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DETERMINATION OF THE TIME-OF-TRAVEL CAPTURE ZONES AND TIME-DEPENDENT RECHARGE AREAS FOR THE CLINTON, ILLINOIS WATER SUPPLY WELLS

DeWitt County

MICHAEL L. GREENSLATE

A Thesis Submitted in Partial
Fulfillment of the Requirements
for the Degree of

MASTER OF SCIENCE

Department of Geography-Geology

ILLINOIS STATE UNIVERSITY

1996

DETERMINATION OF THE TIME-OF-TRAVEL CAPTURE ZONES AND

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Modeled five and fifty year time of travel capture zones for Clinton's wells extend 0.5 and 2.5 miles southeast. Surface recharge occurs at least 12 miles and 514 years southeast.

APPROVED:

4/26/96 Lawrence J. Barrows
Date Lawrence J. Barrows, Chair

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Date Samuel Boateng

ACKNOWLEDGMENTS

I would like to dedicate this thesis to the memory of John W. Foster. My thanks also go to Dr. Barrows for his assistance and understanding throughout this endeavor, and my wife Jennifer whose encouragement and support made this possible.

M.L.G.

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With approximately one-half of Illinois residents relying upon groundwater as their primary source of drinking water, protection of this precious resource from the threat of contamination is paramount. The state of Illinois has in place a variety of laws such as the Wellhead Protection Program (WHPP) by which groundwater is protected. An important aspect of the WHPP is the delineation of areas that contribute water to a well. Once these areas are located, wellhead protection plans can be created that protect the well from contamination. The use of three-dimensional computer modeling techniques is currently the best means by which recharge areas can be delineated.

A three-dimensional groundwater model was created for the city of Clinton, Illinois in an effort to delineate their likely recharge areas as well as their five year time-of-travel capture zones. Time-dependent surface recharge areas are surface areas that contribute water to the well. Time-of-travel capture zones are subsurface volumes that contribute water to the well.

According to the model, none of the particles tracked reached the surface within the modeled study area, thus indicating that the recharge areas for Clinton's wells are located at *least* 12 miles southeast of the wells themselves. The average particle travel-time associated with this distance is approximately 514 years. The limit of the five year time-of-travel capture zones for the wells were found to be approximately one-half mile southeast of or upgradient from the wells. The limit of the 50 year time-of-travel capture zones are located approximately 2.5 miles southeast of or upgradient from the wells.

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CHAPTER 1

THE PROBLEM AND ITS BACKGROUND

Introduction

About 7.5 million people in Illinois, approximately one-half of the population, rely upon groundwater as their primary source of drinking water. Not only do Illinois residents use groundwater for human consumption, they also use this resource for irrigation, livestock, and industry. Between 1980 and 1987, one billion gallons of groundwater were pumped daily to fulfill the needs of the state (Bowman, 1991). Nearly 50 percent of this total was used by approximately 2000 municipal water supply systems (Bowman, 1991). Because such a large percentage of the population relies upon groundwater, protection of this resource is vital. As growth and development within the state increase, so does the state's dependence on this precious resource. With this growth comes an increase in the potential for groundwater contamination and therefore an increase in the need to protect water supply systems.

Legislative Action

The ever-increasing reliance on and vulnerability of groundwater resources has prompted legislation aimed at groundwater protection. In 1974, the federal government established the Safe Drinking Water Act (SDWA). The SDWA lists maximum contaminant levels (MCL's) that are not to be exceeded in drinking water. In 1986, amendments to the SDWA extended the list and lowered the maximum permissible levels of contaminants detectable in public drinking water supplies. The 1986 amendments also established the federal Wellhead Protection Program (WHPP). The WHPP gives states the option of creating their own groundwater protection plans and is completely voluntary. Should a state elect to participate they must submit their protection plan to the United States Environmental Protection Agency (U.S. EPA) for approval. In compliance with this, the Illinois Environmental Protection Agency (IEPA) submitted and gained approval for its groundwater protection program. The plan was implemented into law in the Illinois Groundwater Protection Act (IGPA).

The Illinois Groundwater Protection Act (P.A. 85-0863), approved in 1987, acknowledges the need for groundwater protection and sets forth certain provisions for doing so. The Act itself relies upon a state and local partnership in its protection efforts. Under the authority granted by this Act, the IEPA has required that commercial or public water supply systems that utilize groundwater develop and submit to the IEPA a groundwater protection plan for approval.

Wellhead Protection in Illinois

The Illinois Wellhead Protection Plan recognizes that it is in the state's best interest to take a *proactive* rather than a *reactive* approach to groundwater protection. Communities are all too often faced with costly site remediation that could have been averted if the necessary precautionary measures had been taken. The IEPA has placed particular importance on the delineation of Wellhead Protection Areas (WHPA's). WHPA's are defined as "the surface area surrounding a water well or well field, supplying a public water system, through which contaminants are reasonably likely to move toward and reach such water well or well field (Horsley and Witten, 1993)." The focus of the Illinois Wellhead Protection Plan is on locating any potential sources of contamination as well as on effectively regulating and managing any activities taking place within WHPA's that could pose the threat of contamination to a public water well.

There are several methods that a community can use (singly or in combination) to delineate its WHPA's. The following is a list of the IEPA-approved methods and a brief description of each:

Arbitrary Fixed Radius - A circle with an arbitrarily assigned radius is drawn around the wellhead and represents the WHPA boundaries.

Calculated Fixed Radius - A circle with a fixed radius is drawn around the wellhead. The radius of the WHPA is calculated using data such as aquifer characteristics, pumping rate and well construction.

Simplified Variable Shapes - This method utilizes simple geometric shapes that are designed to approximate the hydrologic characteristics of the area around a pumping well.

Numerical and Analytical Methods - Simulation of groundwater flow as a function of pumping rate, aquifer characteristics and piezometric conditions is achieved by the use of mathematical equations.

In addition to delineating the WHPA, the community is required to identify potential sources of contamination within the WHPA boundaries, formulate management and contingency plans, and support public education regarding the Wellhead Protection Program. Once WHPA delineations are confirmed by the IEPA, the community may then create or amend ordinances and/or zoning regulations that are geared toward the protection of the groundwater resource.

Two-Dimensional Vs. Three-Dimensional Modeling

The U.S. EPA has developed 'WHPA,' a modular, semi-analytical groundwater flow model to assist state agencies and communities with making WHPA delineations. The model allows for the calculation of a well's capture zone, and can be used for particle tracking and uncertainty analysis. An unfortunate short-coming of this flow model is that it solves the analytical equations for two-dimensional flow into a well. Davies (1995) demonstrated that the migration of groundwater cannot always be portrayed adequately using two-dimensional modeling techniques because groundwater flow occurs in three dimensions. Because well screens in an aquifer are commonly at a considerable depth below the ground surface, this third dimension (depth) must be taken into account if a groundwater flow system is to be understood.

Two-dimensional WHPA delineations differ significantly from the delineations achieved by utilizing three-dimensional modeling techniques. In three-dimensional modeling, water enters the well only through the well screen while in two-dimensional modeling, the water enters the well through the entire thickness of the aquifer. For three-dimensional delineations, a distinction between time-dependent surface recharge areas and time-of-travel capture zones is necessary. A time-dependent surface recharge area is the *area* on the ground surface that contributes water to a well screen within a given interval of time. A time-of-travel capture zone represents a subsurface *volume* that contributes water to a well screen within a specified time interval. Figure 1 is a diagram showing the relationship between the time-dependent surface recharge areas and the time-of-travel capture zones for an individual well.

For some water supply systems, the WHPA for an individual water well would be overly extensive for effective management unless some time constraint is introduced. The use of a time constraint is also consistent with the very large uncertainties inherent in flow systems with longer travel times. Also many contaminants are diluted, decomposed, or adsorbed during subsurface flow. It is for these reasons that the IEPA has approved a five-year limit on WHPA's. This five-year limit represents the area from which contaminants are most likely to enter a well within a five-year time interval and serves to keep the WHPA manageable.

Study Area

The city of Clinton is located in east-central Illinois and is the largest population center in DeWitt County (Figure 2). Clinton has a population of approximately 8,000

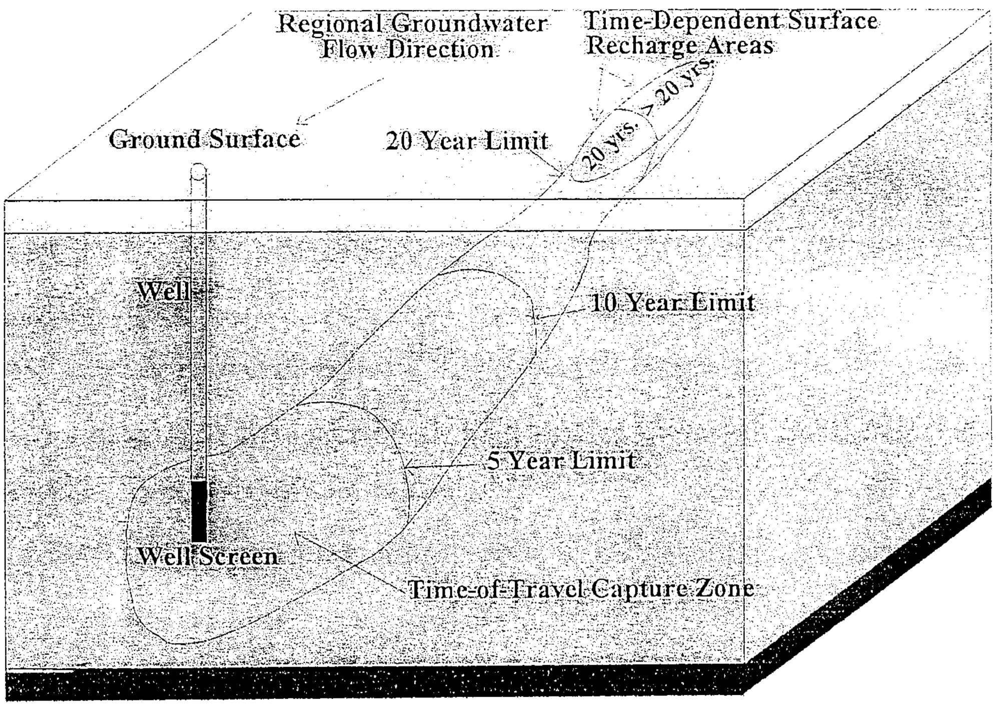


Figure 1. Relationship between the time-dependent surface recharge areas and time-of-travel capture zones for an individual well. (Modified from Davies, 1995.)

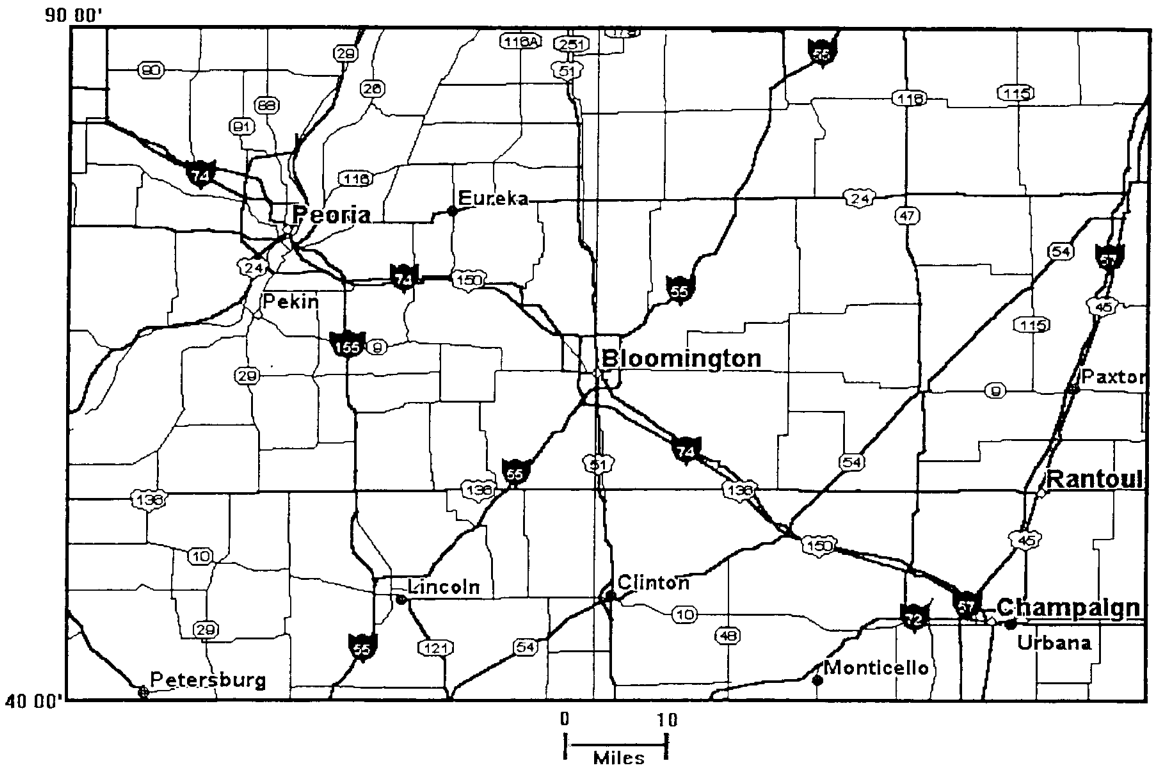


Figure 2. Location map showing the City of Clinton and other central Illinois communities.

residents. Most of the people in Clinton use groundwater that is provided by the city's municipal water supply system. A few factories are located within the city but agriculture and related industries are the main businesses in the surrounding rural areas. The Clinton Nuclear Power Station is located approximately ten miles east of the city.

