Ground-Water Flow in the Saginaw Aquifer in the Vicinity of the North Lansing Well Field, Lansing, Michigan--Part 2, Simulations with a Regional Model Using a Reduced Cell Size

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page v Follows

CONTENTS

FIGURES

TABLES

Ground-Water Flow in the Saginaw Aquifer in the Vicinity of the North Lansing Well Field, Lansing, Michigan -- Part 2, Simulations with a Regional Model Using a Reduced Cell Size

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

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. The effects of reduced grid spacing for the existing Tri-County regional ground-water-flow model on local ground-water movement were investigated. This refinement of the grid eliminated multiple wells in a cell and reduced the number of wells represented as weak sinks. Two pumping scenarios were developed to investigate the effects of pumping conditions, plume size, and hypothetical purge well locations on the movement of the vinyl chloride plume in the Saginaw aquifer.

Under 1995 pumping conditions, water that originates in the central portion of the Saginaw aquifer known to be contaminated with vinyl chloride is prevented from reaching Lansing Board of Water and Light supply wells when hypothetical purge wells located west of the plume are simulated as pumping either 100 gallons per minute or 200 gallons per minute. Purge wells located north of the plume are effective at preventing contamination from reaching Lansing Board of Water and Light supply wells when simulated as pumping 200 gallons per minute. Water that originates within and surrounding the area known to be contaminated with vinyl chloride is not prevented from reaching Lansing Board of Water and Light supply wells under 1995 conditions using either purge well location or pumping rate.

Under 1997 pumping conditions, water that originates in the central portion of the Saginaw aquifer known to be contaminated with vinyl chloride is prevented from reaching Lansing Board of Water and Light supply wells when hypothetical purge wells located either west or north of the plume are simulated as pumping 200 gallons per minute. Water that originates within and surrounding the area known to be contaminated with vinyl chloride is not prevented from reaching Lansing Board of Water and Light supply wells under 1997 conditions using either purge well location or pumping rate.

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 of water per day (Mgd). Hydrogeologic investigations near the north Lansing well field have shown that water from some monitoring wells in the Saginaw aquifer is 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 includes Clinton, Eaton, and Ingham Counties (Holtschlag and others, 1996, 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.

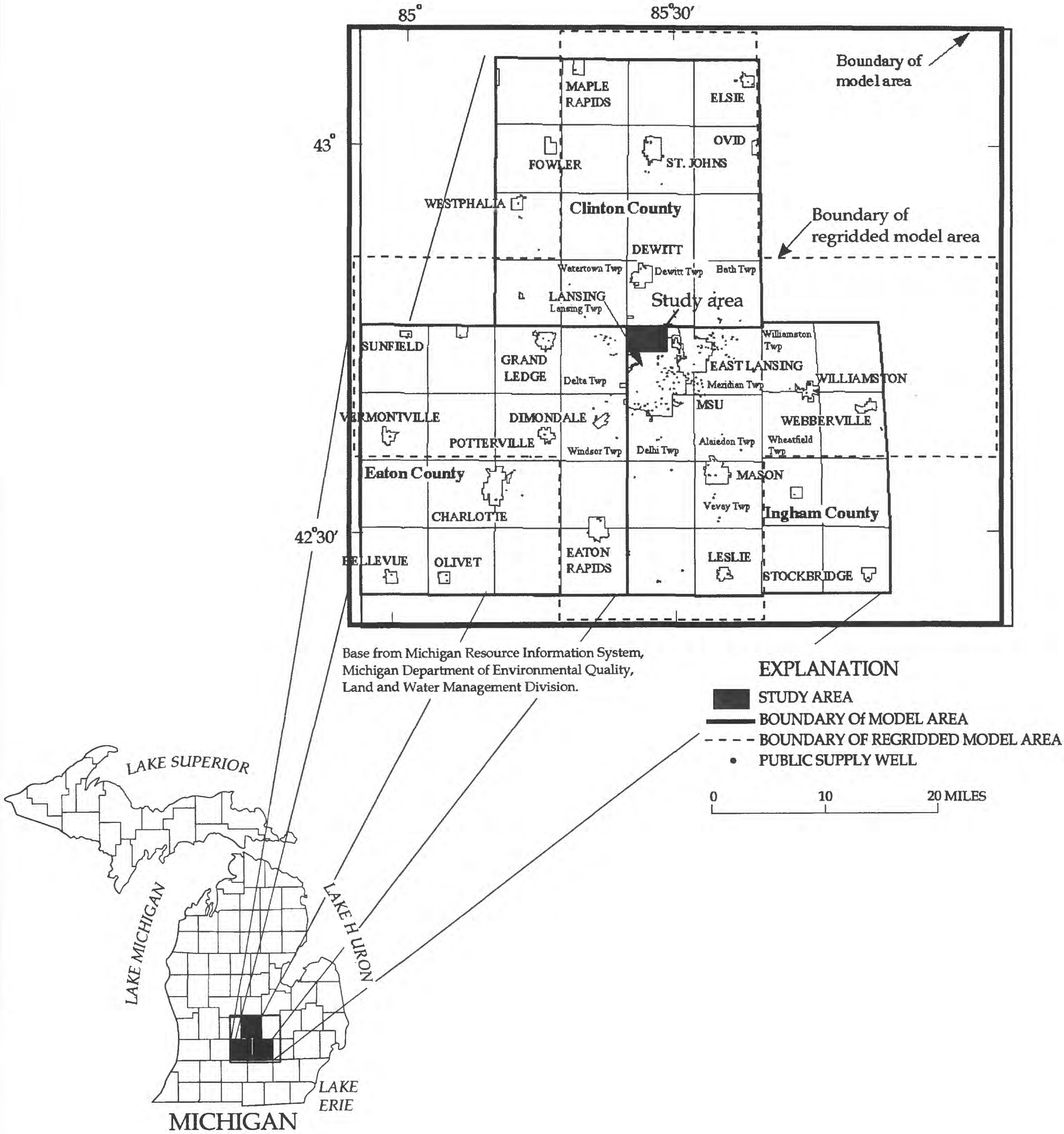


Figure 1. Location of the model area and the study area in the Tri-County Region, Lower Peninsula of Michigan.

A previous report (Luukkonen and others, 1997) investigated the effects of existing ground-water pumping conditions and alternative ground-water management options on the movement of the plume in the Saginaw aquifer. Simulation results using a particle-tracking program (Pollock, 1989) indicated that smaller grid spacing, transient simulation, and more detailed hydrogeologic information would improve the analysis and aid determination of the potential impact on BWL public-supply wells. This report describes the effects of reduced grid spacing for the existing Tri-County regional ground-water-flow model. This refinement of the grid eliminated multiple wells in a cell and reduced the number of wells represented as weak sinks. This report describes how the regridded model was used to investigate the effects of pumping conditions, plume size, and hypothetical purge well locations on the movement of the vinyl chloride plume in the Saginaw aquifer.

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 nine-township area surrounding Lansing, Michigan comprises Alaiedon, Bath, Delhi, Delta, Dewitt, Lansing, Meridian, Watertown, and Windsor Townships. This is the principal area of ground-water withdrawals in the Tri-County region and the study area is approximately in the middle of the nine-township area. Within this area, grid spacing of the Tri-County regional model was halved so that each cell is 660 by 660 ft. Two rows or columns of cells form the transition from the finer to coarser grid. In this transition zone, rows and columns change in height and width, respectively, from 660 to 880 to 1,100 to 1,320 ft. River cells were reconnected and streambed conductances changed to reflect the shorter cell lengths. No other changes were made to the Tri-County regional model or parameters.

