Ground-Water Flow in the Saginaw Aquifer in the Vicinity of the North Lansing Well Field, Lansing, Michigan--Part 1, Simulations with a Regional Model

By C.L. Luukkonen, N.G. Grannemann, and D.J. Holtschlag

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U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Gordon P. Eaton, Director

For additional information
write to:

District Chief
U.S. Geological Survey, WRD
6520 Mercantile Way, Suite 5
Lansing, MI 48911-5991

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ABSTRACT

Vinyl chloride has been detected in water from the Saginaw aquifer near Lansing Board of Water and Light wells in the north Lansing well field. These public-supply wells have the potential to withdraw contaminated ground water. Ground-water-flow simulations and particle-tracking analyses with a regional model were used to investigate local ground-water movement. The effectiveness of hypothetical purge wells to remove ground water containing vinyl chloride was also evaluated. Five pumping scenarios were developed to assess effects of existing ground-water pumping conditions and alternative ground-water management options on the movement of the vinyl chloride plume in the Saginaw aquifer. Results indicate that under 1995 average pumping conditions, four public-supply wells in the north Lansing well field will remove water that originates in a portion of the Saginaw aquifer known to be contaminated with vinyl chloride. When pumping rates by wells in the north Lansing well field are reduced to simulate winter withdrawals, four public-supply wells to the west and south of the north Lansing well field remove water that originates in a portion of the Saginaw aquifer known to be contaminated with vinyl chloride. Simulation results indicate that purge wells can be used to capture most contaminated water and prevent interception of contaminated water by supply wells. However, further analysis is needed to determine the full extent of the vinyl chloride plume and the potential impact on Lansing Board of Water and Light public-supply wells.

INTRODUCTION

The Saginaw aquifer is the source of water for about 115,000 residents and for many industries in the Lansing metropolitan area. The Lansing Board of Water and Light (BWL) alone pumps about 23.4 million gallons per day (Mgd). Hydrogeologic investigations near the north Lansing well field have shown that water from some monitoring wells in the Saginaw aquifer are contaminated with vinyl chloride (Sharp and Associates, 1996). Although the full extent of this plume of contaminated ground water is unknown, BWL public-supply wells have the potential of being contaminated by withdrawing ground water containing vinyl chloride.

The Groundwater Management Board, of which the Lansing Board of Water and Light is an active member, and the U.S. Geological Survey (USGS) recently completed an analysis of ground-water resources of the Tri-County region which is documented by Holtschlag and others (1996). The Tri-County region includes Clinton, Eaton, and Ingham Counties (fig. 1). A major product of this study was a computer model of ground-water flow that can be used to assess the effects of pumping on ground-water levels and directions of ground-water flow.

This report describes how the existing model was used to make a preliminary evaluation of ground-water-flow directions and rates of movement in the Saginaw aquifer near the north Lansing well field. Contributing areas for wells were determined using the existing Tri-County regional ground-water-flow model in conjunction with a particle-tracking analysis. In addition, the