The city owns and operates six production wells that provide water to the public and to the industries present within the city limits. Figure 3 shows the city of Clinton and the approximate location of the six wells. Total pumpage for 1995 was 398,498,000 gallons or an average of 145,870 cubic feet per day (Buchanan, personal communication). Currently, the city does not have five-year capture zones mapped for their production wells and is not certain of the exact location or extent of their respective time-dependent recharge areas. Prior to this research Richard Helton, Clinton's City Manager, conveyed an interest on the city's part in this project. As chairman of the Mahomet Valley Water Authority, the city manager has an active interest in groundwater and realizes the benefits this project will have for the community.

Study Objectives

- Delineate three-dimensional time-of-travel capture zones and time-dependent recharge areas for the wellfield of the city of Clinton, Illinois.
- Determine the sensitivity of the delineations to uncertainties in the hydrologic parameters.

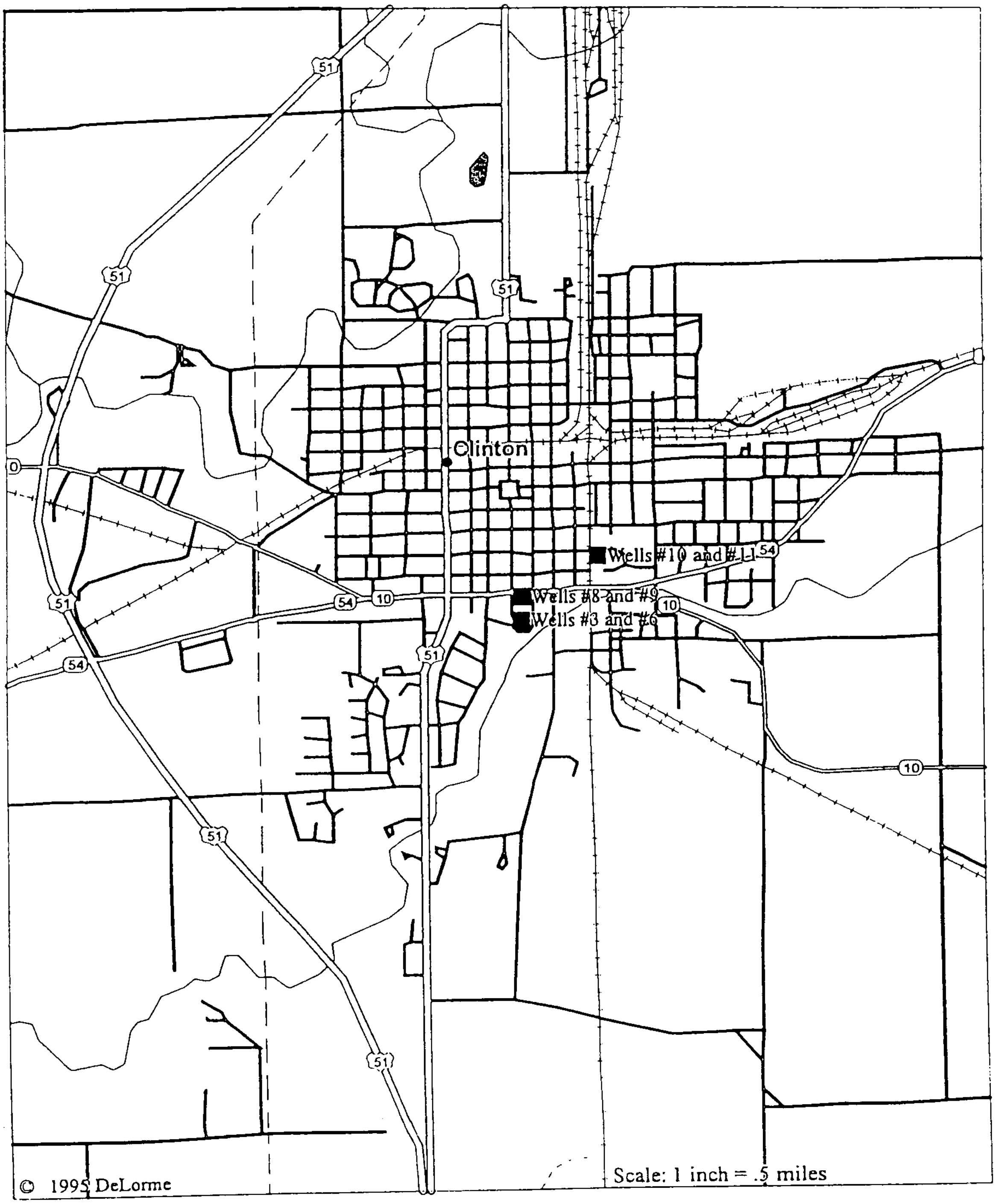


Figure 3. City map showing the approximate locations of the six municipal water wells.

- Provide geohydrologic assistance to the city of Clinton and the IEPA in the development of the Clinton, Illinois Wellhead Protection Plan.

Previous Work

There exists a significant amount of literature which results from previous research on the Mahomet Bedrock Valley. "Geology for Planning in DeWitt County" (Hunt and Kempton, 1977) was written partly in response to Illinois Power Companies' plans to construct the Clinton Nuclear Power Station and proved especially helpful in writing this report. The document contained detailed geologic descriptions of the study area as well as a summary of the groundwater resources in Dewitt County. Also included were maps showing the distribution, thickness, and elevation of the Mahomet Sand which were used for the groundwater model.

The city of Decatur's decision to construct a well field in DeWitt County prompted studies by both the ISWS and the ISGS. A recent ISWS report (Anliker and Sanderson, 1995) was the result of an extensive study of the groundwater levels and withdrawals in DeWitt and Piatt counties. Of special significance to this report were the potentiometric surface maps for the Glasford and Banner Formations found in the aforementioned document. These maps were used during the calibration phase of the groundwater computer simulation and proved invaluable in the completion of the model.

Visocky and Schicht (1969) published a report on the groundwater resources of DeWitt and Piatt counties in which the geohydrologic characteristics of the Mahomet

Sand were described. A cooperative report by the ISWS and the ISGS (Kempton and others, 1982) also presented a geohydrologic characterization of the Mahomet Sand which was of use during the construction of the conceptual model.

On a regional scale is Geological Society of America Special Paper 258 (Kempton and others, 1991) which contains information not only on the Mahomet Bedrock Valley but the entire Teays Valley system. The hydraulic conductivity values used in this study were taken from that document.

Saelens' Masters Thesis (1995) contained a regional groundwater simulation for DeWitt County. This model was used as a regional foundation for the construction of the model resulting from this study. Davies' Masters Thesis (1995) included model simulations for the towns of Havana, Green Valley, and Easton, all in Illinois and resulted in time-of-travel capture zone and time-dependent recharge area delineations for those towns. The methodologies and procedures used by Davies were applied to this study.

CHAPTER II

GEOLOGY

Regional Geology

The city of Clinton is situated in one of the most geologically favorable regions with respect to groundwater resources in Illinois. The Mahomet Bedrock Valley directly underlies Clinton and the glacial deposits that fill the valley are the source of the city's groundwater. This buried valley is a segment of an ancient drainage system of much greater extent, the origin of which reaches into West Virginia (Figure 4). The Teays Valley, as this drainage system is formally known, has been the subject of much study and speculation since its discovery nearly a century ago. In recent years, workers have challenged the classical interpretation of the Teays Valley. It is now thought that the Teays was not a single river system, but rather a complex drainage system composed of at least three separate rivers (Kempton and others, 1991). The Mahomet Bedrock Valley, the Illinois segment of the Teays Valley, is now thought to represent one of these ancient rivers. The Teays Valley enters east-central Illinois in Vermillion County and traverses northwestward into Tazewell County, where it joins the Mackinaw Bedrock Valley. The Mahomet Bedrock Valley is cut into the Pennsylvanian strata that constitute approximately two-thirds of the bedrock in Illinois (Willman and others, 1975). This

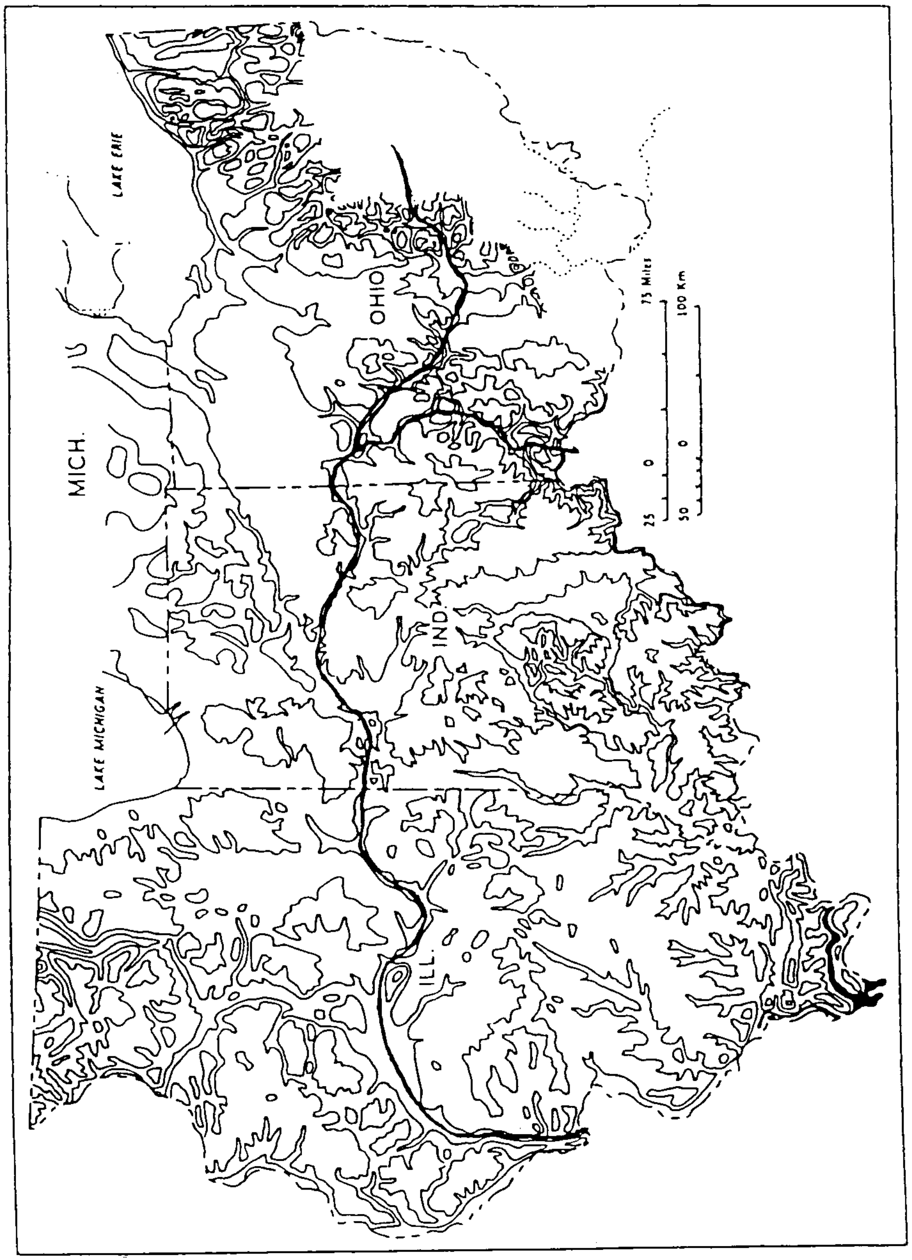


Figure 4. Regional map showing the Teays Valley System from Illinois to West Virginia. (Melhorn and Kempton, 1991).

valley served as a glacial meltwater drainageway during the Pleistocene for most of northeastern Illinois and for portions of northern Indiana (Kempton and others, 1991).

Study Area Physiography

The nature of the topography and surficial deposits in the study area are the direct result of Pleistocene glaciation and associated running meltwater (Hunt and Kempton, 1977). Unconsolidated deposits, collectively known as glacial drift, cover the bedrock surface of the entire county. These deposits include sand, silt and clay. Some coarser materials also occur locally within the succession. In areas where bedrock elevation is low, the drift is thick relative to areas where bedrock occurs at higher elevations. Most of the drift in the county is overlain by Wisconsinan-Stage loess that is composed of silt-sized, wind-deposited sediment. Modern soils have developed on the loess and on the overlying Holocene alluvial deposits.

The topography of the study area is fairly flat. Some relief, however, is provided by the Shelbyville moraine located to the west and the Heyworth moraine located to the south and east of Clinton. The Shelbyville Moraine represents the furthest extent of the Wisconsinan Age ice sheets (Hunt and Kempton, 1977). Salt, Ten Mile and Coon creeks also provide some relief in the glaciated terrain. As a result of the trend of the aforementioned moraines, drainage within the study area is to the south and southwest. The most recent deposits are alluvium along the creeks.

Study Area Geology

The bedrock in the study area is comprised of the Pennsylvanian Bond and Modesto formations. These formations consist of shale and sandstone with thinner, less significant beds of limestone and coal. Elevation of the bedrock surface ranges from approximately 350 to 500 feet above MSL within the study area (Herzog and others, 1994). For purposes of the current study, the bedrock in the study area is assumed to be a geohydrologic barrier that is not involved in the groundwater flow system. Below the Pennsylvanian units lies a thick succession of limestones, sandstones and shales deposited during earlier Paleozoic periods (Hunt and Kempton, 1977). The Mahomet Bedrock Valley is cut into the Pennsylvanian bedrock strata and is approximately 15 miles wide and 300 feet deep in the Clinton area. Figure 5 shows the bedrock topography and elevation of the study area.