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).

Comparison of Original and Regridded Models

In order to ensure that the regridded model accurately represented the regional flow system in the Tri-County region under 1992 pumping conditions, model budget and simulated heads were compared for the original and regridded models. The model budget summarizes the total amounts of water moving into and out of the model for each type of cell. The error in the model budget was less than 0.05 percent for both models with the percent discrepancy equaling 0.00 in the original model budget and 0.03 in the regridded model budget. The combined differences between water flowing into and out of the model area for constant head, recharge, well, and river cells for the original and regridded models were all less than 1 percent. The difference for constant head cells was less than 0.6 percent, for recharge less than 0.1 percent, for wells no change, and for river cells 0.1 percent.

The root mean squared error (RMS) was computed for both models to compare simulated heads to measured heads at 2,791 measurement points. For the original model, RMS was 215.6 for the whole model, 66.8 for the upper layer, and 148.8 for the lower layer. For the regridded model, RMS was 215.9 for the whole model, 67.5 for the upper layer, and 148.4 for the lower layer. These values are all within 1 percent and indicate that the regridded model is in agreement with the original model.

Particle-Tracking Description

Results of the simulations were used in conjunction with a particle-tracking program (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.

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 are 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 might withdraw some contaminated water at some time if it is in the flow path of 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. The potential impact of a vinyl chloride plume on the public-supply wells depends on which wells are pumping and on the plume's extent which, currently, is not well defined. Simulations were made to investigate the effects of different pumping conditions, plume sizes, and purge well locations and pumping rates on local ground-water movement.

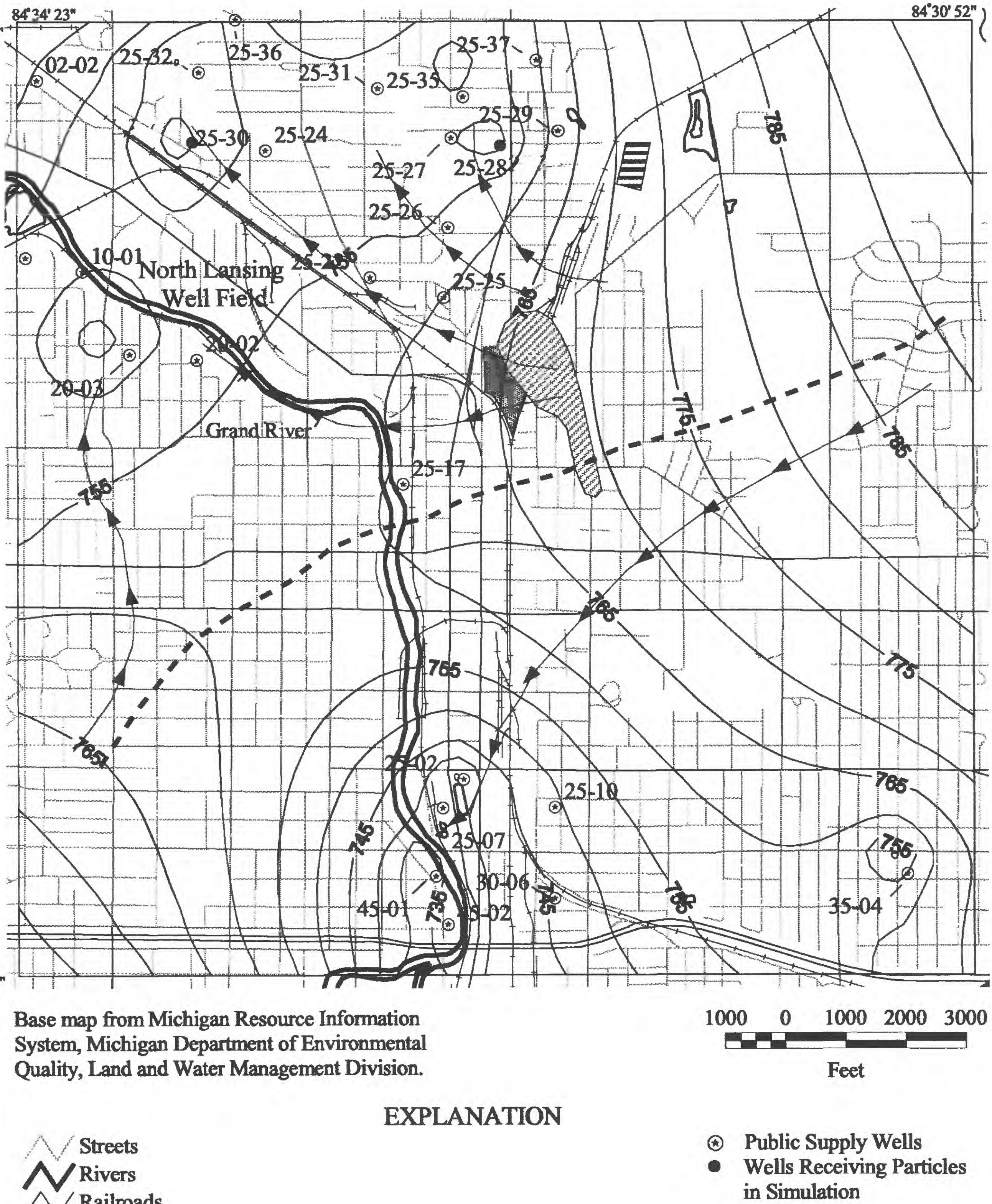
1995 Pumping Conditions

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 to the west and northwest. South of the divide, ground water moves toward a regional cone of depression associated with 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 the aquifer is isotropic. Forward particle tracking was used to describe these ground-water-flow conditions more precisely.

Average pumping rates

Eighteen thousand hypothetical particles were located on the five active faces (top, north, east, south, and west) of the four model cells in the Saginaw aquifer nearest the center of the known vinyl chloride plume. The movement of these particles through the Saginaw aquifer was



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
Public Supply Wells
Wells Receiving Particles in Simulation
Flowpaths
Groundwater Divide
Potentiometric Surface
Contour interval = 5 feet

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

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 are removed by BWL wells 25-28 and 25-30 (fig. 2). Results of the particle-tracking simulation indicate that well 25-28, which is pumped at a rate of 373 gpm, removes 54 percent of the particles from the source cells. Well 25-30, which is pumped at a rate of 353 gpm, removes 46 percent of the particles.

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 were removed from a cell only 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, 25-22, and 25-27 remove 41, 25, 21, and 13 percent of the particles, respectively. Well 25-30 was a strong sink for both simulations. However, wells 25-26, 25-22, and 25-27 were weak sinks in the previous simulation. Wells 25-24 and 25-25 are weak sinks in which less than half of the water entering the cell is withdraw by the simulated well and may potentially withdraw contaminated water because they are within the flow path of the plume.