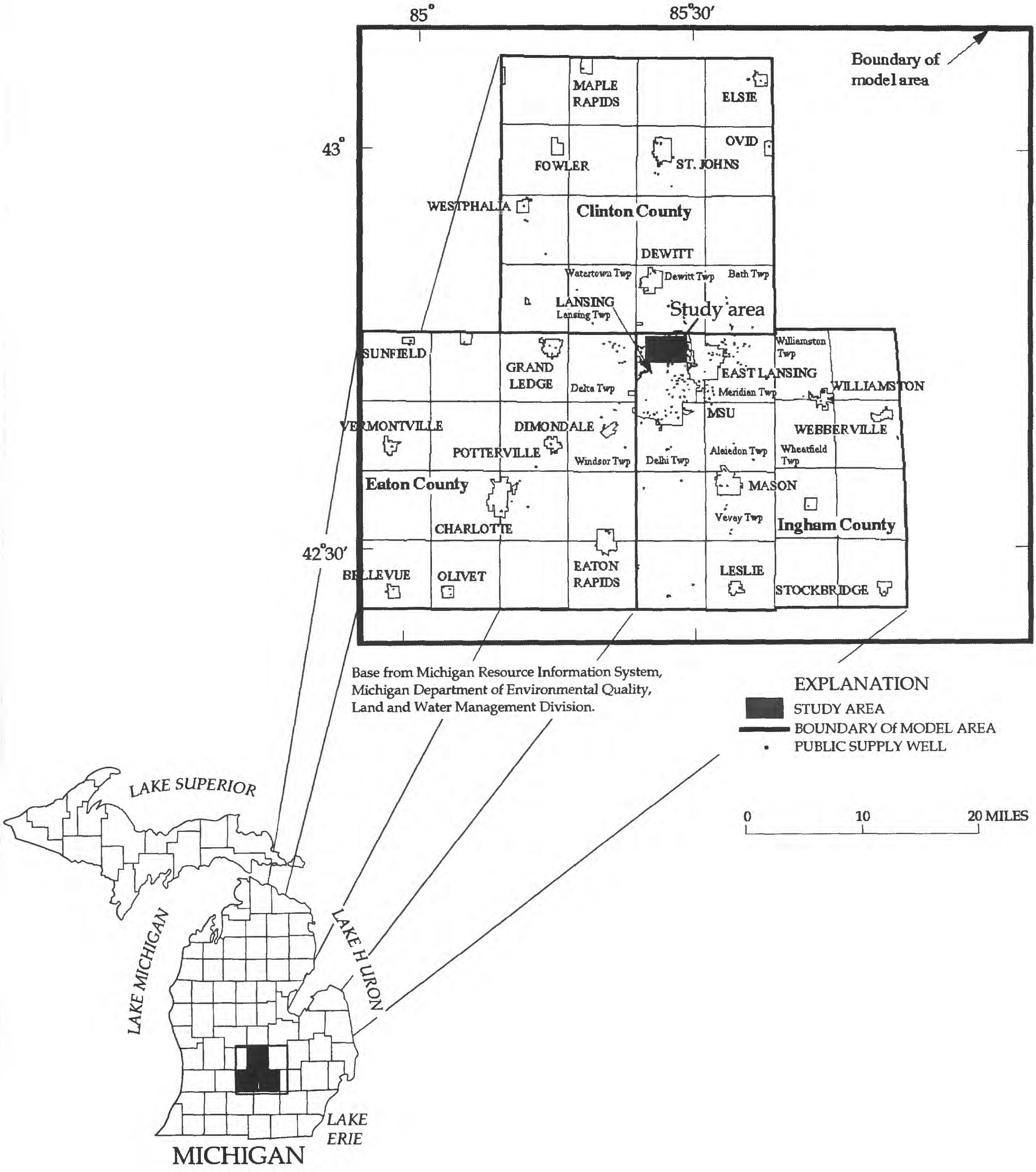


Figure 1. Location of the model area and the study area in the Tri-County Region, Lower Peninsula of Michigan.

effectiveness of hypothetical purge wells in the Saginaw aquifer was assessed to determine if such purge wells would keep known contaminated water from moving into the well field.

The study area comprises about 9 mi^2 in north Lansing near the border of Ingham and Clinton Counties in a mixed residential and industrial part of the city of Lansing (fig. 1). The Saginaw aquifer, from which almost all water for public supply is pumped, underlies the entire study area. The Grand River flows north and northwest on the west side of the study area and the Mason Esker, a prominent deposit of sand and gravel, is located on the east.

Previous studies (Wheeler, 1967; Wood, 1969; Vanlier and others, 1973; and Tri-County Regional Planning Commission, 1992) describe the ground-water resources in the Tri-County region. A report by Holtschlag and others (1996) documents how the regional ground-water-flow model was developed and used to determine contributing areas for most public-supply wells in the Tri-County region. Two reports have been written about the nearby Motor Wheel Disposal site, where the vinyl chloride originated, by Sharp and Associates (1995, 1996) and one report by Fishbeck, Thompson, Carr, and Huber (1994).

The authors gratefully acknowledge the assistance of the following Lansing Board of Water and Light personnel: Sue F. McCormick, Manager, Water Technical Services; William Maier, Water Quality Administrator; and Gail Peterson, Environmental Engineering for providing reports and pumping information. Charles Graff, Michigan Department of Environmental Quality; Kim Stemen, Sharp and Associates; and Richard Mandle, Fishbeck, Thompson, Carr, and Huber all provided data and hydrogeological insight for the study area.

MODEL DESCRIPTION

The Tri-County regional model simulates ground-water flow by dividing the Tri-County region into a grid containing 33,560 active cells in each of 2 layers. Each cell of the model grid represents a land-surface block 0.25 miles on a side. The study area for this report is represented by 144 cells in the model in a 12-row by 12-column configuration. The model has two layers: the upper layer represents flow in the glacial deposits and the lower layer represents flow in the Saginaw aquifer. Water enters the glacial deposits as recharge from precipitation and moves to streams or to the Saginaw aquifer in response to head gradients. Ground water exits the model at streams or wells. Details on model development, parameters, and calibration are described by Holtschlag and others (1996).

The steady-state model simulates flow conditions under which wells are pumped at constant rates, infiltration reaches the water table at a uniform rate, and no changes in aquifer storage occur. Results of the simulations were used in conjunction with a particle-tracking program documented by Pollock (1989) to track hypothetical particles as their movement through the ground-water system is simulated. The particle paths, and the locations where they enter and leave the simulated ground-water system, approximate ground-water flow paths in the aquifers. Particle-tracking analyses were limited to the Saginaw aquifer because the model was primarily designed to simulate ground-water flow in this aquifer. Ground-water flow in the overlying glacial aquifer is complex because of the heterogeneity of glacial deposits, especially in the vicinity of the Mason Esker.

The existing Tri-County regional ground-water-flow model was calibrated using 1992 pumping conditions and water levels. To represent more current conditions, 1995 pumping rates were used for most simulations described in this report. The model budget, which summarizes the total amounts of water moving into and out of the model for each type of cell, and simulated heads for 1995 closely resemble those for 1992. The percent discrepancy in the model budget equalled 0.0 for both 1992 and 1995 conditions. The differences between water flowing into and out of the model for constant head cells and river cells were each less than 0.5 percent. The largest difference (4.2 percent) in the amount of water flowing out of the model was for wells. Overall ground-water pumping rates have increased from 1992 to 1995, however, ground-water pumping rates have decreased in Delta Township and increased in Lansing Township since 1992. The root mean squared error (RMS) was computed for both 1992 and 1995 pumping conditions to compare the difference between measured and simulated heads at 2,791 measurement points. For pumping conditions in both years, RMS was 215.6 for the whole model and 66.8 for the upper layer. For 1992 pumping conditions, RMS was 148.8 for the lower layer. For 1995 pumping conditions, RMS was 148.9 for the lower layer.