The bedrock is overlain by glacial drift and loess deposits which vary in thickness. The thickness of the Pleistocene deposits is controlled by the elevation of the bedrock surface. Thicknesses range from approximately 400 feet over the center of the valley to about 200 feet over its flanks. The buried bedrock valley is filled with glacial outwash which is overlain by glacial tills and alluvium deposited during several glacial advances. The drift present in the study area was deposited during the pre-Illinoian, Illinoian, and Wisconsinan stages of glaciation. Separating the units are paleosols and/or loess deposits that represent interglacial stages. Sand and gravel lenses occur throughout the drift and are routinely encountered during drilling. In some instances, these lenses yield enough water for domestic or farm wells (Hunt and Kempton, 1977).

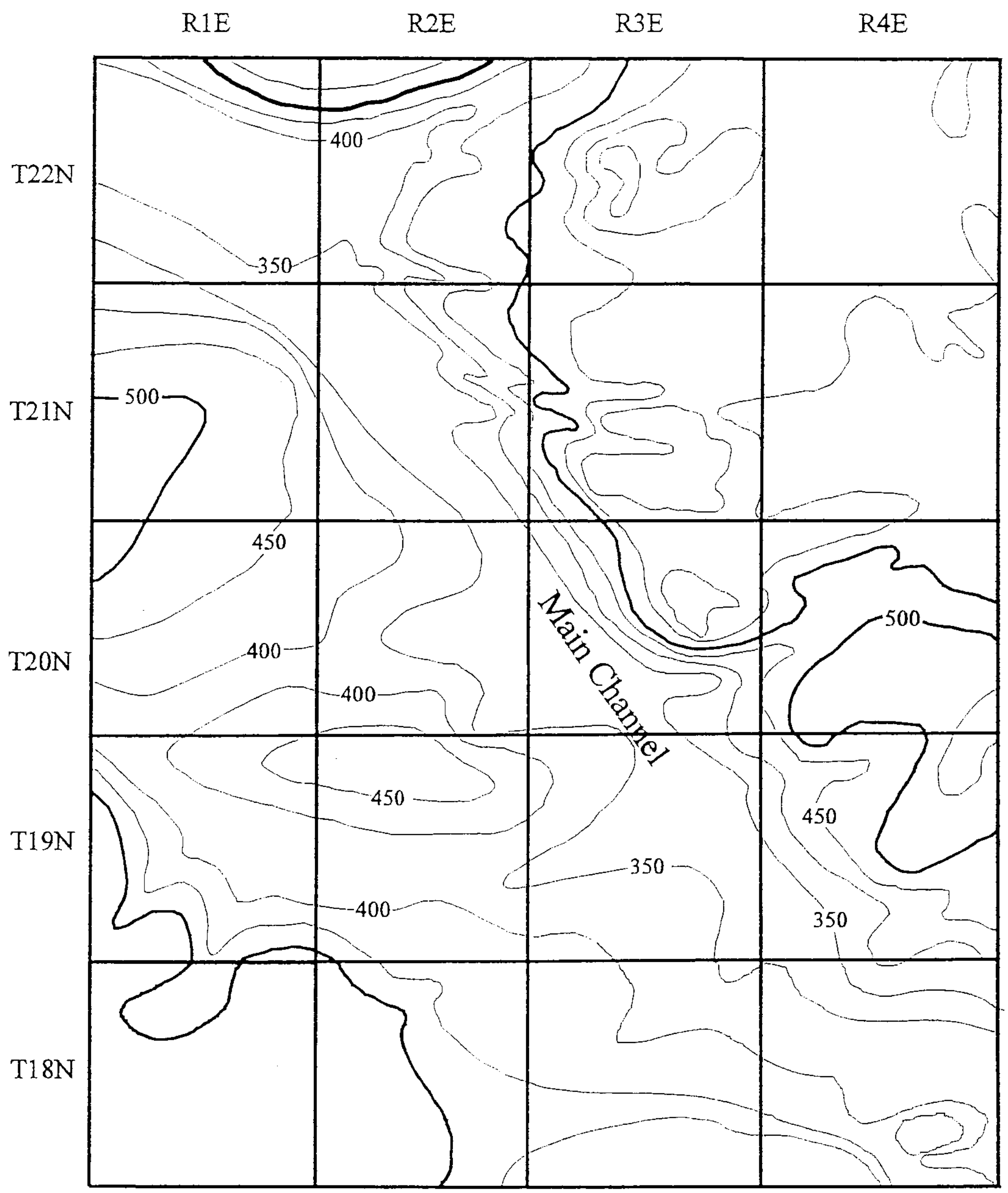


Figure 5. Study area bedrock map (modified from Herzog and others, 1994).

Cross sections were constructed by Saelens (1995) and are included on the following pages to aid in the descriptions of the Pleistocene deposits. Figure 6 shows the locations of the cross sections with respect to the Mahomet Bedrock Valley in the study area. Figure 7, cross section A-A', is from Kenney to Clinton. Figure 8, cross section B-B', is along U.S. Route 51 from Clinton to Wapella.

Within the Mahomet Bedrock Valley, the Banner Formation directly overlies the Pennsylvanian strata and represents deposits of the pre-Illinoian Stage. The Mahomet Sand Member of the Banner Formation is the basal unit and is composed of thick sand and gravel deposits of glacial outwash. The outwash fills the channel of the Mahomet Bedrock valley to a depth of 100 feet, giving its upper boundary an elevation of approximately 475 feet above mean sea level (Hunt and Kempton, 1977).

The Glasford Formation (Illinoian) overlies the pre-Illinoian deposits and consists of several till layers separated by thin, discontinuous sand and gravel lenses (Hunt and Kempton, 1977). The Radnor Till Member of the Glasford Formation, described as a gray, silty till, is the uppermost till in the formation. The Illinoian till is pervasively fractured. This fracturing is probably caused by loading of the till. These fractures, which have been subsequently filled with fine sediments, may act as conduits for the vertical migration of fluids from the overlying deposits (Saelens, 1995).

The Wedron Formation (Wisconsinan) consists of two till members. The Fairgrange Till Member is present in the study area, as well as in the entire western half of the county, and the Piatt Till Member is in the eastern half of the county and absent in the study area (Hunt and Kempton, 1977). The Robein Silt, where present, is an organic

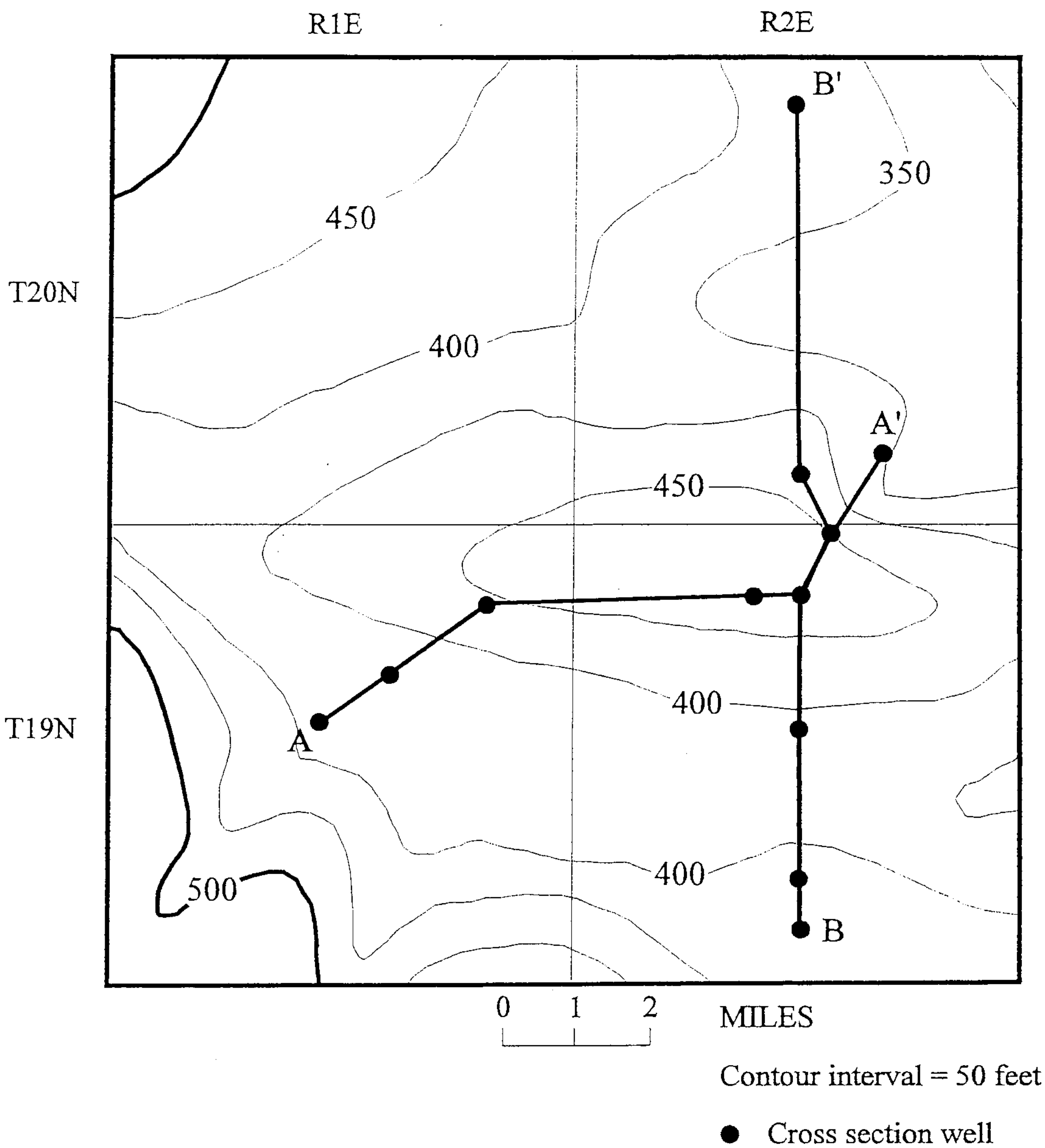


Figure 6. Study area bedrock map showing locations of cross sections. (Modified from Saelens, 1995)

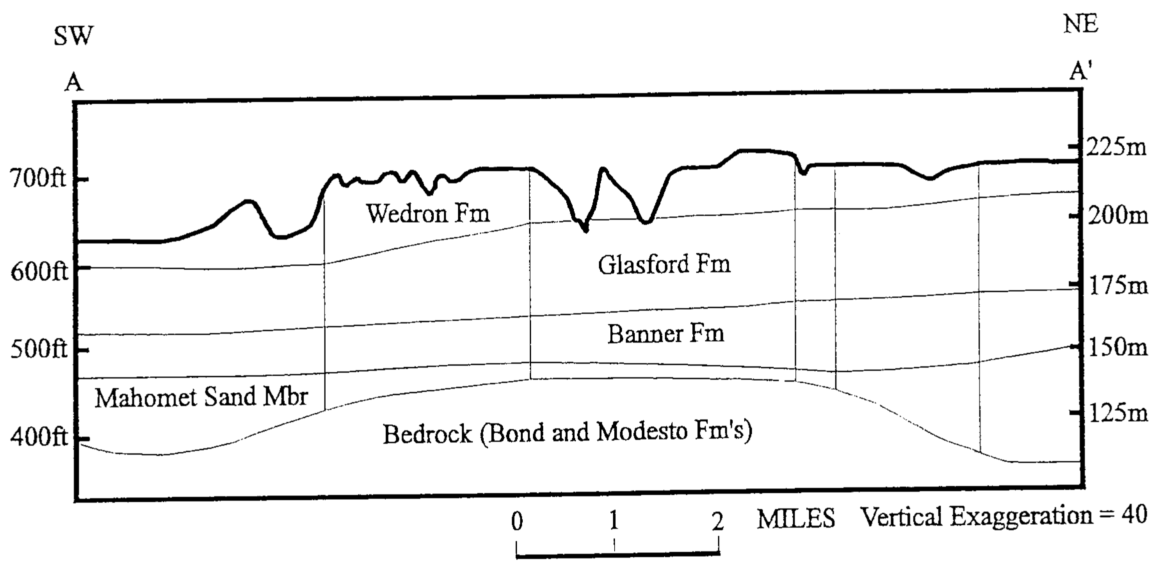


Figure 7. Cross-section from Kenney to Clinton. (Modified from Saelens, 1995)

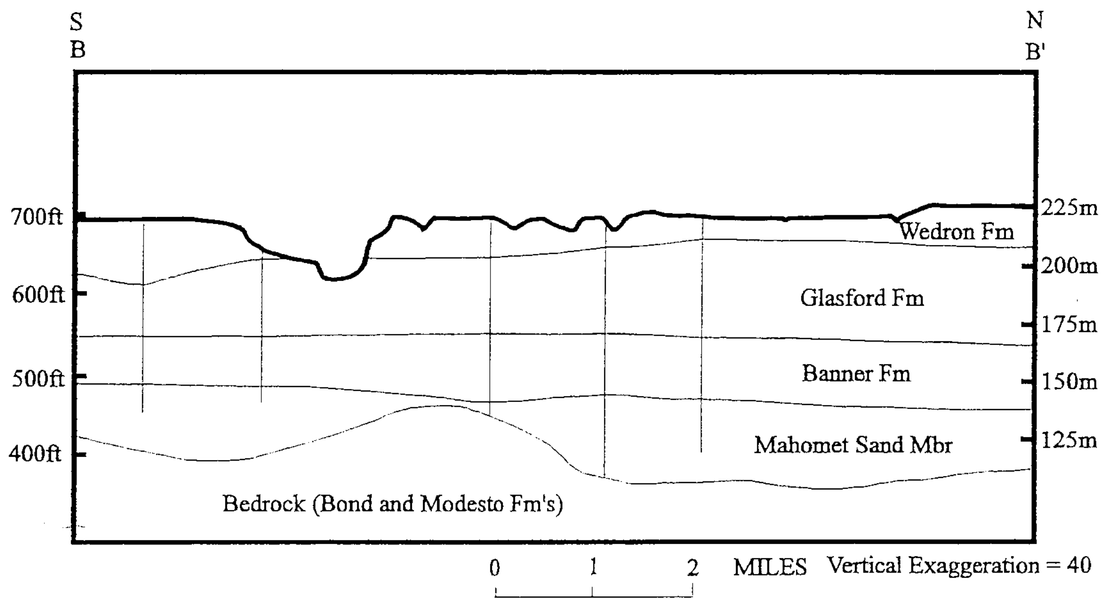


Figure 8. Cross section along US 51. (Modified from Saelens, 1995)

sediment that commonly contains twigs, and marks the base of the Wedron Formation. The breakdown of organic matter in the Robein Silt produces methane gas that occurs in some water wells in the region (Hunt and Kempton, 1977).