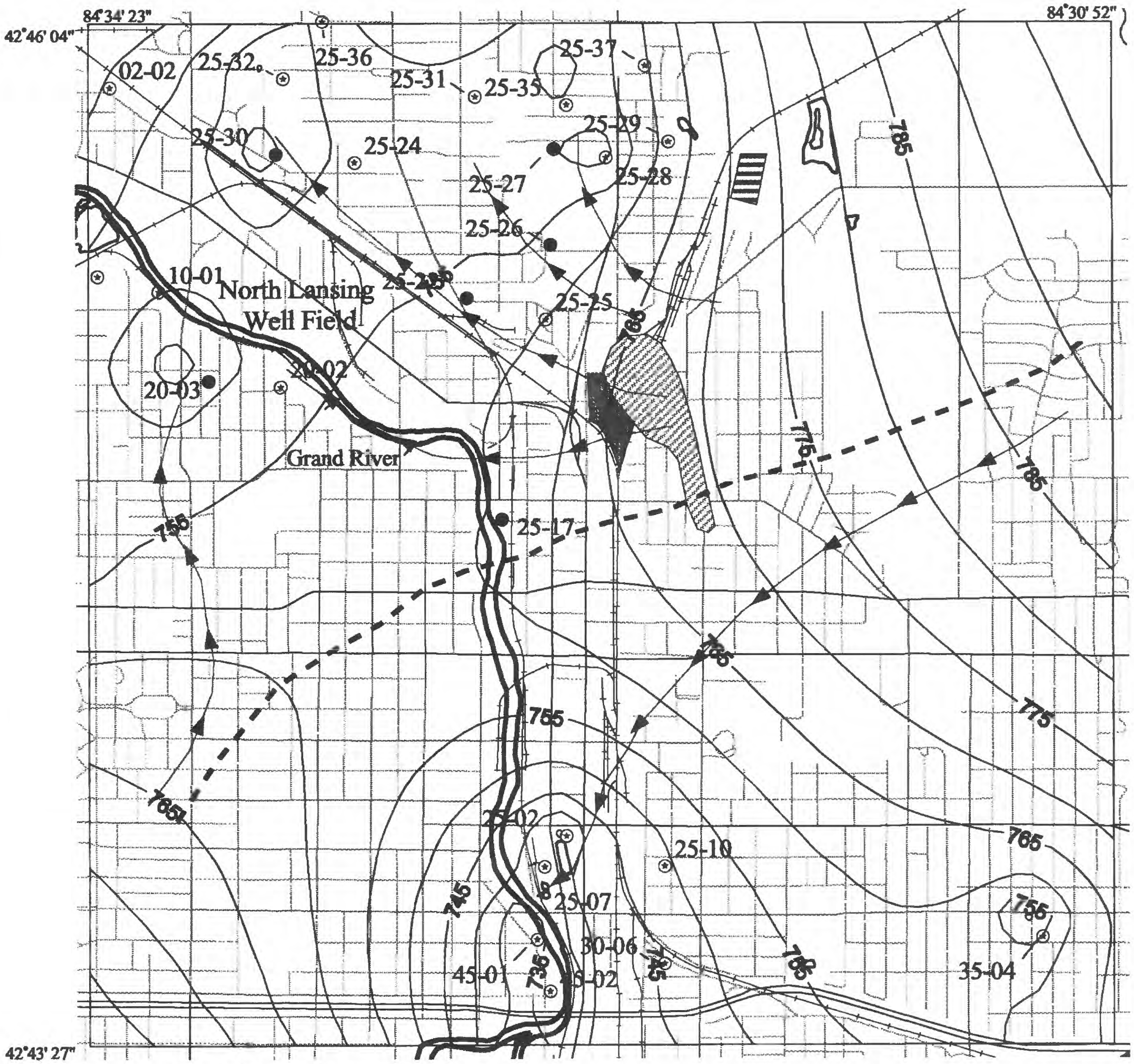
Because the extent of contamination by vinyl chloride in the Saginaw aquifer is uncertain, an additional forward tracking simulation was done for the 1995 average pumping conditions and the purge wells to represent a larger plume area. For the first simulation, 4,500 particles were started in each of the four cells as previously described, but the same number of particles also were placed in 12 adjoining and nearby cells, for a total of 72,000 particles. In this simulation, particles are ultimately removed from the ground-water system by three wells. Wells 20-03, 25-30, and 25-28 remove 14, 35, and 51 percent of the particles, respectively.

In the next simulation, particles were removed from a cell only 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 20-03, 25-30, 25-22, 25-17, 25-26, and 25-27 remove 6, 18, 17, 8, 43, and 8 percent of the particles, respectively (fig. 3). Wells 20-03 and 25-30 were strong sinks for both simulations. However, wells 25-22, 25-17, 25-26, and 25-27 were weak sinks in the previous simulation. Particle-tracking results for 1995 pumping conditions are summarized in Table 1.

Particle-tracking results using the regridded model differ slightly from the results using the original model. Under 1995 average conditions, when particles were tracked from the center of the plume, BWL wells west of the plume remove particles using the original model but not using the regridded model. Under 1995 average conditions, when particles were tracked from a larger plume, BWL wells south of the plume remove particles using the original model but not using the regridded model. Due to the larger cell size in the original model, some particles were started south of the ground-water flow divide and thus wells south of the north Lansing well field were affected. Reducing the cell size in the model allowed separation of results for wells 25-27 and 25-28 and reduced the number of weak sinks. A summary of particle-tracking results using both models for 1995 average pumping conditions is shown in Table 2.

Purge wells located west of the plume

Sharp and Associates, Inc. (Charles Graff, Michigan Department of Environmental Quality, oral communication, 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 and 200 gpm. When tracked from four cells at the center of the vinyl chloride plume and allowed to pass through cells that acted as weak sinks, all the particles are removed by the north purge well when the purge wells were simulated as pumping 100 gpm (fig. 4). When the purge wells were simulated as pumping 200 gpm, however, all of the particles are removed by both purge wells. A second simulation was performed in which particles are removed from a cell when the total



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

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Feet

EXPLANATION

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

Figure 3: Wells receiving particles from the larger plume under 1995 average pumping rates, north Lansing well field, Lansing, Michigan.