Particle tracking was used to determine flow paths and directions of water originating in the portion of the Saginaw aquifer known to be contaminated with vinyl chloride. Particles can be tracked either down gradient or up gradient, which is referred to as "forward" or "backward" tracking, respectively. The particles' position at the end of a steady-state simulation represents their "ultimate fate." When forward tracking is used, hypothetical particles are located on each of the five active faces of a model cell in the lower layer and followed down gradient with the simulated flow of ground water until they exit the aquifer. When backward tracking is used, the same number of particles are located in the model cell that is used to simulate a well and followed up gradient until the simulated ground water reaches the place where it recharges the Saginaw aquifer. In addition, particles can be tracked for a specified amount of time. Thus, the particles' position after 20 years can be estimated. Particle tracking describes the advective movement of ground water and does not incorporate the effects of diffusion, dispersion, and degradation. Therefore, particle tracking is not intended as a substitute for modeling the transport of dissolved chemicals in the ground-water system.

For all simulations in this report, wells remove all particles introduced to the flow system in the Saginaw aquifer. If a well is pumping a large amount of water relative to the total amount moving through the cell, it is considered a "strong sink", and it will remove particles from the system. If a well is pumping a small amount of water relative to the total amount of water moving through the cell, it is considered a "weak sink", and it may or may not remove particles from the system. Weak sinks in the model are in reality wells with a low pumping rate, wells that are idle part of the year, wells with a radius of influence that is smaller than the cell dimensions, or wells that are screened in the upper part of the aquifer.

A well may have a low pumping rate either because it is used very little or it is idle part of the year. The Tri-County regional ground-water-flow model represents steady-state conditions under which wells are pumped continuously and at constant rates. Wells that are idle for part of the year are simulated in the model as pumping all year long at a lower pumping rate. For example, a well that operates at 500 gallons per minute (gpm) for half of the year and is idle for the remainder is simulated in the model as pumping all year long at 250 gpm. Thus, in reality, ground water would flow past the well when it is idle. Ground water could also flow under a well if it is screened in the upper part of the aquifer or around a well beyond the cone of depression caused by pumping. Because a well that is represented in the model as a weak sink may or may not remove particles, results of particle-tracking simulations must be interpreted with caution.

To represent the ground-water-flow system using particle tracking, one of three conditions must be specified for a simulated well in a cell to remove particles. These conditions include 1) particles pass through cells with weak sinks and are removed by cells with strong sinks, 2) particles are removed by some cells with weak sinks and cells with strong sinks, or 3) particles are removed by all cells with weak sinks. For initial simulations to determine the direction of movement of the contaminated water, particles were allowed to pass through cells with weak sinks and were only removed by cells with strong sinks. However, a simulated well that is a weak sink will likely withdraw some contaminated water at some time if it is in the flow path of the ground water containing vinyl chloride. A second set of simulations were run in which weak sinks were allowed to remove particles from the flow system. Because a cell with a weak sink will not always remove particles from the flow system, only some weak sinks were allowed to remove particles. For particles to be removed by only some of the cells with weak sinks, the amount of water leaving the cell relative to the amount entering the cell must be specified. An arbitrary amount of fifty percent was chosen to represent the differences in particle-tracking results when particles do not pass through all weak sinks. Thus, in the second set of simulations, particles were removed by cells in which more than half of the water entering the cell was withdrawn by the simulated well. In reality, however, any well within the flow path of the plume, even those withdrawing less than fifty percent of the water entering the cell, has the potential to withdraw contaminated water even though it does not remove particles during these simulations.

PARTICLE-TRACKING SIMULATIONS IN THE NORTH LANSING WELL FIELD

Directions of ground-water flow in the Saginaw aquifer in the study area change depending on which supply wells are pumping in the north Lansing well field, which is within one mile of the Motor Wheel Disposal site. Simulations were made to help understand local ground-water movement under five different pumping conditions. The conditions are as follows: 1) 1995 annual average pumping rates for the Saginaw aquifer, 2) 1995 winter average pumping rates, 3) 1960's generalized pumping rates, 4) hypothetically located purge wells with 1995 average pumping rates, and 5) reduced pumping from supply wells in the north Lansing well field.

Annual Average Pumping Conditions for 1995

Pumping rates for the BWL supply wells for 1995 were used as the simulated pumping stress on the aquifer for the first set of model simulations. Total pumping was 23.4 Mgd for the BWL supply wells. Withdrawal was estimated to be about 4.2 Mgd from the 25-series wells which are located in the north Lansing well field. The simulated pumpage did not exactly duplicate actual pumpage but was considered typical for most years. The simulated potentiometric surface and approximate directions of ground-water flow for these pumping rates are shown in Figure 2. The surface configuration indicates the presence of a ground-water flow divide in the Saginaw aquifer south of the disposal site. Water in the aquifer on the north side of the divide generally moves toward the west and northwest. South of the divide, ground water moves toward a regional cone of depression associated with pumping in wells south of the study area. Vinyl chloride has been detected in water pumped from the Saginaw aquifer near the divide (Sharp and Associates, Inc., 1996, fig. 2). The directions of ground-water flow indicate that water from this area may be moving toward BWL supply wells, assuming that the aquifer is isotropic. Forward and backward particle tracking were used to more precisely describe these ground-water-flow conditions.

Twelve thousand, five hundred hypothetical particles were located on the five active faces (top, north, east, south, and west) of the model cell in the Saginaw aquifer nearest the center of the known vinyl chloride plume. The movement of these particles through the Saginaw aquifer was simulated until they reached their "ultimate fate," that is, until all of the particles were discharged from the ground-water system. Because pumping so strongly controls the local direction of ground-water flow, all of the particles discharge to simulated pumping in BWL wells 25-27, 25-28, 25-30, and 20-03 (fig. 2). Due to the close proximity of wells 25-27 and 25-28 in relation to the cell size, these wells were represented as a single well. Results of the particle-tracking simulation indicate that wells 25-27 and 25-28, which have a combined pumping rate of 435 gpm, remove 40 percent of the particles from the source cell. Similarly, well 25-30, which has a pumping rate of 353 gpm, removes 31 percent of the particles; well 20-03, which has a pumping rate of 377 gpm, removes 29 percent of the particles.