Glacial outwash deposits of sand and gravel of the Henry Formation (late-Wisconsinan) consist of two members, the Mackinaw and the Batavia. The Mackinaw Member is composed of fairly-well sorted valley train sands and gravels that are present along the terraces of Salt Creek. The Batavia Member typically forms the gently-sloping outwash plain of sand to medium gravel at the margin of the Shelbyville Moraine (Hunt and Kempton, 1977).

With the exception of the stream valleys, the Richland Loess covers the entire study area. Recent (Holocene) deposits in the Clinton area include the Cahokia Alluvium, which is found in stream valleys. The Cahokia Alluvium consists of silts and sands and may include reworked materials from the Henry formation, as well as erosional products derived from the upland till and loess deposits (Hunt and Kempton, 1977).

Groundwater Geology and Occurrence

The tight shales, interbedded with limestones and sandstones, that comprise the upper Pennsylvanian sequence are generally not suitable for groundwater resource development. However, a few small-yield wells have been developed in these layers where drilling has encountered fractures (Hunt and Kempton, 1977). The lower Pennsylvanian strata typically contain water that can not be developed as a resource or is not potable. This is because of the low permeability of the rocks themselves as well as the high concentration of dissolved ions in the waters contained within these strata (Visocky and Schicht, 1969).

The best sources of groundwater in the region are the pre-Illinoian sand and gravel deposits found within the buried Mahomet Bedrock Valley. The name "Mahomet Sand" was given to these deposits by Leland Horberg in 1953. It is the Mahomet Sand that serves as the aquifer from which the city of Clinton pumps its water.

The conditions that govern the flow of water within the Mahomet Sand can be classified as leaky or semi-confined. These conditions exist where an aquifer is overlain by material that retards but does not prevent the vertical flow of water into the aquifer (Visocky and Schicht, 1969). The overlying drift confines the aquifer in the case of the Mahomet Sand. When such conditions exist, the pressure difference between water above and below the tills causes water to migrate vertically between them. Within the Mahomet Valley, leakage into the aquifer is possible both upwards and downwards, but the latter is more common, especially for the Mahomet Sand (Visocky and Schicht, 1969).

CHAPTER III

GROUNDWATER MODELING

Introduction

Groundwater modeling is a tool that allows us to gain insight into the many complexities of groundwater flow systems. Despite groundwater modeling's inherent limitations, when properly applied, it can often provide us with the most viable answers to complex groundwater problems. Included in these problems are the calculation of approximate time-of-travel capture zones and time-dependent surface recharge areas of municipal water supply wells.

The following discussion is based largely on the work of Davies (1995) who conducted a similar study resulting in time-of-travel capture zone and time-dependent surface recharge area delineations for three Illinois communities.

Mathematical Foundations

The mathematical foundation of groundwater modeling is Darcy's law. Darcy's law states that the rate at which water flows through a porous material is proportional to the gradient of the hydraulic head (Fetter, 1988). For one-dimensional flow in an isotropic material, Darcy's law is commonly expressed as the following equation:

$$Q_x = -K_x\,(\partial h/\partial x) \qquad (1)$$

where: Q_x = the volumetric flux of water expressed in cubic feet per square foot of area per day (feet per day),
K_x = the hydraulic conductivity of the material in the x-direction (feet per day)
h = hydraulic head (feet), and
$(\partial h/\partial x)$ = a partial derivative representing the gradient of the hydraulic head in the x-direction (dimensionless).

Hydraulic head is defined as the sum of elevation (gravitational potential energy), and fluid-pressure energy expressed as an equivalent column of water for a unit weight of the fluid. In other words, hydraulic head is the total mechanical energy per unit weight of fluid (Fetter, 1988). Hydraulic head is equivalent to the elevation to which water will rise in a well.

When Darcy's law is combined with the water balance equation, (inflow minus outflow equals change in storage), the resulting equation is fundamental to groundwater modeling. This equation, called the constitutive or governing equation, must be satisfied by the hydraulic head everywhere within the problem domain. The constitutive equation, when applied to steady state situations, has the following form:

$$\partial/\partial x\,[K_x\,(\partial h/\partial x)] + \partial/\partial y\,[K_y\,(\partial h/\partial y)] + \partial/\partial z\,[K_z\,(\partial h/\partial z)] + R^* = 0 \qquad (2)$$

where: K_x, K_y, K_z = hydraulic conductivities in the x, y, and, z directions,
h = hydraulic head,

R^* = volumetric recharge (or discharge) of water into the material per unit volume per unit time and, for anisotropic materials the x, y, and z axes are assumed to be parallel to the principle hydraulic conductivities.

The hydraulic head must satisfy the constitutive equation within the problem domain as well as the conditions that exist on the boundaries of the problem domain. The following is a list of three types of boundary conditions that are commonly encountered in groundwater modeling problems:

1) Specified heads at the boundary

$$h = h_o(x, y, z, t) \tag{3}$$

2) Specified flux through the boundary (including no-flow)

$$(\partial h/\partial w) = 1/K_w\,[Q_o(x, y, z, t)] \tag{4}$$

Where: $Q_o\ (x, y, z, t)$ = the flux through the boundary,

w = a direction oriented perpendicular into the problem domain.

3) Head-dependent flux through the boundary

$$(\partial h/\partial w) = 1/K_w\,[Q_o(h, x, y, z, t)] \tag{5}$$

where: $Q_o(h, x, y, z, t)$ = head dependent flux.

Because boundary conditions are a part of the problem domain that the hydraulic head must satisfy, groundwater modeling is a boundary value problem. Once the boundary value problem is solved and the head values throughout the problem domain are known, the flux through the groundwater system can be calculated by using Darcy's law.

Typically, groundwater flow systems are complex and exact solutions for their boundary value problems cannot be found. Approximate solutions to these boundary value problems, however, can be found using numerical computer techniques such as the finite-difference method.

When using the finite-difference method, the problem domain is subdivided into a finite number of blocks, known as cells. The hydraulic head values in each of the cells within the specified domain represent the unknowns for the problem. Figure 9 shows three adjacent cells within the subdivided problem domain.

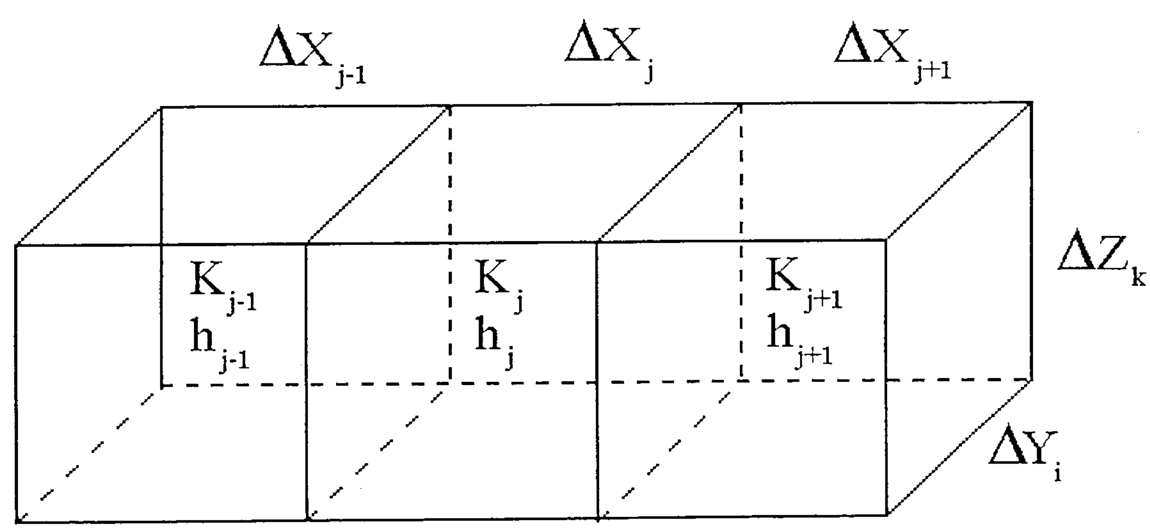


Figure 9. Representation of the subdivided problem domain.

To arrive at the value that represents the hydraulic gradient between cells j and j+1, the differences between the hydraulic heads for each cell are divided by the average distance between the cells.

$$(\partial h/\partial x) \approx (\Delta h_{j+}/\Delta X_{j+}) = [(h_{j+1}-h_j)/\tfrac{1}{2}(\Delta X_j+\Delta X_{j+1})] \qquad (6)$$

The hydraulic conductivity between cells j and j+1 can be approximated by the conductance value C_{j+}.

$$1/K_{j+} \approx 1/C_{j+} = [1/(K_j \Delta Y_i \Delta Z_k)/(\Delta X_j)/2] +$$

$$[1/(K_{j+1} \Delta Y_i \Delta Z_k)/(\Delta X_{j+1})/2] \qquad (7)$$

The first term in the constitutive equation can then be approximated by the following closed-form equation:

$$\partial/\partial \mathrm{x}\,(K_x\,(\partial h/\partial x)) \approx [C_{j+}(\Delta h_{j+}/\Delta X_{j+})$$

$$-\, C_{j-}(\Delta h_{j-}/\Delta \mathrm{X}_{j-})]/\Delta \mathrm{X}_j \qquad (8)$$

Similarly, substitutions are made for $\partial/\partial y\,[K_y\,(\partial h/\partial y)]$ and $\partial/\partial z\,[K_z\,(\partial h/\partial z)]$. The recharge term, R*, can then be approximated by the net flux into or out of the cell.

Once the above substitutions have been made, the constitutive equation for each cell is reduced to a single equation which has a linear dependence on the hydraulic head in the cell and the heads in each of the adjacent cells. The boundary conditions in the problem can then be introduced based on their contributions to the coefficients of the hydraulic heads and the net flux. There is now one equation for every cell in the model and the boundary value problem has been effectively reduced to n-equations in n-unknowns.

The equations for each of the cells in the problem domain are then arranged into a matrix equation with the form:

$$[K]\{h\} = \{g\} \tag{9}$$

where: $[K]$ = the conductivity matrix of the coefficients of the hydraulic heads,
$\{h\}$ = a column vector of the unknown heads, and
$\{g\}$ = a column vector of constants.

The iterative computer technique known as successive over-relaxation is used to invert the matrix equation and solve for the hydraulic heads for each of the cells in the model. Iterations begin with an arbitrary set of head values which the user specifies for each cell. Successive adjustments to these head values are then made in an effort to reduce the errors within the matrix equation. For each iteration, head dependent values are calculated and the results are used in the following iteration. A description of the applications of matrix algebra to groundwater modeling can be found in Wang and Anderson (1982).

The resulting computer-derived hydraulic head values can then be used to calculate the flux between adjacent cells. The flux from cell j into cell j+1 is given by

$$q_{j+} = C_{j+}(h_j - h_{j+1}) \tag{10}$$

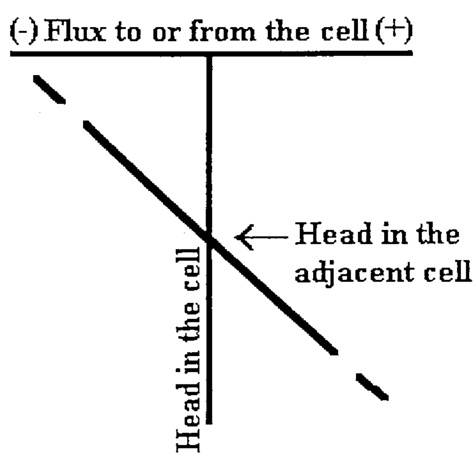
MODFLOW - A Modular Finite-Difference Groundwater Flow Model

There are a number of groundwater modeling codes available for flow system analysis and "generic" simulations. The U.S.G.S. finite-difference code MODFLOW (McDonald and Harbaugh, 1988) was chosen for the current study because of its versatility and adaptability to a variety of groundwater problems. However, the level of sophistication present within the code itself dictates that the data input structure be rather complex (Anderson and Woessner, 1992). Simulations can be performed for a variety of aquifer configurations in either a time-independent (steady-state) or time-dependent (transient) setting.