Table 1: Particle Tracking Results for 1995 Average Pumping Rates

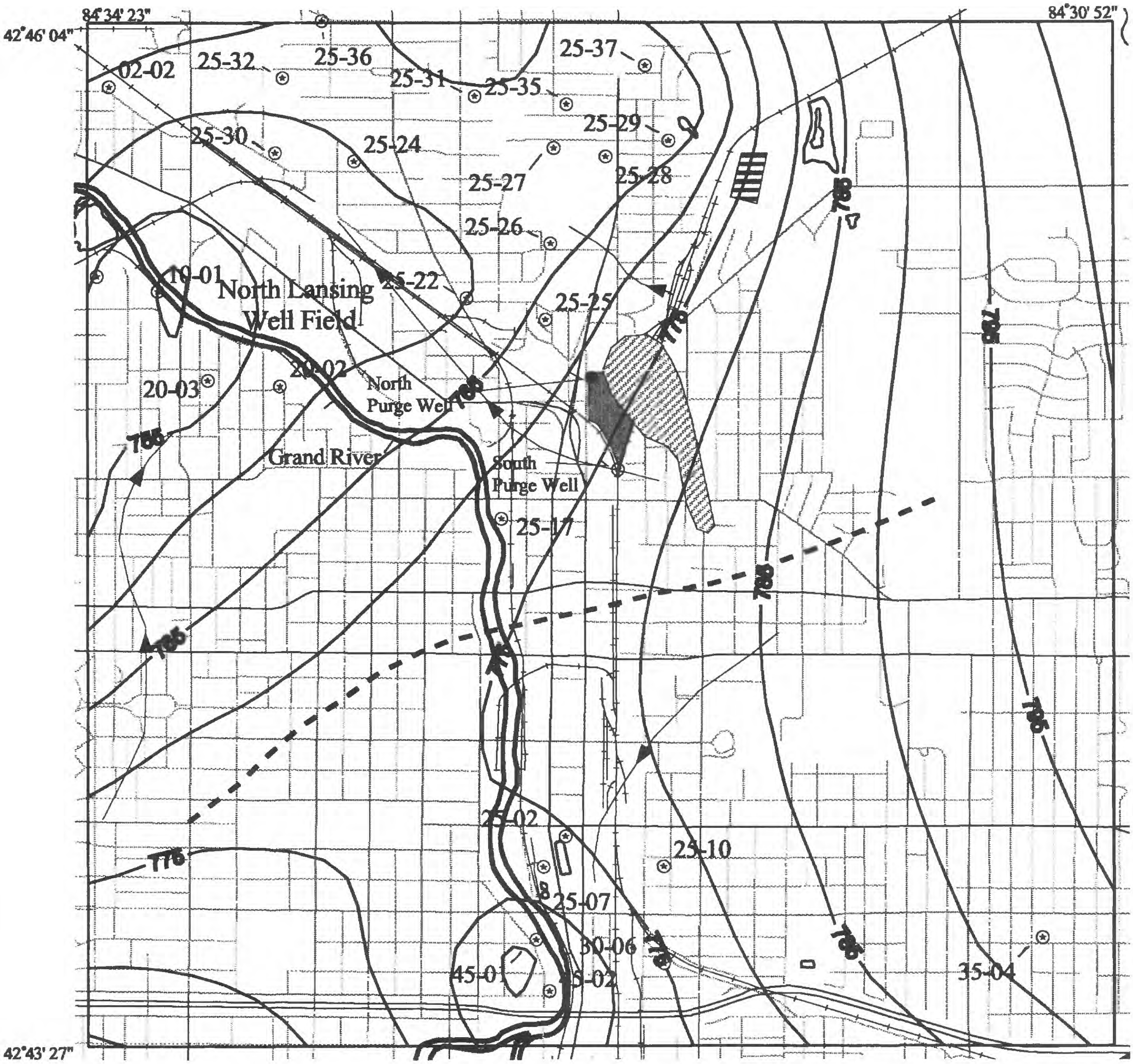
Simulation			Wells Receiving Particles (percent of particles)
Average	Particles in Center of Plume	Particles pass through weak sinks	25-28 (54 %); 25-30 (46 %)
		Particles stop in some weak sinks	25-26 (41 %); 25-30 (25 %); 25-22 (21 %); 25-27 (13 %)
	Particles in Large Plume	Particles pass through weak sinks	25-28 (51 %); 25-30 (35 %); 20-03 (14 %)
		Particles stop in some weak sinks	25-26 (43 %); 25-30 (18 %); 25-22 (17 %); 25-27 (8 %); 25-17 (8 %); 20-03 (6 %)
100 gpm purge wells located west of plume	Particles in Center of Plume	Particles pass through weak sinks	North purge well (100 %)
		Particles stop in some weak sinks	North purge well (77 %); South purge well (23 %)
	Particles in Large Plume	Particles pass through weak sinks	North purge well (75 %); 25-26 (23 %); 25-30 (1.5 %); 25-28 (.5 %)
		Particles stop in some weak sinks	North purge well (49 %), South purge well (26 %); 25-26 (23 %); 25-22 (1 %); 25-30 (<1 %); 25-27 (<1 %)
200 gpm purge wells located west of plume	Particles in Center of Plume	Particles pass through weak sinks	North purge well (68 %); South purge well (32 %)
		Particles stop in some weak sinks	North purge well (68 %); South purge well (32 %)
	Particles in Large Plume	Particles pass through weak sinks	North purge well (63 %); South purge well (29 %); 25-26 (8 %)
		Particles stop in some weak sinks	North purge well (63 %); South purge well (29 %); 25-26 (8 %)

Table 1: Particle Tracking Results for 1995 Average Pumping Rates

Simulation			Wells Receiving Particles (percent of particles)
100 gpm purge wells located north of plume	Particles in Center of Plume	Particles pass through weak sinks	25-26 (100 %)
		Particles stop in some weak sinks	West purge well (79 %); 25-26 (21 %)
	Particles in Large Plume	Particles pass through weak sinks	25-26 (86 %); 25-30 (10 %); 25-28 (4 %)
		Particles stop in some weak sinks	West purge well (38 %); East purge well (6 %); 25-26 (44 %); 25-22 (9 %); 25-30 (2 %); 25-27 (<1 %)
	Particles in approxi-mate extent of plume	Particles pass through weak sinks	25-26 (64 %); 25-30 (14 %); 20-03 (11 %); 25-02 (8 %); 25-28 (3 %)
		Particles stop in some weak sinks	West purge well (38 %); East purge well (5 %); 25-26 (23 %); 25-22 (11 %); 25-17 (9 %); 25-02 (8 %); 25-30 (4 %); 20-03 (2 %); 25-27 (<1 %)
200 gpm purge wells located north of plume	Particles in Center of Plume	Particles pass through weak sinks	West purge well (100 %)
		Particles stop in some weak sinks	West purge well (99.7 %); East purge well (0.3 %)
	Particles in Large Plume	Particles pass through weak sinks	West purge well (84 %); 25-26 (16 %)
		Particles stop in some weak sinks	West purge well (77 %); East purge well (7 %); 25-26 (16 %)
	Particles in approxi-mate extent of plume	Particles pass through weak sinks	West purge well (78 %); 25-26 (18 %); 25-02 (4 %); 25-30 (<1 %); 20-03 (<1 %)
		Particles stop in some weak sinks	West purge well (71 %); East purge well (7 %); 25-26 (10 %); 25-22 (5 %); 25-02 (4 %); 25-17 (3 %); 25-30 (<1 %); 20-03 (<1 %)

Table 2: Particle Tracking Results for Original and Regridded Models

Simulation			Wells receiving particles under 1995 conditions
Original model	Average	Center of plume	20-03, 25-27, 25-26, 25-27, 25-28, 25-30
		Large plume	20-03, 25-02, 25-27, 25-26, 25-27 and/or 25-28, 25-30, 45-01, 45-03 and/or 45-04
	100 gpm purge wells	Center of plume	North purge well, South purge well, 20-03, 25-30
		Large plume	North purge well, South purge well, 20-03, 25-22, 25-26, 25-27 and/or 25-28, 25-30
	200 gpm purge wells	Center of plume	North purge well, South purge well
		Large plume	North purge well, South purge well, 25-22, 25-26, 25-27 and/or 25-28, 25-30
Regridded model	Average	Center of plume	25-22, 25-26, 25-27, 25-28, 25-30
		Large plume	20-03, 25-17, 25-22, 25-26, 25-27, 25-28, 25-30
	100 gpm purge wells	Center of plume	North purge well, South purge well
		Large plume	North purge well, South purge well, 25-22, 25-26, 25-27, 25-28
	200 gpm purge wells	Center of plume	North purge well, South purge well
		Large plume	North purge well, South purge well, 25-26



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
- Public Supply Wells
- Wells Receiving Particles in Simulation
- Flowpaths
- Groundwater Divide
- Potentiometric Surface Contour interval = 5 feet

Figure 4: Simulated potentiometric surface for the Saginaw aquifer under 1995 average pumping rates with purge wells pumping at 100 gallons per minute, north Lansing well field, Lansing, Michigan.

well discharge was larger than 50 percent of the total water inflow to the cell. Under these conditions, both purge wells simulated as pumping either 100 gpm or 200 gpm remove all of the particles.

Particles were introduced into sixteen cells to represent the position of a larger vinyl chloride plume, because the full extent of the plume is unknown. When these particles were forward tracked with the two purge wells simulated as pumping 100 gpm, about 75 percent of the particles are removed by the north purge well and the rest are removed by supply wells 25-26, 25-30, and 25-28. If particles were removed from a cell when the total well discharge was larger than 50 percent of the total water inflow to the cell, then both purge wells together remove about 75 percent of the particles, and the rest are removed by 25-30, 25-22, 25-26, and 25-27. When purge wells were simulated as pumping 200 gpm, the purge wells remove about 92 percent of the particles with the remainder removed by supply well 25-26 whether particles pass through cells with weak sinks or are removed by weak sinks withdrawing more than half of the water entering the cell (fig. 5).