Examination of figure 2 shows that wells 20-02, 25-17, 25-22, 25-24, 25-25, and 25-26 lie within the apparent flow path of the plume, but did not remove any particles during the simulation. To determine the importance of weak sinks versus strong sinks, a second simulation was performed using the 1995 average pumping conditions. In this simulation, particles are removed from a cell when the total well discharge was larger than 50 percent of the total water inflow to the cell. For these conditions, different wells remove particles from the ground-water system. Wells 25-26, 25-30, 25-17, and 20-03 remove 40, 31, 22, and 7 percent of the particles, respectively. Wells 25-30 and 20-03 were strong sinks for both simulations. However, wells 25-26

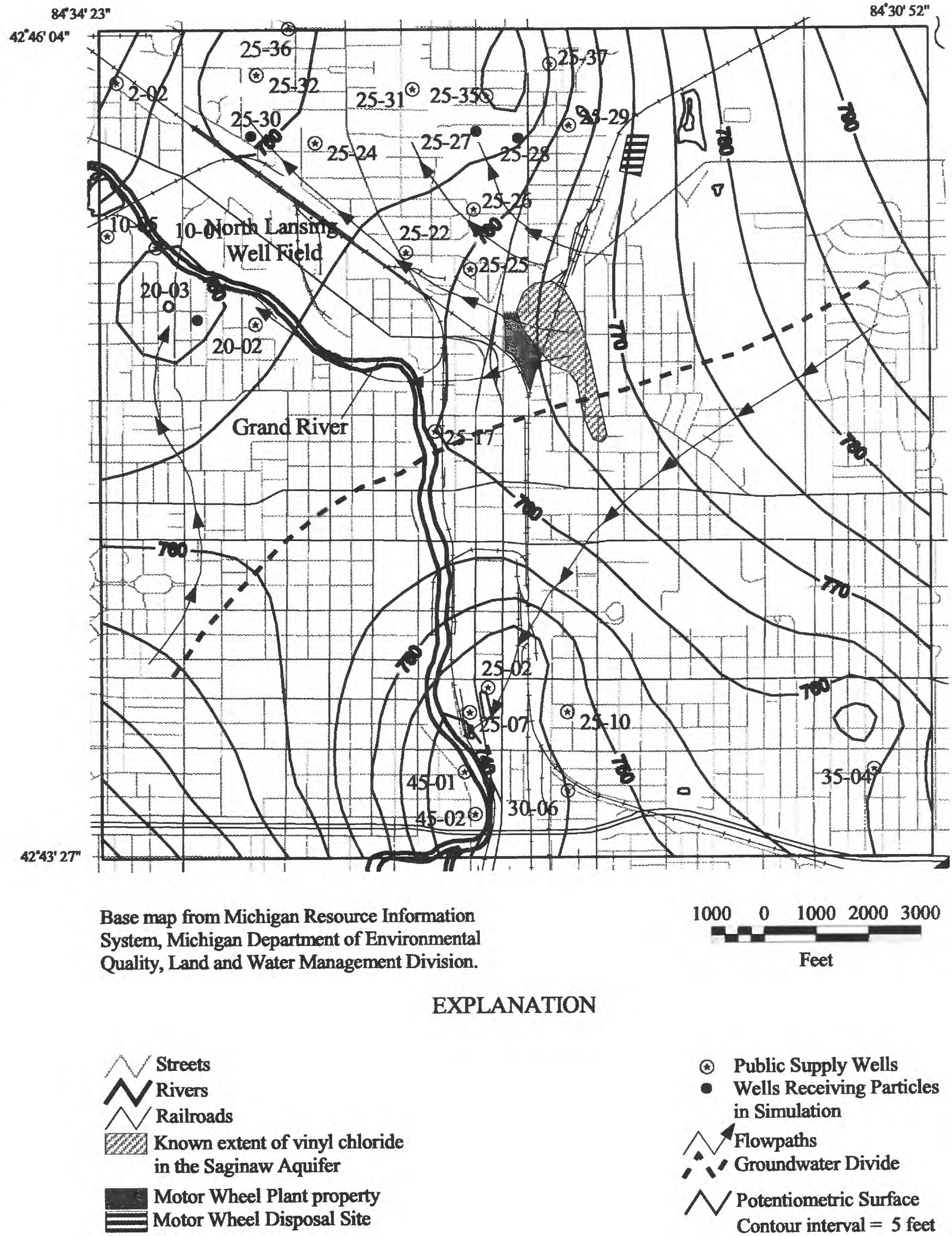


Figure 2: Simulated potentiometric surface for Saginaw Aquifer under 1995 average pumping rates, north Lansing well field, Lansing, Michigan.

and 25-17 were weak sinks in the previous simulation. Wells 20-02, 25-22, 25-24, and 25-25 did not remove any particles during the second simulation. The simulated wells in these cells withdraw less than 50 percent of the water entering the cell. Although they did not remove any particles in these simulations, these wells might withdraw contaminated water at some time since they are in the apparent path of the plume.