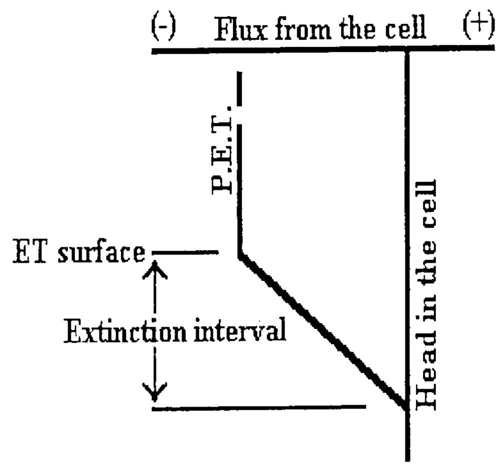
For purposes of three-dimensional modeling, the problem domain is enclosed in a rectangular volume that is then subdivided into a three-dimensional grid of cells arranged in a row, column, and layer fashion. The cell widths along the rows or columns are held constant across the model, but the thicknesses can vary within an individual layer to simulate geologic layers of varying thickness. Individual cells can be designated as inactive if they are within the rectangular volume, but are not directly within the problem domain. Other cells can be designated as "fixed head" giving them a constant head value. When cells are assigned as such, they act as infinite sources or sinks of water. Within each cell, the porosity, x and y-directed conductivities, and the vertical conductance with the corresponding cell in the underlying layer are specified by the user. In order to simulate the effects of vertical or horizontal anisotropy or the presence of aquitards between more conductive layers, the vertical conductances are utilized by MODFLOW in a pseudo three-dimensional layer approach.

MODFLOW is structured in a manner that allows a variety of modules or "packages" to be used to simulate flux into or out of the model. The fluxes specified by the use of these packages are incorporated into the model through the recharge term (R*) in the constitutive equation. A description of the individual MODFLOW packages and their effects on the groundwater model follows:

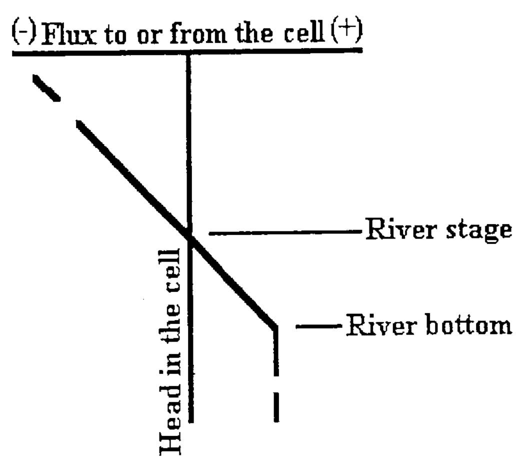
1. The General Head Boundary Package: This package is used to simulate head-dependent flux through the boundaries of the model. The slope of the general head boundary graph represents the ease with which the surrounding material will yield or accept water.



2. The Evapotranspiration Package: This package is used to simulate the combined effects of evaporation and plant transpiration. The amount of water loss is dependent on the relative elevation of the head and the evapotranspiration surface. This surface, called the "ET surface" is typically set at a fixed depth below the ground surface.

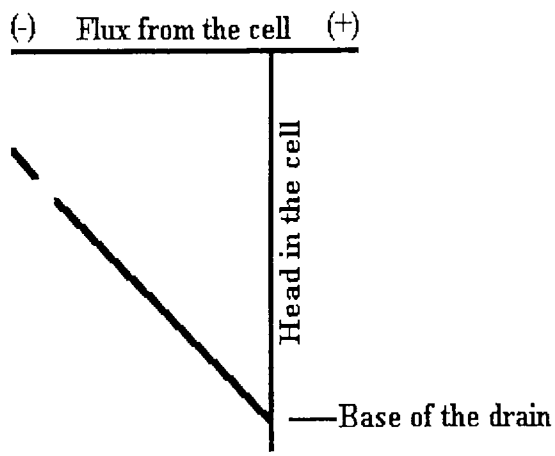


3. The River Package: This package is used to simulate discharge to or recharge from a stream or lake. If the hydraulic head in the cell falls below the base elevation of the river or lake bed, the recharge is constant.



4. The Recharge Package: This package is used to simulate the effect of recharge via the ground surface. The parameter is entered as cubic feet of water per unit surface area per unit time. This value is multiplied by the upper surface area of the cell to find flux to the cell.

5. The Drain Package: This package is used to simulate the effect of springs, seeps, or drains. Water is allowed to leave but not enter the cell through the drain.



6. The Well Package: This package is used to simulate the effect of a pumping or injection well. The parameter is the flux from or into the cell. Drawdown at the well, however, is not simulated by the package.

An assumption is made by the use of the general head boundary, the river and the drain packages that there is a layer of material that lies between the cell and the source or sink of water. The layer's conductance is given by the product of the area of contact and the hydraulic conductivity of the material divided by the layers' thickness.

MODPATH - An Advective Particle Tracking Code

The cell-to-cell fluxes that are generated by MODFLOW (McDonald and Harbaugh, 1988) are used by MODPATH (Pollock, 1989) to calculate the advective flow paths and travel times of particles within the model. Advective flow is the average movement of water through a material and equals the flux divided by the effective porosity.

For illustrative purposes, consider the flux of water through the faces of the following finite-difference cell:

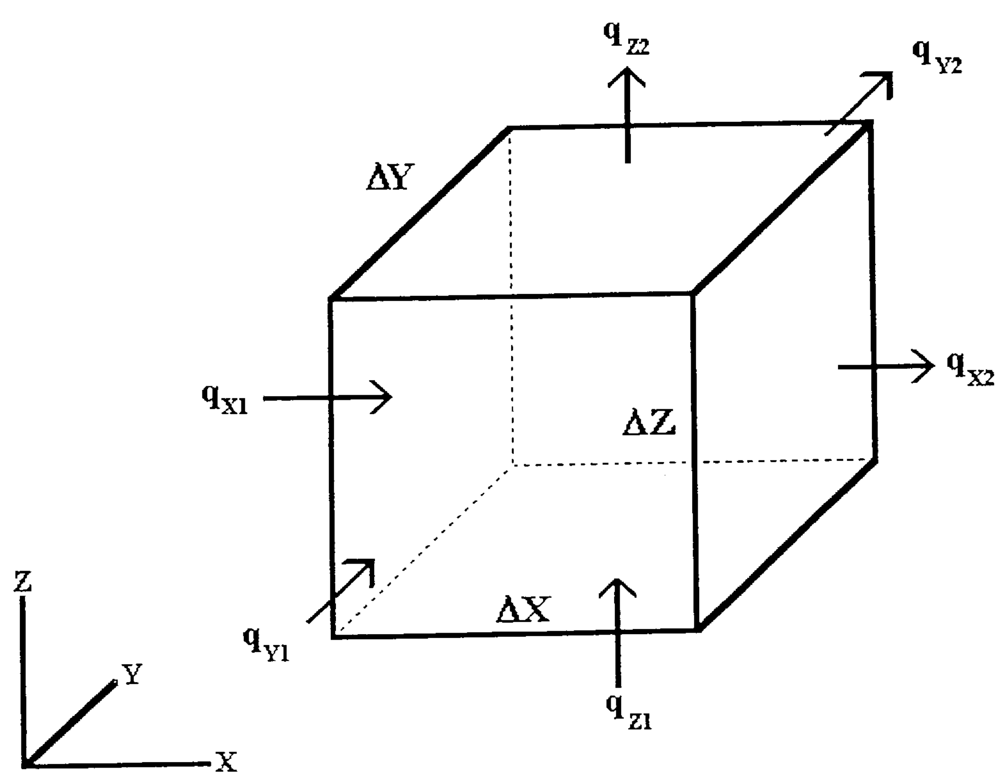


Figure 10. Depiction of the flux of water through the faces of a finite-difference cell.

The average velocities inside the x-directed faces of the cell (both positive and negative) are $V_{x1} = (1/\eta)q_{x1}$ and $V_{x2} = (1/\eta)q_{x2}$ respectively, where η is the effective porosity of the cell. MODPATH assumes that the advective velocity varies linearly between the faces of the cell for its calculations. For example, the x-directed velocity is given by:

$$V_x (X) = V_{x1} + [(V_{x2}-V_{x1})/(X_2-X_1)](X-X_1) \tag{11}$$

$$V_x (X) = V_{x1} + A_x(X-X_1) \tag{12}$$

Noting

$$dv_x/dt = (dv_x/dx)(dx/dt) \tag{13}$$

$$dv_x/dt = A_x V_x \tag{14}$$

Then

$$dv_x/v_x = A_x dt \tag{15}$$

Integrating both sides of the above equation from t_1 to t_2

$$\ln [(V_x(t_2))/(V_x(t_1))] = A_x(t_2-t_1) = A_x\Delta t \tag{16}$$

Raising both sides of the previous equation to exponential powers

$$(V_x(t_2))/(V_x(t_1)) = \exp (A_x\Delta t) \tag{17}$$

Substitute

$$V_x(t_2) = V_{x1} + A_x(X(t_2) - X_1) \tag{18}$$

Yielding

$$X(t_2) = X_1 + (1/A_x)[V_x(t_1)\exp(A_x \Delta t) - V_{x1}] \qquad (19)$$

where: $V_x(t_1) = V_{x1} + A_x(X(t_1)-X_1)$

Assuming that the velocity varies linearly between the faces of the cell results in a closed form expression which represents the future location $X(t_2)$ of the advective flow position $X(t_1)$. The y and z coordinates are calculated similarly.

MODPATH uses the initial model parameters that were entered into the MODFLOW program along with the cell-by-cell fluxes calculated by MODFLOW, and a file containing the initial or starting flowpath coordinates. For each of these starting coordinates, MODPATH calculates successive incremental coordinates and travel times along the particle's flowpath. Flowpaths extend from their starting locations to a groundwater sink or source, depending upon whether the calculations performed by MODPATH are in a forward or reverse direction. For time-of-travel capture zone and time-dependent recharge area delineations, infinitely small, imaginary particles are placed around the edges of the cell in which the pumping well is located. The reverse flow paths of these particles are then calculated based on their initial positions within the well cell.

Limitations of Groundwater Modeling

A degree of caution should be exercised when interpreting the results of a groundwater model. One of the greatest limitations within the field of groundwater modeling lies in the uncertainty of the parameters used in the model. Many of the values for specific model parameters used are not known accurately enough to predict the behavior of a groundwater flow system, and a certain degree of guesswork is therefore involved. Parameters are subsequently adjusted during the calibration stage to depict real-world results more accurately. The interdependencies of certain model parameters, as well as the uncertainty of their true values, dictate that there is no single, unique model for any flow system. Further uncertainty is associated with the complexities of an actual subsurface flow system. Typically, such systems are more complex than the available geophysical, hydrologic, and geologic information would indicate.

Also, caution is required when advective flow models are used to interpret contaminant transport scenarios. The derived cell-to-cell fluxes and advective velocities represent average values for the entire cell. It then follows that for a heterogeneous material, the majority of the flux would occur through the most conductive materials. If these conductive materials occupy only a small fraction of the total cell volume (for example 5%) the actual velocities would be proportionately faster (about 20 times the average velocity for 5%). This becomes particularly important when modeling horizontal flow in stratified materials. Under these circumstances, the critical velocity is that of the most conductive layer. Advective flow does not take into account certain factors which might in actuality effect a particles flowpath and travel time. Such factors include the effects of a finite velocity distribution, lateral spreading, dispersion, ionic or molecular diffusion, adsorption of chemicals onto mineral grains, or the effects of chemical or biological reactions. Although these factors can, and in many cases do, introduce uncertainties of several orders of magnitude, advective flow modeling remains a convenient and acceptable means by which delineations of capture zones and wellhead protection areas are achieved.

CHAPTER IV

GROUNDWATER MODEL

Model Design

Initially, a 24 column by 30 row (720 cell) finite-difference grid was constructed and superimposed over the 720 square mile study area. In the remainder of this report, this model will be refereed to as the coarse model. Figures 11 and 12 show the grids used for layers 1 and 2 respectively for the coarse model. The cells had side-lengths of 5,280 feet, allowing each cell to represent about one section on a topographic map. Once the initial model was calibrated, the row and column length was reduced so that the model would show more detail in the area of interest (Clinton). A 36 column by 39 row (1,404 cell) grid was used for the detailed model. Cell side-lengths ranged from 1,320 feet in the areas surrounding the wells and was gradually increased to 5,280 feet at the model's edges. Caution was exercised to ensure that the relative increases in cell lengths between adjacent cells did not exceed a factor of 2.0. This was done so that there would be no compromise in the accuracy of the calculated head values. Figures 13 and 14 show the grids used for layers 1 and 2 respectively for the detailed model.

For both models, 2 layers were used. The first, or uppermost layer included all geologic units from the ground surface to the top of the Mahomet Sand. The second, or

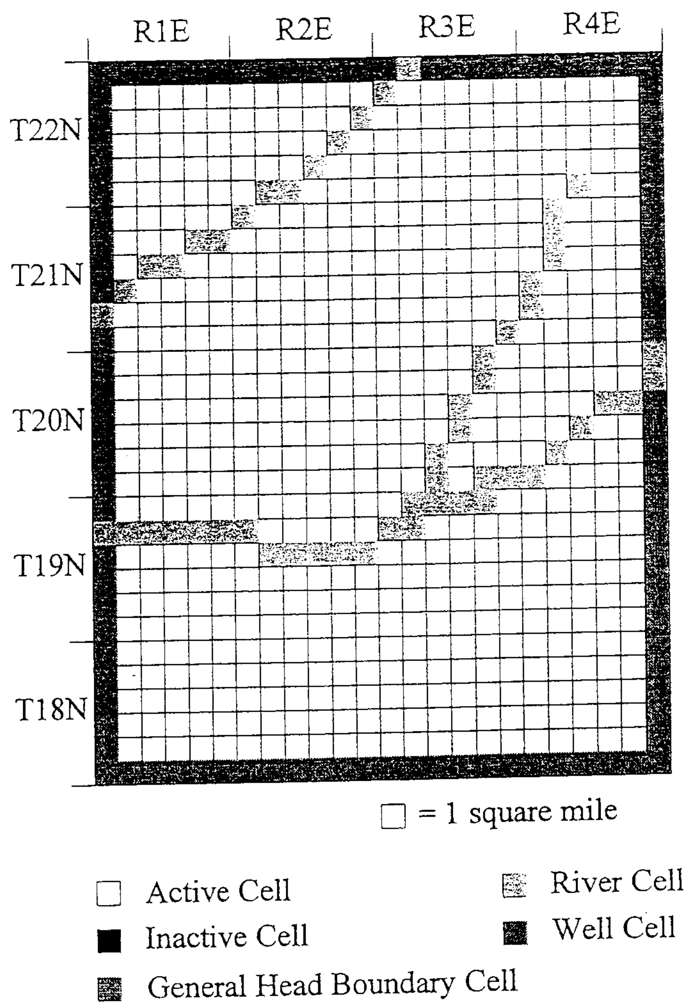


Figure 11. Layer 1 grid used in coarse model.