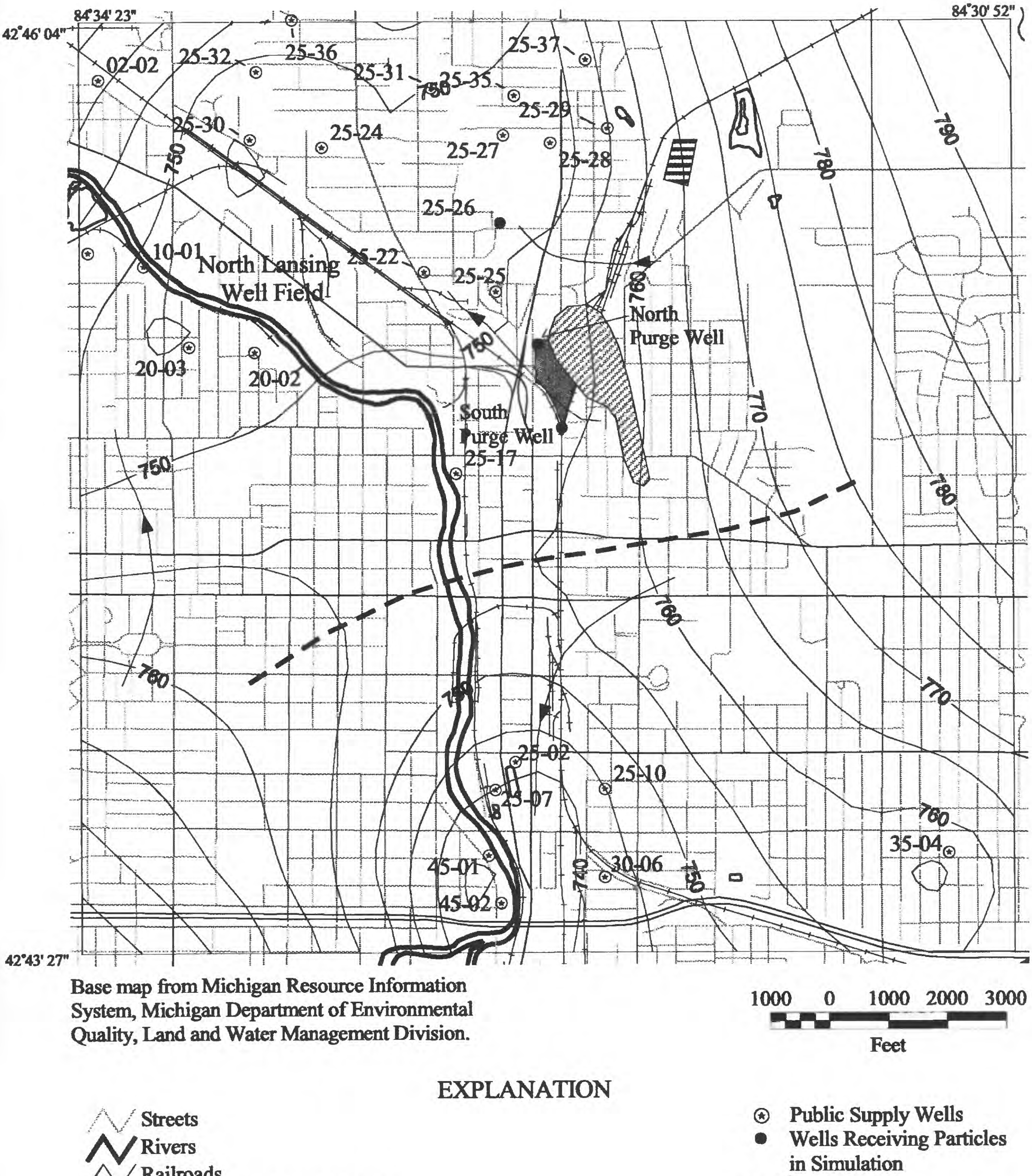
Particle-tracking results using the regridded model differ slightly from the results using the original model for some of the hypothetical purge well simulations. Under 1995 average conditions, with purge wells simulated as pumping 100 gpm, BWL wells west and northwest of the plume remove some particles using the original model, while purge wells remove all particles using the regridded model. Under 1995 average conditions, with purge wells simulated as pumping 200 gpm, the purge wells remove all particles using either model. Under 1995 average conditions, with purge wells simulated as pumping 100 gpm and particles tracked from a larger plume, well 20-03 removes particles using the original model but not using the regridded model. Under 1995 average conditions, with purge wells simulated as pumping 200 gpm and particles tracked from a larger plume, five BWL wells remove particles in addition to the purge wells using the original model while only one additional BWL well removes particles using the regridded model.

Purge wells located north of plume

Sharp and Associates, Inc. (Charles Graff, oral communication, 1997) has drilled two wells to the north of the existing vinyl chloride plume in the Saginaw aquifer and proposes to use these as purge wells. The model was used to simulate these two wells pumping at rates of 100 and 200 gpm. When tracked from four cells at the center of the vinyl chloride plume and allowed to pass through cells that acted as weak sinks, all the particles are removed by well 25-26 when the purge wells were simulated as pumping 100 gpm. When the purge wells were simulated as pumping 200 gpm, however, all of the particles are removed by the west purge well. A second simulation was performed in which particles were removed from a cell when the total well discharge was larger than 50 percent of the total water inflow to the cell. Under these conditions, 25-26 and the west purge well remove particles when the purge wells are simulated as pumping 100 gpm. Under these conditions, both purge wells remove all particles when the purge wells are simulated as pumping 200 gpm.

When particles were introduced into sixteen cells to represent the position of a larger vinyl chloride plume and forward tracked with the two purge wells simulated as pumping 100 gpm, wells 25-26, 25-28, and 25-30 remove all of the particles. If particles are removed from a cell when the total well discharge was larger than 50 percent of the total water inflow to the cell, the purge wells together remove about 44 percent of the particles, and the rest are removed by 25-30, 25-22, 25-26, and 25-27. When purge wells were simulated as pumping 200 gpm, the west purge well removes 84 percent of the particles and the rest are removed by well 25-26. When particles are removed by cells in which more than half of the water entering the cell is withdrawn by the simulated well, the purge wells remove 84 percent of the particles and the rest are removed by well 25-26.

Because purge wells have been drilled north of the plume, a third set of simulations were run in which particles were placed in cells that define the approximate extent of the known vinyl chloride plume to determine whether any wells to



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- Groundwater Divide
- Potentiometric Surface Contour interval = 5 feet

Figure 5: Simulated potentiometric surface for Saginaw Aquifer under 1995 average pumping rates with purge wells pumping at 200 gallons per minute, north Lansing well field, Lansing, Michigan.

the south of the north Lansing well field may be affected. Earlier runs had particles starting within the center of the plume or within a hypothetical larger plume. When the purge wells are simulated as pumping 100 gpm and particles pass through weak sinks, wells 25-02, 20-03, 25-26, 25-28, and 25-30 remove particles. When particles are removed by cells in which more than half of the water entering the cell is withdrawn by the simulated well, the purge wells remove 43 percent of the particles and the rest are removed by wells 25-02, 20-03, 25-17, 25-22, 25-26, 25-27, and 25-30. When the purge wells are simulated as pumping 200 gpm and particles pass through weak sinks, the purge wells remove 78 percent of the particles and the rest are removed by wells 25-02, 20-03, 25-26, and 25-30. When particles are removed by cells in which more than half of the water entering the cell is withdrawn by the simulated well, the purge wells remove 78 percent of the particles and the rest are removed by wells 25-02, 20-03, 25-17, 25-22, 25-26, and 25-30.