Particle tracking was used to identify the "zone of transport" for selected wells in the Saginaw aquifer. This zone was identified by using particles to follow the ground-water-flow path backward in time until all particles reached the top face of a cell in model layer 2. All of the model cells through which the particles pass collectively define the zone of transport for the well. This zone is illustrated on Figure 3 for well 20-03, a strong sink. The potentiometric surface contours are also shown on this figure to illustrate the relation between the directions of ground-water flow (fig. 2) and the zone of transport. The zone of transport for wells 25-27 and 25-28 is shown on Figure 4.

Because the extent of contamination by vinyl chloride in the Saginaw aquifer is uncertain, an additional forward tracking simulation was done for the 1995 average pumping conditions to represent a larger plume area. For this simulation, 12,500 particles were started in the same cell as previously described, but the same number of particles were also placed in 5 adjoining cells (a total of 75,000 particles) and allowed to pass through cells with weak sinks. In this simulation, particles are ultimately removed from the ground-water system by five wells. Wells 20-03, 25-30, and 25-02 remove 34, 14, and 8 percent of the particles, respectively. Wells 25-27 and 25-28 together remove 43 percent of the particles, and wells south of the study area remove 1 percent of the particles. Additional wells within the flow path of the plume may withdraw contaminated water at some time during the year.

Particles also were tracked for simulated 20-year time frames under 1995 average pumping conditions. In 20 years, no particles reach BWL supply wells when they are initiated at one cell in the center of the known vinyl chloride plume. When particles are initiated using a 6-cell configuration around the plume center representing a larger plume, however, particles reach wells 25-27 and 25-28 in 20 years. An estimated effective porosity of 0.15 (Marsily, 1986, p. 36) was used for these simulations.

Winter Pumping Conditions for 1995

The 25-series wells in the north Lansing well field are used less in winter when demand for water is less than in summer. During 1995, average withdrawal from these wells was about 1.2 Mgd (30 percent) less in winter than in summer. The model was used to help evaluate the effects of these seasonal changes in pumping rates on ground-water flow directions near the north Lansing well field.

Particles were initiated at the center of the known vinyl chloride plume and tracked using simulated winter withdrawal rates. Of 12,500 particles at the beginning of the simulation, 94 percent of them are ultimately removed at well 20-03 (fig. 3). Of the remaining particles, 5 percent are removed by a well west of the study area and 1 percent are removed by wells south of the study area.

To determine the importance of weak sinks verses strong sinks, another simulation was performed using 1995 winter pumping conditions. In this simulation particles were only removed from a cell when the total well discharge for a simulated well was larger than 50 percent of the total inflow to the cell. For these conditions, different wells remove particles from the ground-water system. Wells 25-17, 25-22, and 20-03 remove 56, 23, and 21 percent of the particles, respectively.

To represent a larger plume area, 75,000 particles were introduced on faces of six cells including the center of the known vinyl chloride plume. At ultimate fate, particles are removed from the simulated ground-water system by four wells. Wells 20-03 and 25-26 remove 59 and 20 percent of the particles, respectively. A well west of the study area removes 3 percent of the particles and wells south of the study area remove 18 percent of the particles. Therefore, for winter pumping conditions, a much larger southerly