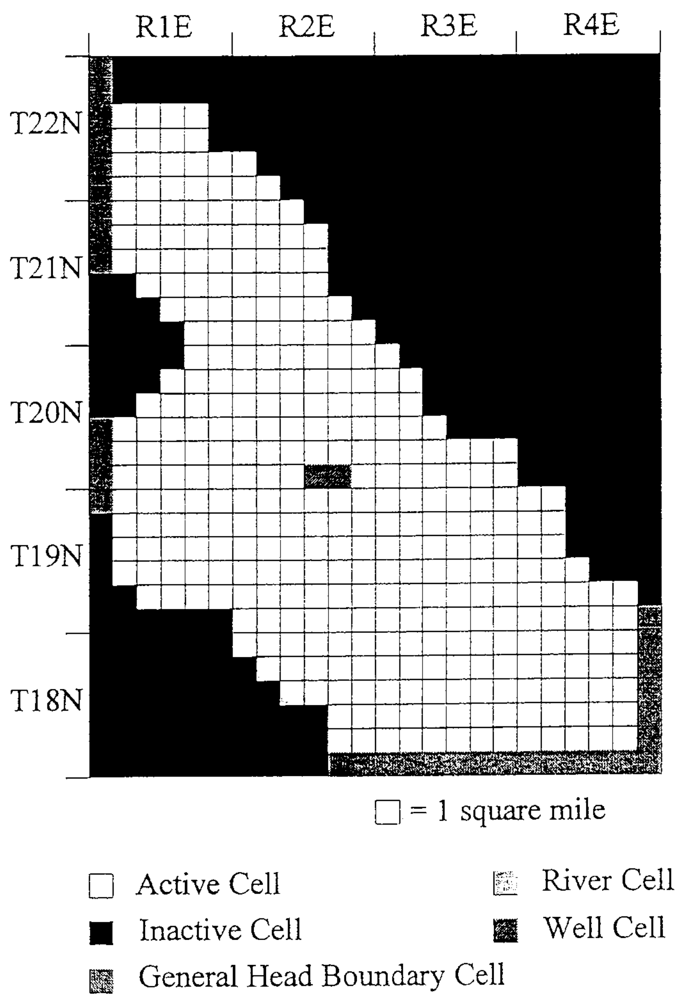


Figure 12. Layer 2 grid used in coarse model.

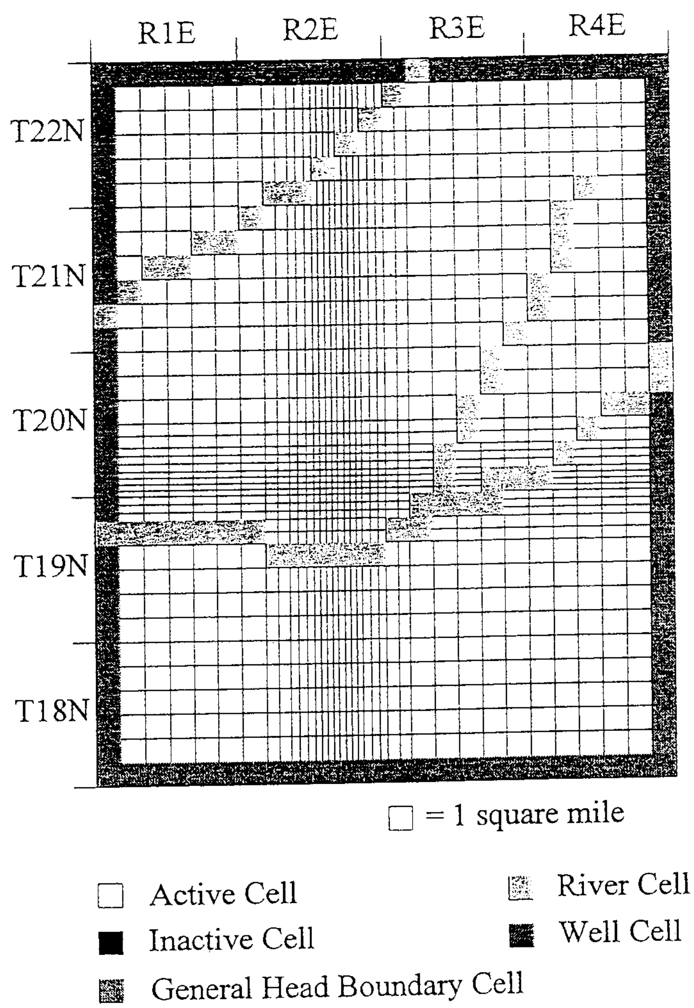


Figure 13. Layer 1 grid used in detailed model.

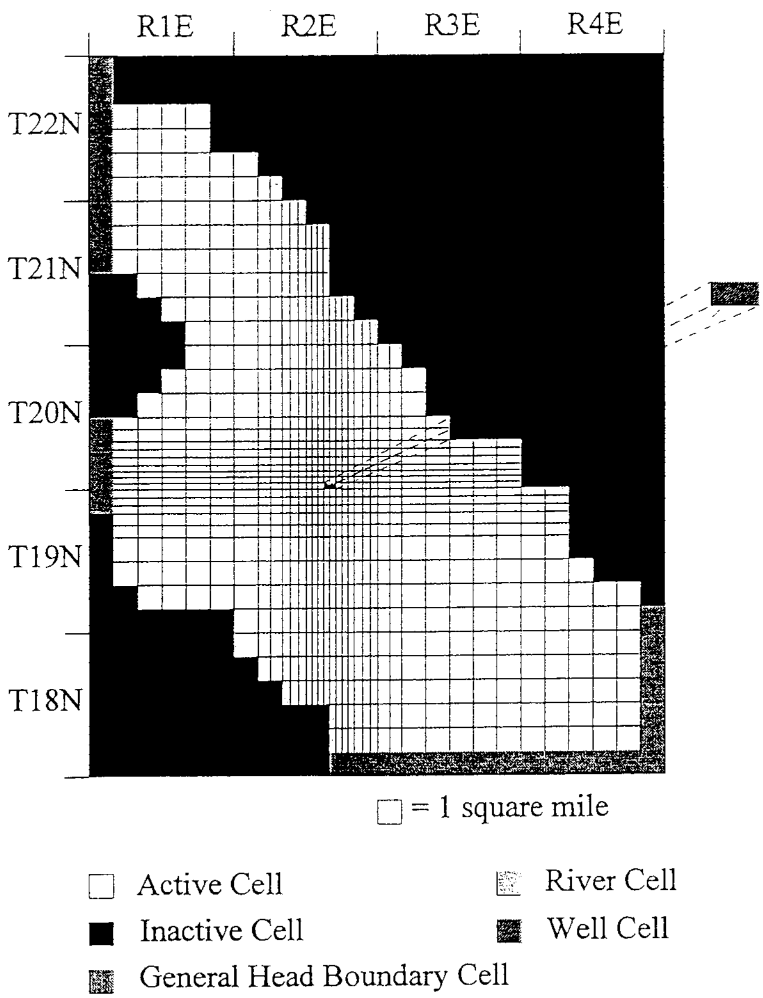


Figure 14. Layer 2 grid used in detailed model.

lower layer was considered to represent the Mahomet Sand. As previously mentioned, the Pennsylvanian bedrock was assumed to be a geohydrologic barrier and was therefore not modeled as part of the flow system.

In order to avoid the interference caused by unrealistic boundary effects, it was necessary to model an area considerably larger than the immediate area of interest. Layer 1 is completely bounded by general head boundary cells (except where streams enter or exit the model) whose reference heads are set to balance evapotranspiration and recharge thus simulating the water table. Layer 2 has general head boundary cells only where the Mahomet Sand is present. The upper surface of the model is unbounded and the bottom is bounded by Pennsylvanian bedrock.

General head boundaries allow for the flux of groundwater to be into or out of the cell from the external material. This flux is proportional to the difference between the head in the cell and the fixed head in the external source. The fact that these boundaries can affect the behavior of the model dictates that such boundaries be located a sufficient distance from the area of interest.

Model Parameters

This section presents the input data that were required for the model. The data required for each active cell in the simulation include:

- Recharge. The recharge rate for the simulation was set at 7.5×10^{-5} ft/day or .33 inches/year. The most common source of recharge in the study area is in the form of precipitation. It is assumed that recharge only occurs to the uppermost layer in the model.

- Evapotranspiration (ET). The ET surface for the model is the same as the topographic surface and represents the elevation of maximum ET. The rate at which ET occurs decreases linearly from its maximum rate (PET) of 6.17×10^{-3} ft/day or 27 in/year at the ground surface through an extinction interval which represents the depth at which ET ceases. The extinction interval for the model was set at 10 feet.
- Well Pumpage. Two well cells were used in the simulation to represent the six municipal wells Clinton operates. The pumping rate is assumed to be 21,180 ft^3/day for each well.
- Hydraulic Conductivity and Leakance. In order to determine the flow between the two layers, the vertical leakance between those layers must be calculated. McDonald and Harbaugh (1988) calculate the vertical leakance (Vcont) with the following equation:

$$\mathrm{Vcont}_{(i,\, j,\, k+1)/2} = 1/\left[\{((\Delta v_k)/2)/K_{z\, i,\, j,\, k}\} + \{((\Delta v_{k+1})/2)/K_{z\, i,\, j,\, k+1}\}\right] \qquad (20)$$

where Δv_k = the thickness of the upper layer,

Δv_{k+1} = the thickness of the lower layer, and

$K_{z\, i,\, j,\, k}$ = the vertical hydraulic conductivity in cell i, j, k.

The hydraulic conductivity values used for layers 1 and 2 were 1 ft/day and 397 ft/day (Kempton and others, 1991) respectively.

- Porosity. Porosity is a measure of the percentage of void space per unit volume of material. Effective porosity is the percentage of interconnected pore space per unit volume of material. Effective porosity is typically less than the actual porosity. An effective porosity value of 20 percent was used for both layers in the model.

Calibration and Groundwater Heads

The output data that resulted from MODFLOW was used by SURFER (Golden Software, 1994) to generate potentiometric surface contour maps of layers 1 and 2 for the study area. During the calibration phase, aquifer parameters were adjusted so that the MODFLOW-generated head maps would resemble the ISWS potentiometric surface maps shown in figures 15 and 16 (Anliker and Sanderson, 1995). Figures 17 and 18 show the calibrated, MODFLOW-generated head maps for layers 1 and 2.

Capture Zone and Recharge Area Delineations

The advective particle tracking code MODPATH was used to determine the locations of the time-dependent recharge areas as well as the five year time-of-travel capture zones for the city of Clinton's six municipal water supply wells. The five year time-of-travel capture zone is the subsurface volume that can contribute water to the well within five years. The capture zone was determined by back-tracking 90 particles from

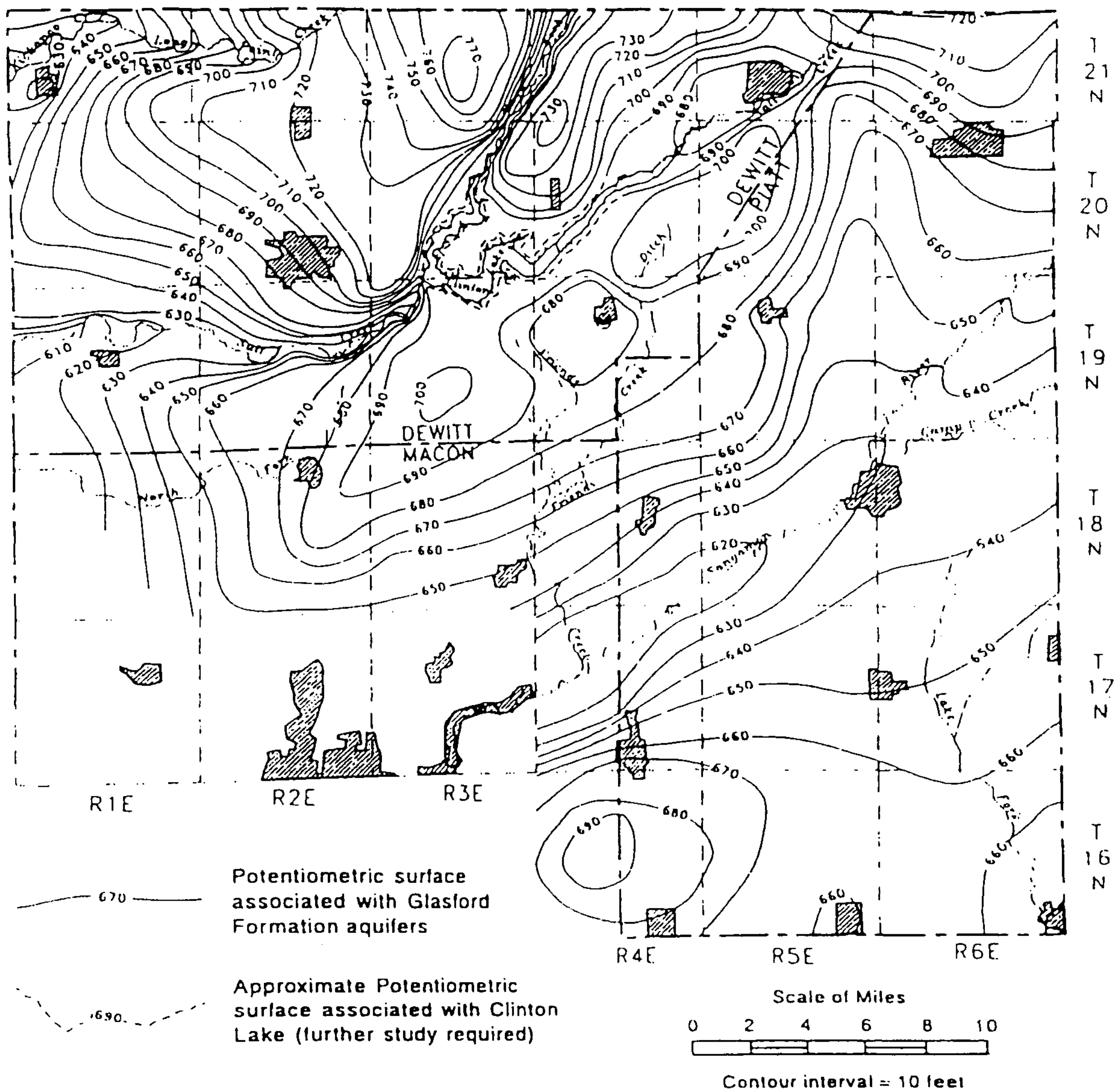


Figure 15. ISWS potentiometric surface map of Glasford Formation aquifers (Anliker and Sanderson, 1995).