1997 Pumping Conditions

Pumping rates for the BWL supply wells for 1997 were used as the simulated pumping stress on the aquifer for the second set of model simulations. Total pumping was 24.2 Mgd for the BWL supply wells. Withdrawal from the 25-series wells was estimated to be about 2 Mgd. This simulated pumpage is anticipated to meet demands while allowing wells nearest the known vinyl chloride plume to be idle.

The simulated potentiometric surface and approximate directions of ground-water flow for these pumping rates are shown in Figure 6. The surface configuration indicates that a ground-water flow divide in the Saginaw aquifer still exists south of the disposal site, although the divide has moved southward slightly compared to 1995 pumping conditions. Water in the aquifer on the north side of the divide generally moves to the west and northwest, and on the south side of the divide generally moves to the south. The generalized directions of ground-water flow indicate that water from the area with vinyl chloride may be moving toward BWL supply wells. Forward particle tracking was used to describe these ground-water-flow conditions more precisely.

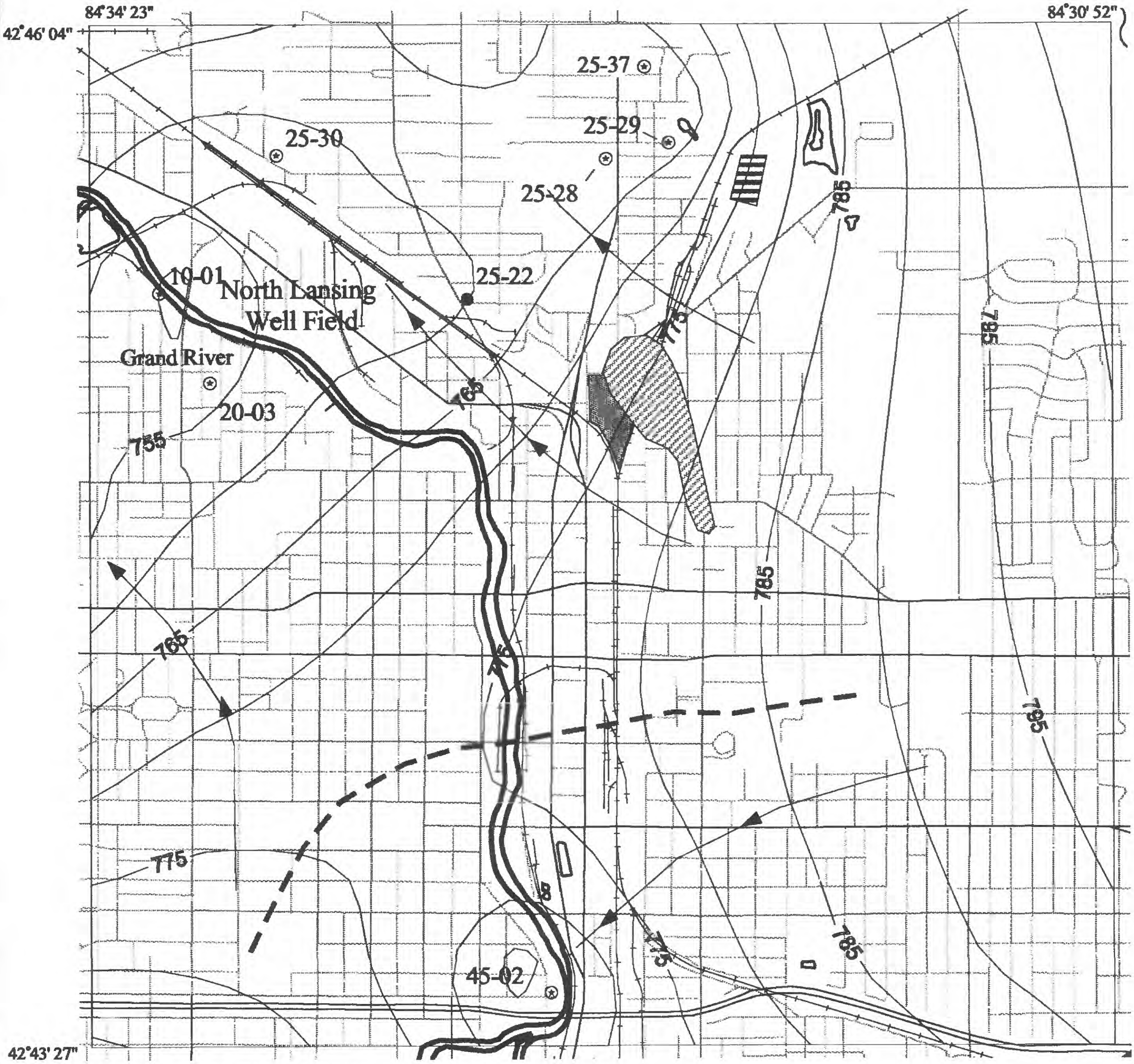
Average pumping rates

Eighteen thousand hypothetical particles were located on the five active faces (top, north, east, south, and west) of the four model cells in the Saginaw aquifer nearest the center of the known vinyl chloride plume. The movement of these particles through the Saginaw was simulated until all of the particles were discharged from the ground-water system. All of the particles discharged to simulated pumping in BWL well 25-22 whether particles pass through cells with weak sinks or are removed by weak sinks withdrawing more than half of the water entering the cell (fig. 6).

Because the extent of contamination by vinyl chloride in the Saginaw aquifer is uncertain, an additional forward tracking simulation was done for the 1997 average pumping conditions and the purge wells. For the first simulation, 4,500 particles were started in each of the four cells as previously described but the same number of particles were also placed in 12 adjoining and nearby cells for a total of 72,000 particles. In this simulation, particles are ultimately removed from the ground-water system by three wells. Well 25-22 removes 97 percent of the particles, while 25-28 and 25-37 remove the rest. In the next simulation particles were removed from a cell only when the total well discharge was larger than 50 percent of the total water inflow to the cell. For these conditions, well 25-22 removes 97 percent of the particles, while 25-28 and 25-29 remove the rest. Well 25-29 was a weak sink in the previous simulation. Particle-tracking results for 1997 pumping conditions are summarized in Table 3.

