. CAPZONE is a two-dimensional model that uses starting water levels and then superimposes drawdown. MODFLOW is a three-dimensional model that can perform similar functions, provided that drawdown of the potentiometric surface is imposed entirely within an unconfined aquifer, or that drawdown arises in a confined aquifer from changes in aquifer thickness or aquifer heterogeneities. In this case, the situation was complicated by an initial position of the potentiometric surface within the surficial unconsolidated material, which behaves as a leaky confining layer. This necessitated assuming that drawdown in the aquifer is influenced by vertical leakage rates from the surficial material, and that results in more circular drawdown surfaces and capture zones for the MODFLOW model than shown for the CAPZONE model.

The sensitivity analyses showed that the semianalytical model was most affected by transmissivity and porosity data, while the numerical model was most affected by aquifer anisotropy data and information about the leaky confining layer. Efforts should be made to determine the best data for these variables.

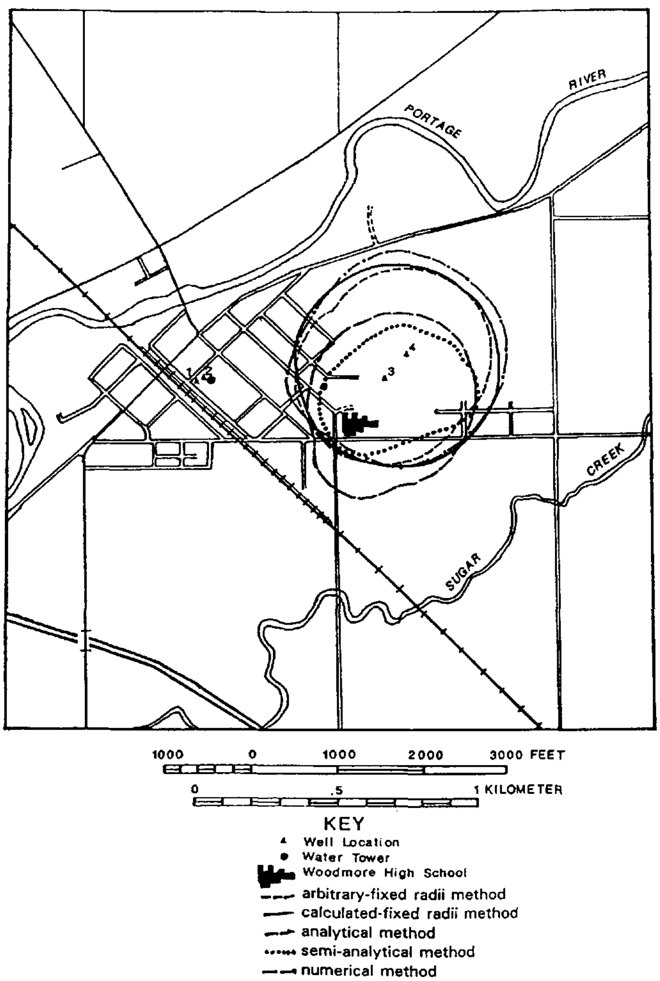


FIGURE 9. Comparison of the results of the 5-year TOT zone calculation using the different methods. See text for discussion.

SUMMARY & CONCLUSIONS

Carbonate aquifers with dissolution-enhanced fractures and joints are difficult to hydrologically characterize, for the purposes of a wellhead protection program. Additional complications might include characterizing clayey and cemented glacial tills as leaky confining layers, karst features, and groundwater-surface water interactions. In such a region, there are significant local variations in important hydrological parameters. Communities facing the need for a Wellhead Protection Program should carefully consider the options available to them. The semianalytical and numerical models pose considerations about access to technical support and cost. These methods, however, have significant advantages and should probably be used in such hydrogeologically complex areas.

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