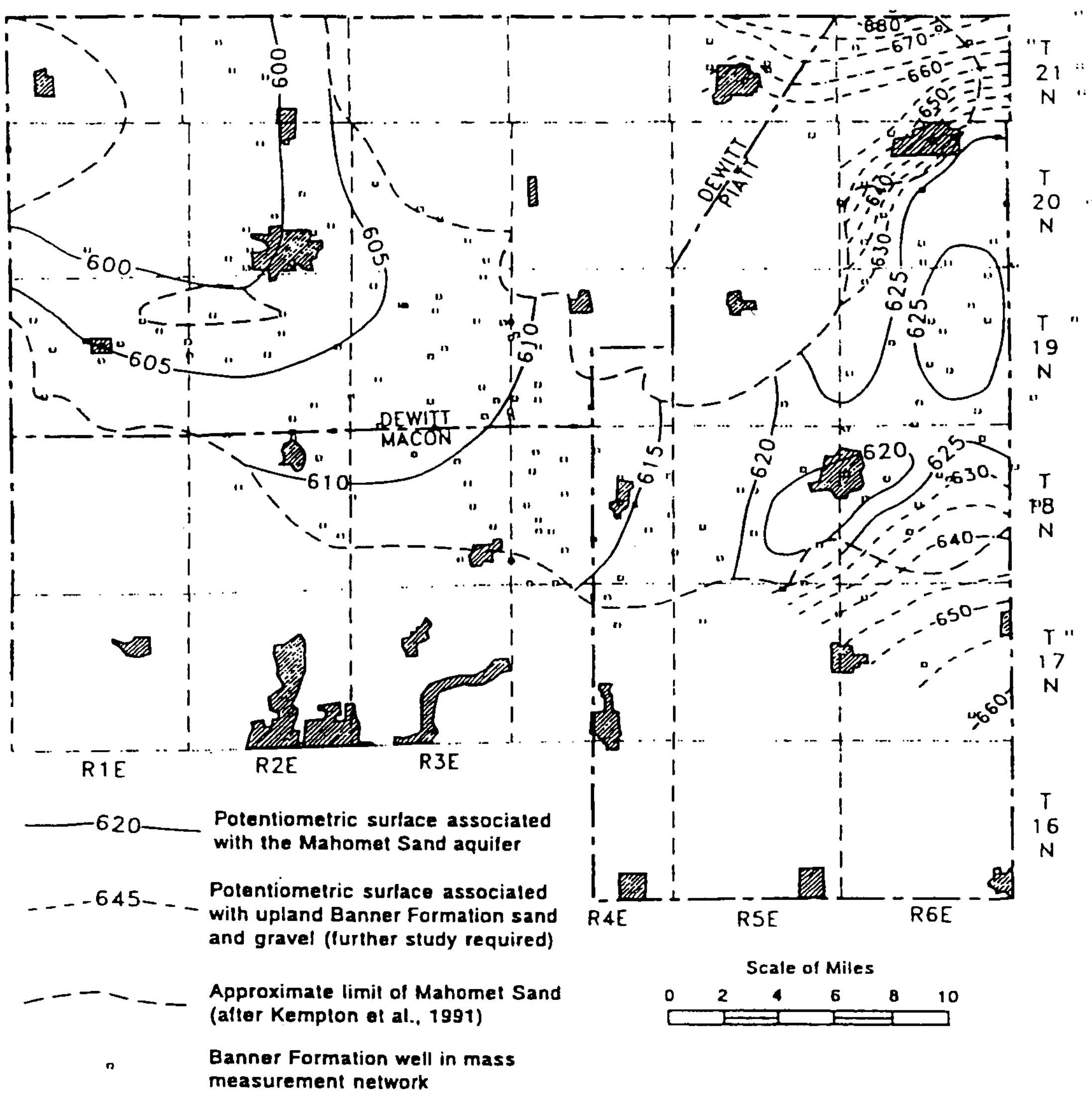


Figure 16. ISWS potentiometric surface map of the Banner Formation aquifers (Anliker and Sanderson, 1995).

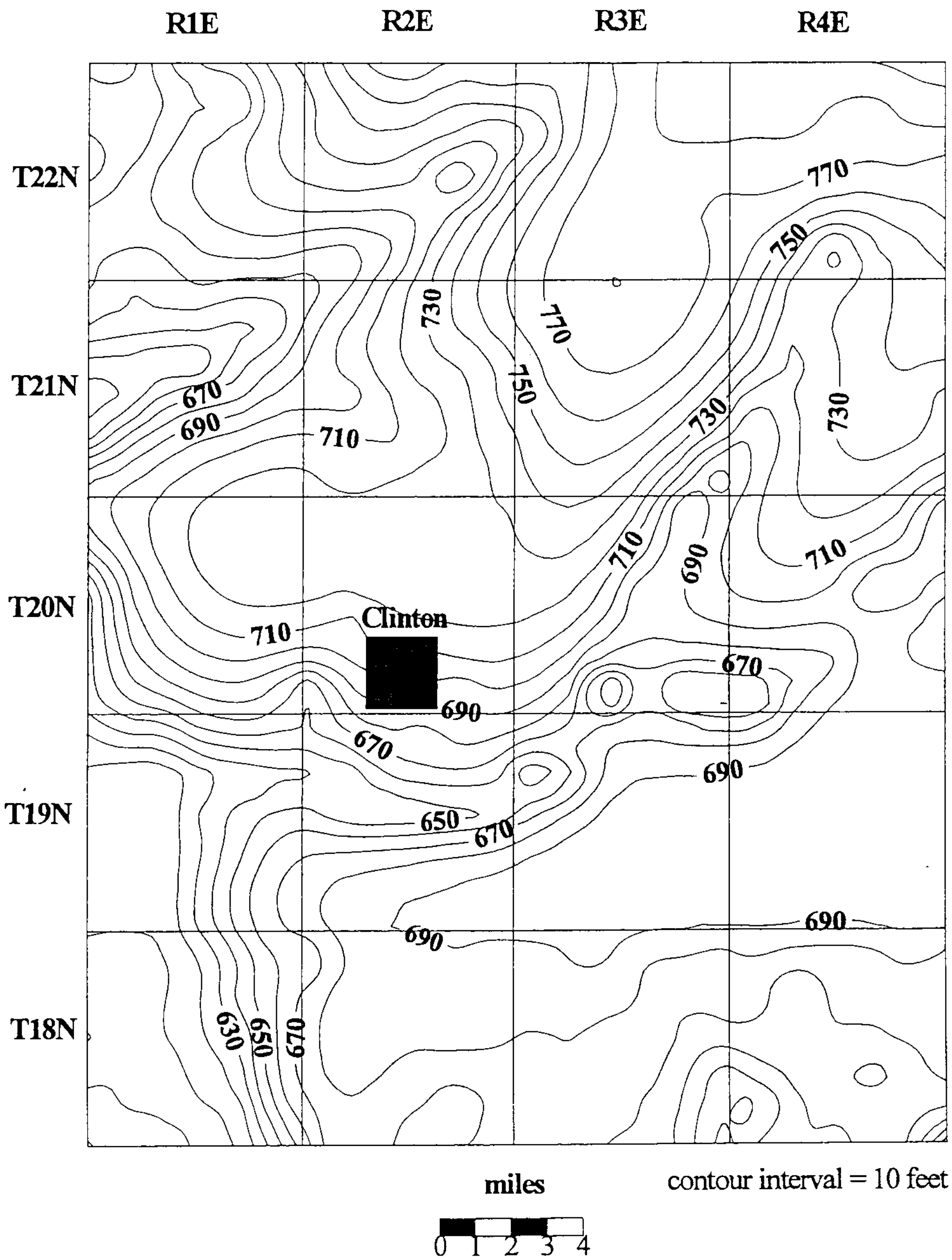


Figure 17. MODFLOW-generated potentiometric surface map for layer 1.

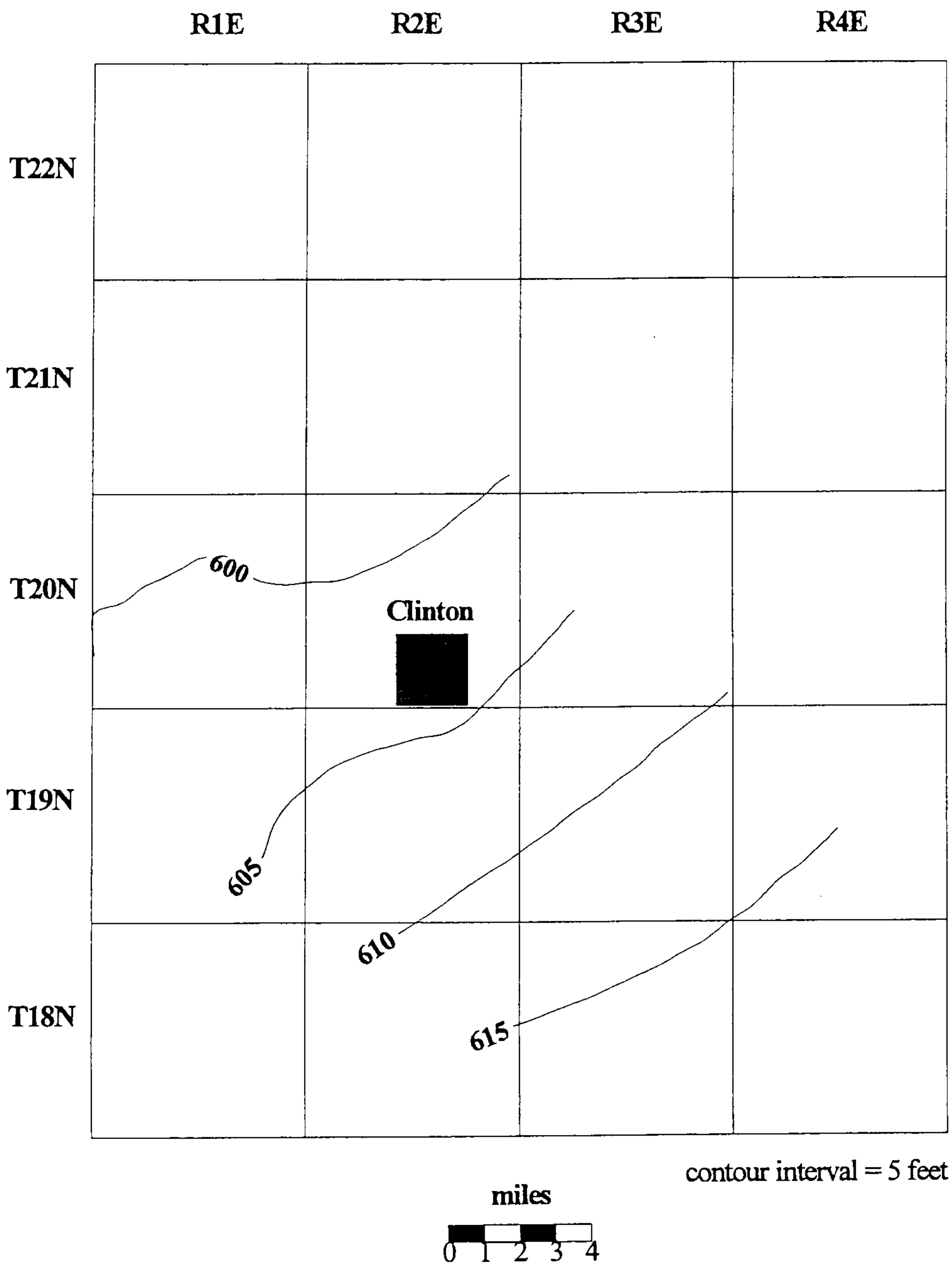


Figure 18. MODFLOW-generated potentiometric surface map for layer 2.

the wells to their 5 year time-of-travel points in the subsurface. The particles were distributed on each of the faces of the 2 well cells with the exception of the bottom faces. Each face had 9 particles at relative positions of z = 0.3, 0.6, and 0.9, where z = 0 is the bottom of the cell and z = 1 is the top of the cell. Figure 19 shows the 5 year time-of-travel capture zone for Clinton's wells. It can be seen from this figure that the 5 year capture zone is located approximately 0.5 miles southeast of the wells. The limits of the 5 year capture zone are represented by the first set of circles closest to the wells themselves. Figure 20 shows the 50 year time-of-travel capture zone. From this figure it can be seen that the southern limit of the 50 year capture zone extends to about 2.5 miles away from the wells.