Purge wells located west of plume

The model was used to simulate 1997 average pumping rates with two hypothetical purge wells west of the plume pumping at rates of



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

Public Supply Wells
Wells Receiving Particles in Simulation
Flowpaths
Groundwater Divide
Potentiometric Surface
Contour interval = 5 feet

Figure 6: Simulated potentiometric surface for Saginaw aquifer under 1997 average pumping rates, north Lansing well field, Lansing, Michigan

Table 3: Particle Tracking Results for 1997 Average Pumping Rates

Simulation			Wells Receiving Particles (percent of particles)
Average	Particles in Center of Plume	Particles pass through weak sinks	25-22 (100 %)
		Particles stop in some weak sinks	25-22 (100 %)
	Particles in Large Plume	Particles pass through weak sinks	25-22 (97 %); 25-28 (2.6 %); 25-37 (<1 %)
		Particles stop in some weak sinks	25-22 (97 %); 25-28 (2.6 %); 25-29 (<1 %)
100 gpm purge wells located west of the plume	Particles in Center of Plume	Particles pass through weak sinks	25-22 (100 %)
		Particles stop in some weak sinks	North purge well (81 %); 25-22 (17 %); South purge well (2 %)
	Particles in Large Plume	Particles pass through weak sinks	25-22 (100 %)
		Particles stop in some weak sinks	25-22 (54 %); North purge well (44 %), South purge well (2 %)
200 gpm purge wells located west of the plume	Particles in Center of Plume	Particles pass through weak sinks	North purge well (83 %); South purge well (17 %)
		Particles stop in some weak sinks	North purge well (83 %); South purge well (17 %)
	Particles in Large Plume	Particles pass through weak sinks	North purge well (58 %); 25-22 (36 %); South purge well (6 %)
		Particles stop in some weak sinks	North purge well (58 %); 25-22 (36 %); South purge well (6 %)

Table 3: Particle Tracking Results for 1997 Average Pumping Rates

Simulation			Wells Receiving Particles (percent of particles)
100 gpm purge wells located north of plume	Particles in Center of Plume	Particles pass through weak sinks	25-22 (100 %)
		Particles stop in some weak sinks	West purge well (87 %); East purge well (3 %); 25-22 (11 %)
	Particles in Large Plume	Particles pass through weak sinks	25-22 (100 %)
		Particles stop in some weak sinks	West purge well (38 %); East purge well (8 %); 25-22 (54 %)
	Particles in approxi-mate extent of plume	Particles pass through weak sinks	25-22 (100 %)
		Particles stop in some weak sinks	West purge well (43 %); East purge well (9 %); 25-22 (48 %)
200 gpm purge wells located north of plume	Particles in Center of Plume	Particles pass through weak sinks	West purge well (100 %)
		Particles stop in some weak sinks	West purge well (96 %); East purge well (4 %)
	Particles in Large Plume	Particles pass through weak sinks	West purge well (66 %); 25-22 (34 %)
		Particles stop in some weak sinks	West purge well (57 %); East purge well (9 %); 25-22 (34 %)
	Particles in approxi-mate extent of plume	Particles pass through weak sinks	West purge well (82 %); 25-22 (18 %)
		Particles stop in some weak sinks	West purge well (73 %); East purge well (9 %); 25-22 (18 %)

100 and 200 gpm. When the purge wells were simulated as pumping 100 gpm, particles tracked from four cells at the center of the vinyl chloride plume and allowed to pass through cells that acted as weak sinks are removed by BWL well 25-22. When the purge wells were simulated as pumping 200 gpm, however, all of the particles are removed by the two purge wells.

A similar evaluation was done in which particles were removed from a cell only when the total well discharge was larger than 50 percent of the total water inflow to the cell. Under these conditions with purge wells simulated as pumping 100 gpm, both purge wells remove about 83 percent of the particles while the remainder is removed by well 25-22. Under these conditions with purge wells simulated as pumping 200 gpm, both purge wells remove all of the particles.

When particles were introduced into sixteen cells to represent the position of a larger vinyl chloride plume and forward tracked with the two purge wells simulated as pumping 100 gpm, all particles are removed by supply well 25-22. When particles were removed from a cell when the total well discharge was larger than 50 percent of the total water inflow to the cell, both purge wells together remove about 46 percent of the particles with the rest removed by well 25-22. When purge wells were simulated as pumping 200 gpm, the purge wells remove about 64 percent of the particles with the remainder removed by supply well 25-22 whether particles pass through cells with weak sinks or are removed by weak sinks withdrawing more than half of the water entering the cell.

Purge wells located north of plume

The model was used to simulate 1997 average pumping rates with two existing purge wells north of the plume pumping at rates of 100 and 200 gpm. When tracked from four cells at the center of the vinyl chloride plume and allowed to pass through cells that acted as weak sinks, all the particles are removed by well 25-22 when the purge wells were simulated as pumping 100 gpm. When the purge wells were simulated as pumping 200 gpm, however, all of the particles are removed by the west purge well. A second simulation was performed in which particles are removed from a cell when the total well discharge was larger than 50 percent of the total water inflow to the cell. Under these conditions, 25-22 and both purge wells remove particles when the purge wells are simulated as pumping 100 gpm. Under these conditions, both purge wells remove all particles when the purge wells are simulated as pumping 200 gpm.

When particles were introduced into sixteen cells to represent the position of a larger vinyl chloride plume and forward tracked with the two purge wells simulated as pumping 100 gpm, well 25-22 removes all of the particles. If particles are removed from a cell when the total well discharge was larger than 50 percent of the total water inflow to the cell, the purge wells together remove about 46 percent of the particles, and the rest are removed by 25-22. When purge wells were simulated as pumping 200 gpm, the west purge well removes 66 percent and the rest are removed by well 25-22. When particles are removed by cells in which more than half of the water entering the cell is withdrawn by the simulated well, the purge wells remove 66 percent of the particles and the rest are removed by well 25-22.

A third set of simulations were run in which particles were placed in cells that define the approximate extent of the known vinyl chloride plume. When the purge wells are simulated as pumping 100 gpm and particles pass through weak sinks, well 25-22 removes all of the particles. When particles are removed by cells in which more than half of the water entering the cell is withdrawn by the simulated well, the purge wells remove 52 percent of the particles and the rest are removed by well 25-22. When the purge wells are simulated as pumping 200 gpm and particles pass through weak sinks, the west purge well removes 82 percent and the rest are removed by well 25-22. When particles are removed by cells in which more than half of the water entering the cell is withdrawn by the simulated well, the purge wells remove 82 percent of the particles and the rest are removed by well 25-22.

Twenty-year Time Frame

Average pumping conditions for 1995

Particles were tracked forward for simulated 20-year time frames for 1995 average pumping conditions and both purge well locations. In 20 years, no particles reached BWL supply wells when they were initiated at four cells in the center of the known vinyl chloride plume. However, when particles were initiated using a 16-cell configuration around the plume center, particles reach well 25-26 in less than 20 years when particles are removed by weak sinks withdrawing more than half of the water entering the cell.

When the two purge wells located west of the plume are simulated as pumping 100 gpm, the north purge well removes some particles in less than 20 years. If weak sinks withdrawing more than 50 percent of the water entering the cell were allowed to remove particles, both purge wells remove some particles in less than 20 years. When particles are initiated using a 16-cell configuration to represent a larger plume, BWL well 25-26 and the two purge wells remove some particles in less than 20 years whether particles pass through cells with weak sinks or are removed at weak sinks withdrawing more than 50 percent of the water entering the cell.

When the two purge wells located west of the plume are simulated as pumping 200 gpm, both purge wells remove some particles in less than 20 years whether particles pass through cells with weak sinks or are removed at weak sinks withdrawing more than 50 percent of the water entering the cell. When particles are initiated using a 16-cell configuration representing a larger plume, BWL well 25-26 and both purge wells remove some particles in less than 20 years whether or not weak sinks can remove particles.

When the two purge wells located north of the plume are simulated as pumping 100 gpm, the west purge well removes some particles in less than 20 years if weak sinks withdrawing more than 50 percent of the water entering the cell are allowed to remove particles. When particles are initiated using a 16-cell configuration to represent a larger plume, BWL well 25-26 removes some particles in less than twenty years if particles are allowed to pass through weak sinks. When particles are removed at weak sinks withdrawing more than 50 percent of the water entering the cell, well 25-26 and both purge wells remove some particles in less than 20 years.