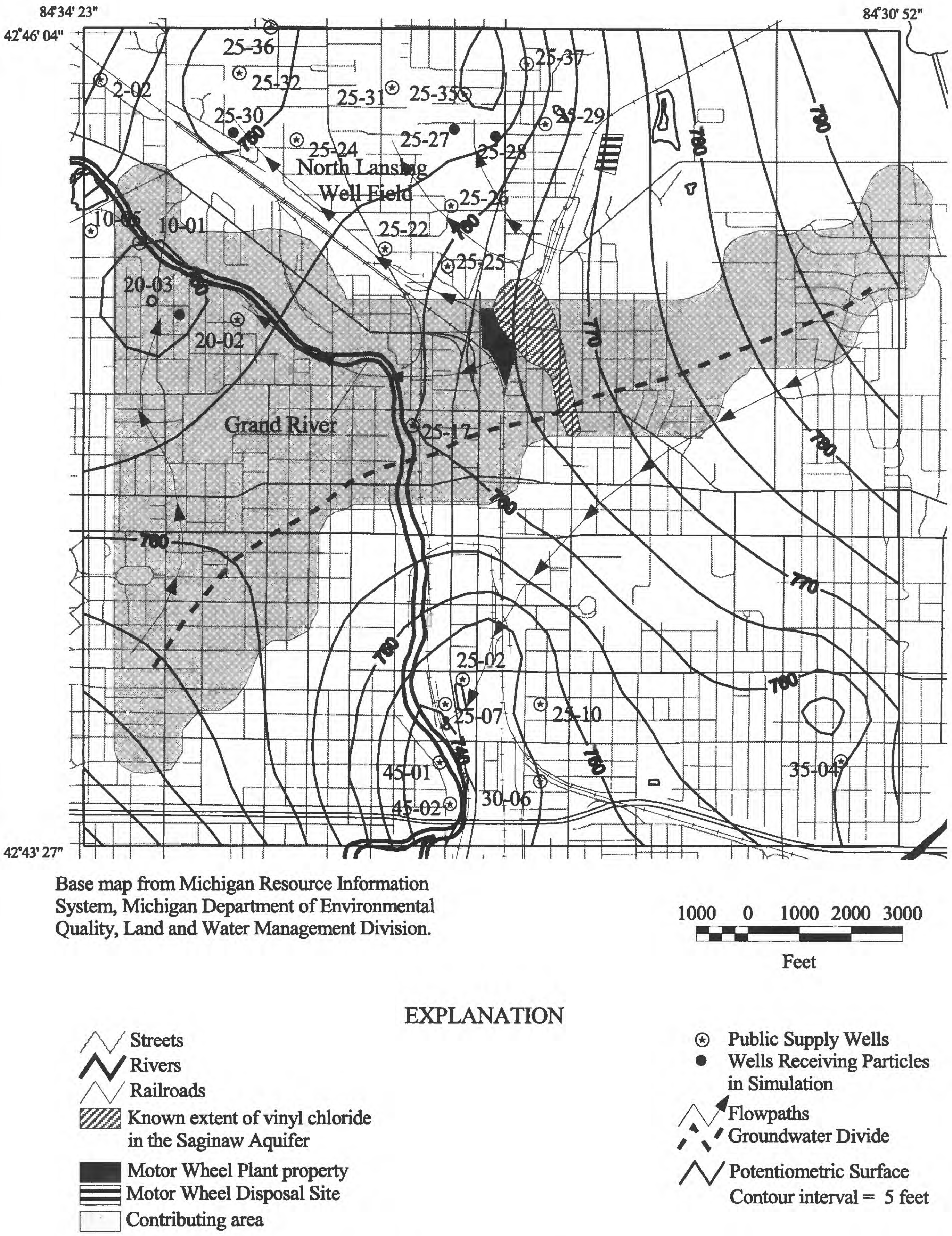
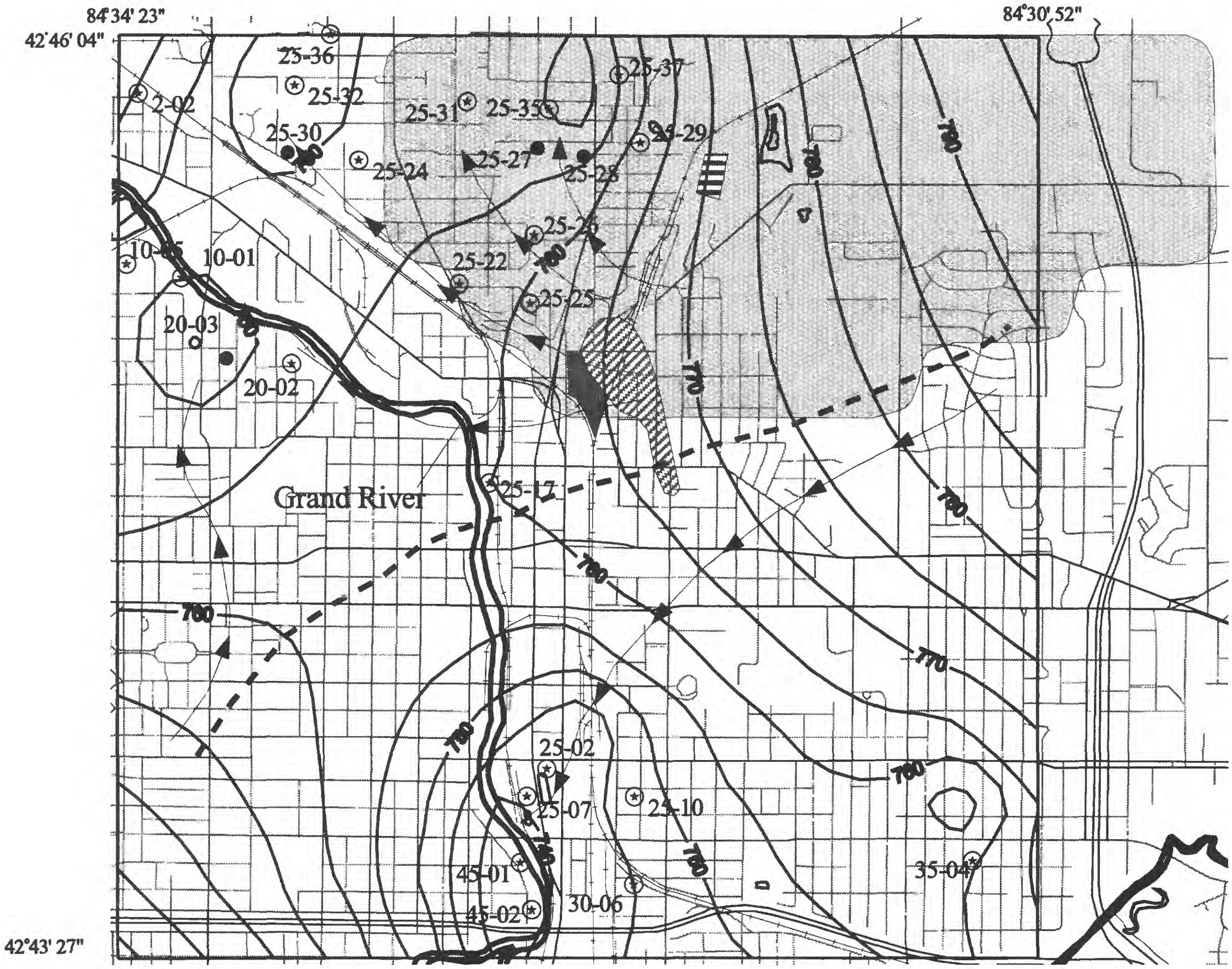


Figure 3: Zone of transport in the Saginaw Aquifer contributing water to well 20-03 for 1995 average pumping rates, north Lansing well field, Lansing, Michigan.



Base map from Michigan Resource Information System, Michigan Department of Environmental Quality, Land and Water Management Division.