When the two purge wells located north of the plume are simulated as pumping 200 gpm, both purge wells remove some particles in less than 20 years when particles are removed at weak sinks withdrawing more than 50 percent of the water entering the cell. When particles are initiated using a 16-cell configuration representing a larger plume, BWL well 25-26 and the west purge well remove some particles in less than 20 years if particles are allowed to pass through weak sinks. When particles are removed at weak sinks withdrawing more than 50 percent of the water entering the cell, well 25-26 and both purge wells remove some particles in less than 20 years. Particle-tracking results for the twenty-year time frame are summarized in Table 4.

Average pumping conditions for 1997

Particles were tracked forward for simulated 20-year time frames for average 1997 pumping conditions and both purge well locations. In 20 years, no particles reached BWL supply wells when they are initiated at four cells in the center of the known vinyl chloride plume. However, when particles are initiated using a 16-cell configuration around the plume center, particles reach well 25-22 whether particles pass through cells with weak sinks or are removed at weak sinks withdrawing more than 50 percent of the water entering the cell.

When the two purge wells located west of the plume are simulated as pumping 100 gpm, the particles do not reach a well in less than 20 years. If weak sinks withdrawing more than 50 percent of the water entering the cell are allowed to remove particles, both purge wells remove some particles in less than 20 years. When particles are initiated using a 16-cell configuration to represent a larger plume, BWL well 25-22 removes some particles in less than 20 years. When particles are removed at weak sinks withdrawing more than 50

Table 4: Particle Tracking Results for Twenty-Year Time Frame

Simulation			Wells receiving particles under 1995 conditions	Wells receiving particles under 1997 conditions
Average	Particles in Center of Plume	Particles pass through weak sinks		
		Particles stop in some weak sinks		
	Particles in Large Plume	Particles pass through weak sinks		25-22
		Particles stop in some weak sinks	25-26	25-22
100 gpm purge wells located west of plume	Particles in Center of Plume	Particles pass through weak sinks	North purge well	
		Particles stop in some weak sinks	North purge well, South purge well	North purge well, South purge well
	Particles in Large Plume	Particles pass through weak sinks	25-26, North purge well	25-22
		Particles stop in some weak sinks	25-26, North purge well, South purge well	25-22, North purge well, South purge well
200 gpm purge wells located west of plume	Particles in Center of Plume	Particles pass through weak sinks	North purge well, South purge well	North purge well, South purge well
		Particles stop in some weak sinks	North purge well, South purge well	North purge well, South purge well
	Particles in Large Plume	Particles pass through weak sinks	25-26, North purge well, South purge well	25-22
		Particles stop in some weak sinks	25-26, North purge well, South purge well	25-22, North purge well, South purge well

Table 4: Particle Tracking Results for Twenty-Year Time Frame

Simulation			Wells receiving particles under 1995 conditions	Wells receiving particles under 1997 conditions
100 gpm purge wells located north of plume	Particles in Center of Plume	Particles pass through weak sinks		
		Particles stop in some weak sinks	West purge well	West purge well, East purge well
	Particles in Large Plume	Particles pass through weak sinks	25-26	25-22
		Particles stop in some weak sinks	25-26, West purge well, East purge well	25-22, West purge well, East purge well
200 gpm purge wells located north of plume	Particles in Center of Plume	Particles pass through weak sinks	West purge well	West purge well
		Particles stop in some weak sinks	West purge well, East purge well	West purge well, East purge well
	Particles in Large Plume	Particles pass through weak sinks	25-26, West purge well	25-22, West purge well
		Particles stop in some weak sinks	25-26, West purge well, East purge well	25-22, West purge well, East purge well

percent of the water entering the cell, BWL well 25-22 and both purge wells remove some particles in less than 20 years.

When the two purge wells located west of the plume are simulated as pumping 200 gpm, both purge wells remove some particles in less than 20 years whether particles pass through cells with weak sinks or are removed at weak sinks withdrawing more than 50 percent of the water entering the cell. When particles are initiated using a 16-cell configuration representing a larger plume, BWL well 25-22 removes some particles in less than 20 years. When particles are removed at weak sinks withdrawing more than 50 percent of the water entering the cell, BWL well 25-22 and both purge wells remove some particles in less than 20 years.

When the two purge wells located north of the plume are simulated as pumping 100 gpm, the west purge well removes some particles in less than 20 years if particles are allowed to pass through weak sinks. If weak sinks withdrawing more than 50 percent of the water entering the cell are allowed to remove particles, both purge wells remove particles in less than twenty years. When particles are initiated using a 16-cell configuration to represent a larger plume, BWL well 25-22 removes some particles in less than twenty years if particles are allowed to pass through weak sinks. When particles are removed at weak sinks withdrawing more than 50 percent of the water entering the cell, well 25-22 and both purge wells remove some particles in less than 20 years.

When the two purge wells located north of the plume are simulated as pumping 200 gpm, the west purge wells removes some particles in less than 20 years if particles are allowed to pass through weak sinks. If weak sinks withdrawing more than 50 percent of the water entering the cell are allowed to remove particles, both purge wells remove particles in less than twenty years. When particles are initiated using a 16-cell configuration representing a larger plume, BWL well 25-22 and the west purge well remove some particles in less than 20 years if particles are allowed to pass through weak sinks. When particles are removed at weak sinks withdrawing more than 50 percent of the water entering the cell, well 25-22 and both purge wells remove some particles in less than 20 years.

LIMITATIONS OF MODEL APPLICATIONS AND SIMULATIONS

The model used in the ground-water flow analyses described in this report still has some weak sinks even though the grid spacing was reduced. The reduction in cell size in the center of the model does allow for separation of individual wells. It is likely that all wells, whether strong or weak sinks, within the path of the plume would withdraw contaminated water at some time during the year. Further reduction of the grid spacing might allow more of the wells acting as weak sinks to become strong sinks, thus allowing the movement of the plume to be determined with greater confidence.

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

Pumping conditions, the extent of the plume, and the locations and pumping rates of purge wells are all important in determining the movement of a vinyl chloride plume in the Saginaw aquifer and the potential impact to BWL public-supply wells. Pumping rates by the BWL wells strongly control the directions of ground-water flow in the Saginaw aquifer and the position of a ground-water flow divide near the area known to contain vinyl chloride. As pumping rates in the north Lansing well field are decreased from 1995 to 1997 pumping conditions, the ground-water flow divide moves to the south. Movement of this divide to the south beyond the extent of the known vinyl chloride plume may prevent contamination of wells to the south of the north Lansing well field. However, the full extent of the plume is unknown, therefore 1997 pumping conditions may not be sufficient to prevent contamination of wells to the south of the study area.

Hypothetical purge wells were proposed west of the known plume and actually drilled north of the known plume. Particle-tracking simulations investigated whether either of these locations were sufficient to intercept water containing vinyl chloride. Under 1995 conditions, purge wells west of the plume pumping at 100 or 200 gpm remove all particles started at the center of the known plume. However, under 1997 conditions, only when purge wells to the west of the plume are simulated as pumping 200 gpm are they effective at removing all particles started at the center of the known plume. Under 1995 and 1997 conditions, purge wells north of the plume simulated as pumping 200 gpm are effective at removing all particles started in the center of the known plume. Under 1995 and 1997 conditions, neither purge well locations or pumping rates are effective at removing all particles started in cells representing the location of a larger plume.

Because the full extent of the plume is unknown, the actual effectiveness of purge wells at either location or pumping rate and the potential impact on BWL public-supply wells is uncertain. Potentially more BWL wells may be affected than the particle-tracking results indicate and the effectiveness of purge wells may be overestimated. Interpretation of particle-tracking results are also affected by the fact that some cells are still weak sinks, all simulated wells are represented as pumping at constant rates, and hydrogeologic information on the glacial deposits is generalized.

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 might further 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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