1000 0 1000 2000 3000
Feet

EXPLANATION

- Streets
- Rivers
- Railroads
- Known extent of vinyl chloride in the Saginaw Aquifer
- Motor Wheel Plant property
- Motor Wheel Disposal Site
- Contributing area
- Public Supply Wells
- Wells Receiving Particles in Simulation
- Flowpaths
- Groundwater Divide
- Potentiometric Surface Contour interval = 5 feet

Figure 4: Zone of Transport in the Saginaw Aquifer contributing water to wells 25-27 and 25-28 for 1995 average pumping rates, north Lansing well field, Lansing, Michigan.

component of ground-water flow is evident than under 1995 average pumping conditions.

Generalized Pumping Conditions for 1960

Ground-water withdrawal by the BWL is now more distributed than it was in the late 1960's when more water was pumped from the north Lansing well field and southwest of the well field. Because of the additional stress from this pumping, water levels in observation wells near the pumping center were lowered by about 150 feet (fig. 5). Pumping was gradually shifted to more southerly well fields beginning in the late 1960's and water levels in some observation wells recovered by nearly 100 feet. A model simulation was run with pumping at the general locations of the pumping centers in the 1960's. Particle tracking based on these simulations indicate that most particles moving down gradient from the center of the known vinyl chloride plume are removed by wells immediately west of the plume. Specific wells were not identified in this analysis because pumping data for individual wells was not readily available. In general, the particles track in about the same directions as for 1995 pumping conditions, however, the gradient is steeper and thus the travel time is less in 1960 simulations than in the 1995 simulations.

Hypothetical Purge Wells and 1995 Average Pumping Conditions

Sharp and Associates, Inc. (Charles Graff, Michigan Department of Environmental Quality, oral commun., 1997) has proposed that migration of the vinyl chloride plume within the Saginaw aquifer can be controlled by two purge wells pumping at 100 gpm near the southern and northwestern boundaries of the Motor Wheel plant property. The model was used to simulate these two wells pumping at rates of 100, 150, and 200 gpm. When tracked from the center of the vinyl chloride plume and allowed to pass through cells that acted as weak sinks, all the particles are removed by supply wells 25-30 and 20-03, even though the purge wells were simulated as pumping either 100 or 150 gpm. When the purge wells were simulated as pumping 200 gpm, however, all particles are removed by the purge wells.

A second simulation was done in which particles are removed by cells in which more than half of the water entering the cell is withdrawn by pumping. Under these conditions, the purge wells remove all particles in less than 20 years. Particles were introduced into six cells to represent the position of a larger vinyl chloride plume since the full extent of the plume is unknown. When particles were forward tracked with the two purge wells simulated as pumping 100 gpm, about 75 percent of the particles are removed by the purge wells but some particles are removed by supply wells 25-22, 25-26, 25-27, and 25-28. When the purge wells were simulated as pumping 200 gpm, the purge wells remove 82 percent of the particles with the remainder removed by supply wells 25-22 and 25-26.

Reduced Pumping from Supply Wells in the North Lansing Well Field

Reduced pumping from supply wells in the north Lansing well field was simulated to determine the effects on ground-water-flow directions. For this simulation, wells 20-03, 25-30, 25-27, and 25-28, which are usually operational, were inactive. The water that would have been withdrawn by these four wells (approximately 1.7 Mgd) was simulated as coming from wells south of the study area.

Particles were initiated at the center of the known vinyl chloride plume and tracked using the distribution of head values determined by reduced pumping from wells near the Motor Wheel Disposal site. Particles were only allowed to discharge to strong sinks. All 12,500 particles started at the beginning of the simulation move south to well 25-02. To determine the importance of weak sinks versus strong sinks, another simulation was performed using these pumping conditions, but particles were allowed to discharge to sinks in which withdrawal was greater than half of the water flowing into the cell.

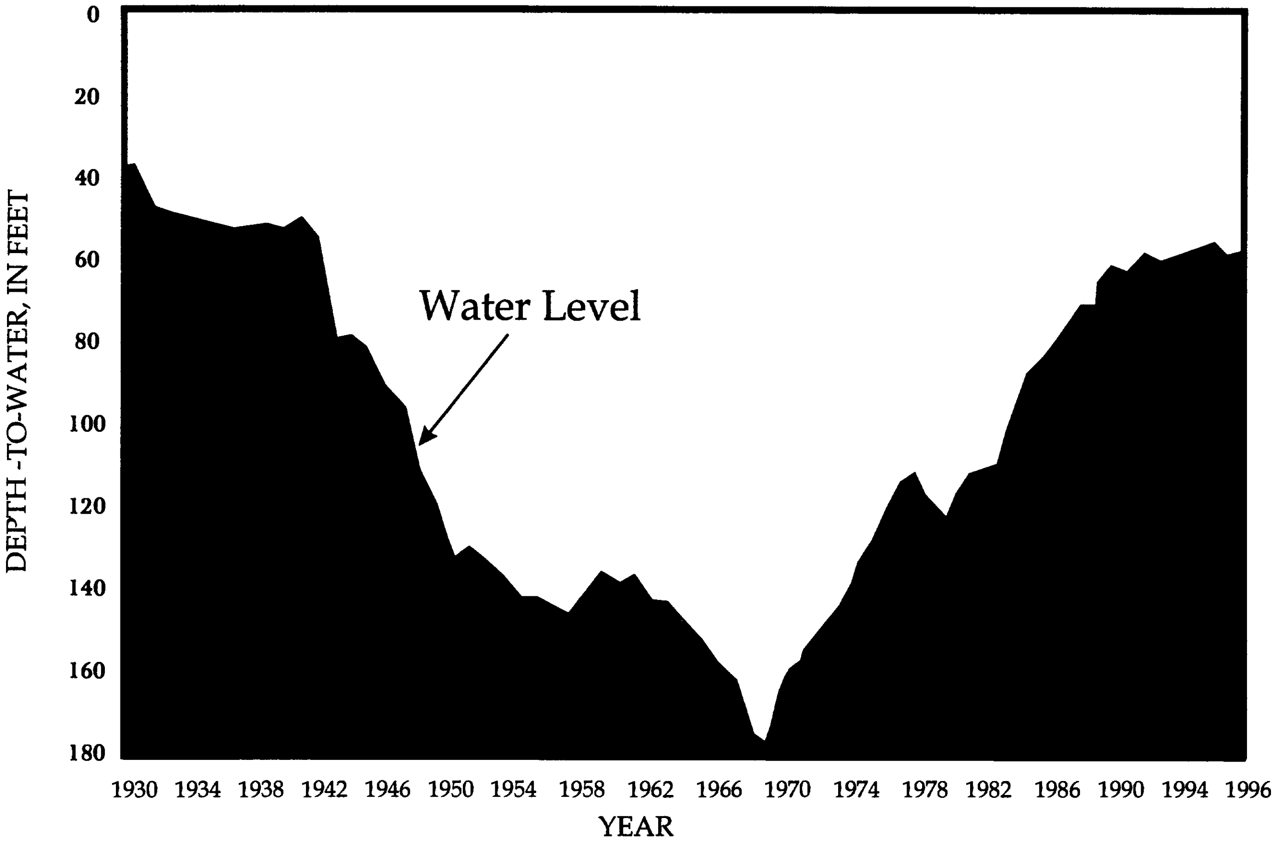


Figure 5. Depth-to-water in the Logan Street well, 1930-96.

In this simulation, 37 percent of the particles move south to well 25-02 and 63 percent move west to well 25-17.

LIMITATIONS OF MODEL APPLICATIONS AND SIMULATIONS

The model used in the ground-water flow analyses described in this report has a large grid spacing - 0.25 miles on each side. This grid size was designed to simulate the entire Tri-County region. The study area for this report, however, contains only 144 of the 33,560 cells per model layer (fig. 1). Because of the grid size, some supply wells were placed in the same cell for simulation purposes. As a result, it is difficult to separate the effects of pumping some individual supply wells. More importantly, grid size affects whether wells are considered strong or weak sinks. Smaller cells would convert some wells from weak to strong sinks.

The model is calibrated for steady-state conditions. As a result, recharge to the upper aquifer is assumed to be constant and pumping rates are averaged over a one-year time frame. For example, a well that operates at 500 gpm for half of the year and is idle for the remainder is simulated in the model as pumping all year long at 250 gpm. While the total amount of water withdrawn is the same, the transient effect of the withdrawal is not. A much better understanding of the effects of intermittent and seasonal pumping on the Saginaw aquifer could be achieved if the model were calibrated for transient conditions.

The Tri-County regional model emphasizes ground-water flow in the Saginaw aquifer. Flow in the overlying glacial deposits was modeled to support analysis of flow in the Saginaw aquifer. In the vicinity of the Motor Wheel Disposal site, the local hydrogeology of the glacial deposits is important to understanding the local movement of ground water in the Saginaw aquifer. Recharge rates to the glacial deposits were determined from an analysis relating base-flow characteristics of streams to land use and basin characteristics (Holtschlag, 1994). The estimate of recharge rates does not account for the effects of impervious surfaces that likely comprise a large percent of the area in Lansing. The recharge rates used in the model could be adjusted for impervious surfaces to describe local variation in recharge rates for the area.

The Tri-County regional model represents transmissivity as the product of a uniform horizontal hydraulic conductivity and the thickness of the sandstone in the Saginaw aquifer, and vertical conductivity is represented by the vertical hydraulic conductivities of the individual layers in the glacial aquifer. One of the recent findings of the Sharp and Associates, Inc. (1996) report is that it is possible to map a shale unit near the surface of the Saginaw aquifer. Inclusion of the effects of this shale unit in the model would improve the accuracy of ground-water flow simulations in the study area. It is likely that the shale unit restricts movement of ground water from the glacial aquifer to the Saginaw aquifer.

CONCLUSIONS

Particle-tracking results using the Tri-County regional ground-water-flow model indicate the potential for wells in the north Lansing well field to intercept contaminated ground water that originated on the Motor Wheel Disposal site. Hypothetical purge wells pumping at 200 gpm could remove the plume of contaminated water. However, particle-tracking results indicate that hypothetical purge wells pumping at 100 gpm or 150 gpm would not remove all particles introduced into the center of the known vinyl chloride plume. Particle-tracking results also indicate that under a larger plume scenario, hypothetical purge wells simulated as pumping 100, 150 or 200 gpm would not be effective at intercepting all particles.

Because the extent of vinyl chloride in the Saginaw aquifer is unknown, potentially more BWL wells may be affected than the particle-tracking results indicate, and the effectiveness of purge wells may be overestimated. Due to the coarseness of the grid, which in some cases caused more than one well to be placed in a cell and some wells to be weak sinks, particle-tracking results should be considered indicative only and not used for specific planning purposes. Furthermore, the hydrogeology is too generalized in the model for detailed planning.

Transient simulation could be used to estimate more precisely the dimension and location of the plume and to better represent the effects of seasonal and intermittent pumping. Smaller grid spacing in the model would allow separation of individual wells and reduce the number of wells considered to be weak sinks. Inclusion in the model of more detailed information on the hydrogeology of the glacial deposits, variation in recharges rates, and hydrogeology of the shale unit between the glacial and Saginaw aquifers would make simulation results more applicable to detailed planning.

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