According to the model results, none of the back-tracked particles reach the surface within the study area. It can therefore be said that the time-dependent surface recharge areas for the city of Clinton's water supply wells are located at *least* 12 miles southeast of or up-gradient from the wells themselves. The average travel-time associated with this 12 mile minimum is approximately 514 years. Figure 21 is a cross-section of the pathlines for six particles entering Clinton's wells.

Sensitivity Analysis

The purpose of a sensitivity analysis is to ascertain the degree of uncertainty present in the calibrated base model due to uncertainties in the model's parameters. Model parameters that can have uncertainties associated with them can include aquifer parameters, stresses and boundary conditions. During the sensitivity analysis, parameters

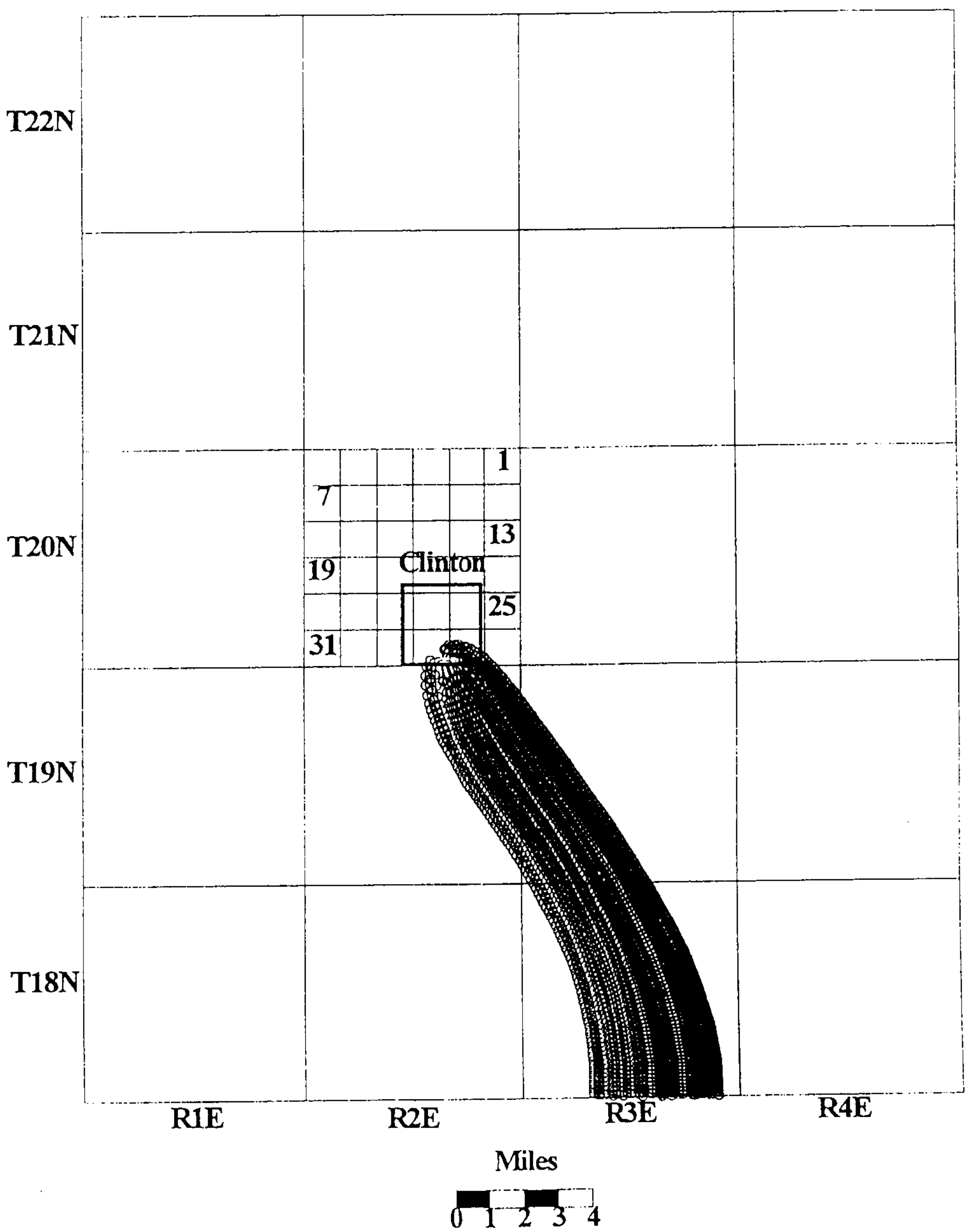


Figure 19. Map showing the 5 year time-of-travel capture zone for the city of Clinton's municipal water supply wells. (Circles represent 5 year time markers.)

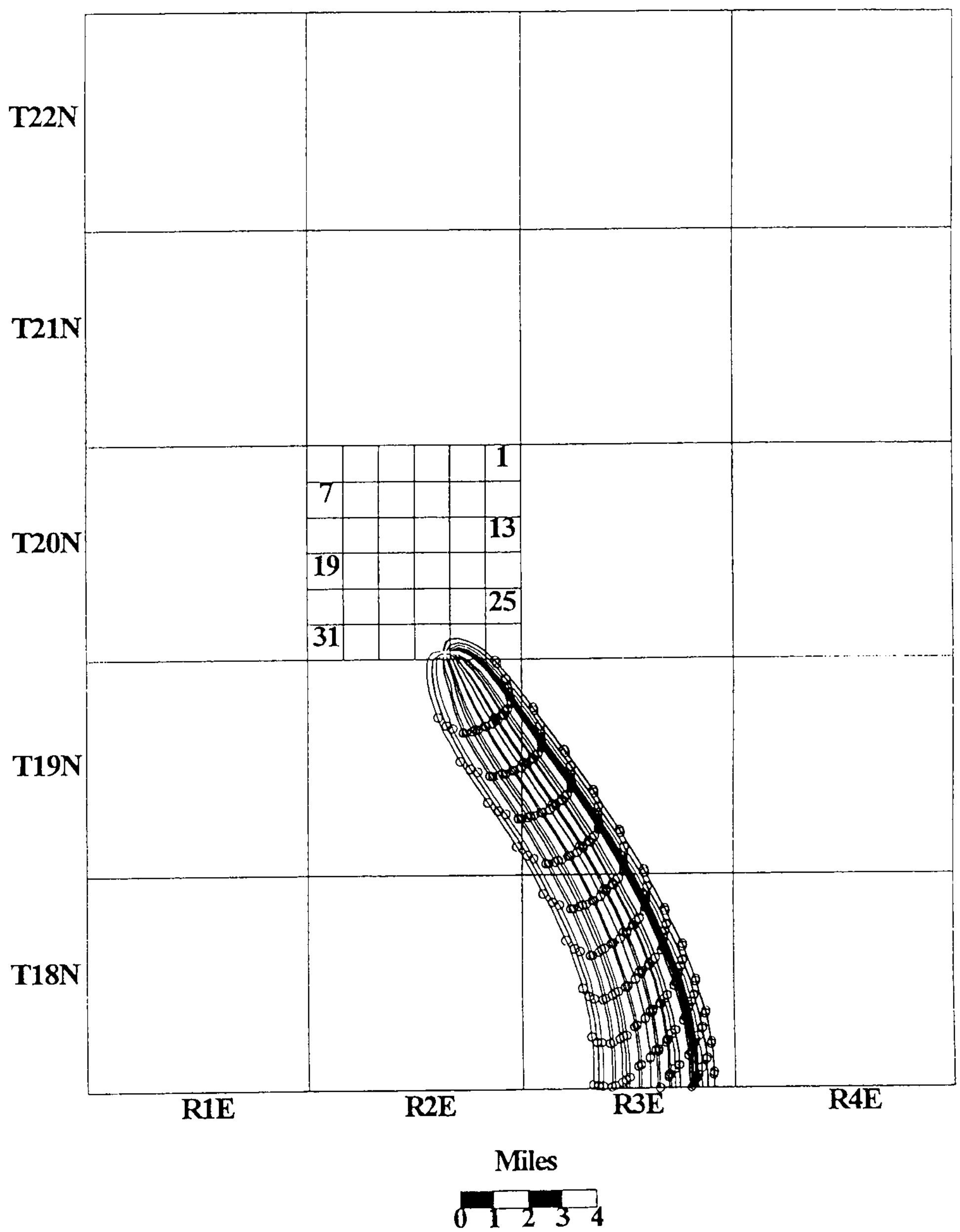


Figure 20. Map showing the 50 year time-of-travel capture zone for the city of Clinton's municipal water supply wells. (Circles represent 50 year time markers.)

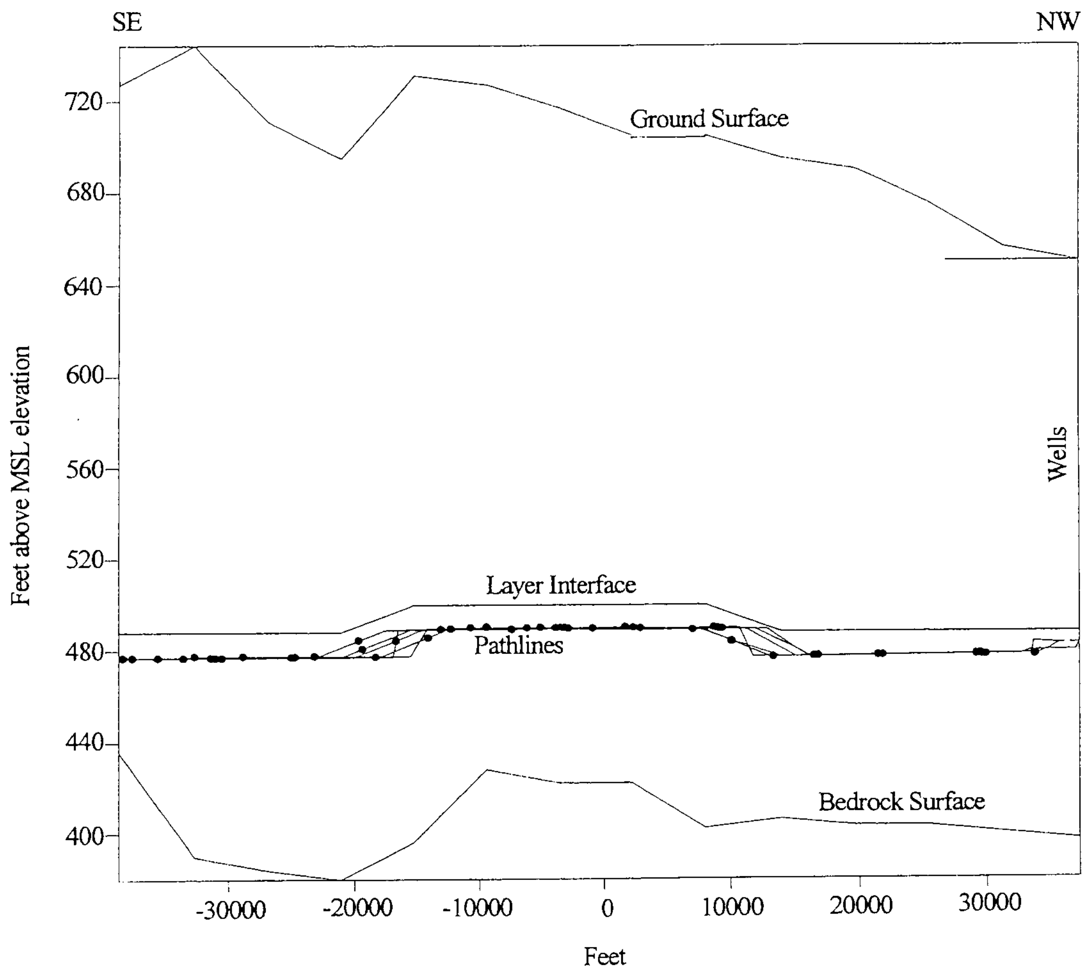


Figure 21. Cross-section of the pathlines for 6 particles entering the city of Clinton's wells. (Circles represent 50 year time-of-travel markers.)

were systematically adjusted by plus and minus 10 percent of their original values. The parameters that were adjusted during the analysis included the hydraulic conductivities of both layers, the recharge rate, and the row to column anisotropy. After a parameter was adjusted, the model was run and the resulting volumetric budget or "water balance" was studied. The volumetric budget shows the flux into or out of the entire model as well as a percent difference between total inflow and total outflow. A low percent difference indicates that the model is running properly. It does not, however, indicate that the model's parameters, boundary conditions or stresses are correct. Pathline maps were also generated at the end of each run and compared to those resulting from the calibrated base model.

The results of the sensitivity analysis follow in two forms. The first is a graphical format in which the pathlines from the runs are displayed. Figure 22 through 29 show the pathlines generated during the sensitivity analysis. An unfortunate shortcoming of this type of display is that differences in the subsequent runs are not easily detectable when compared to the pathlines from the calibrated base model (Figure 20). For this reason a tabular format best shows the effects of the parameter adjustments during the sensitivity analysis. Table 1 shows a comparison of the volumetric budgets from the adjusted models to that of the calibrated base model. Table 2 shows the particle travel time summary information resulting from each adjustment in comparison with those from the calibrated base model.

It can be seen from table 2 that of the parameters tested, the model is most sensitive to the row to column anisotropy and the hydraulic conductivity of layer 2. The

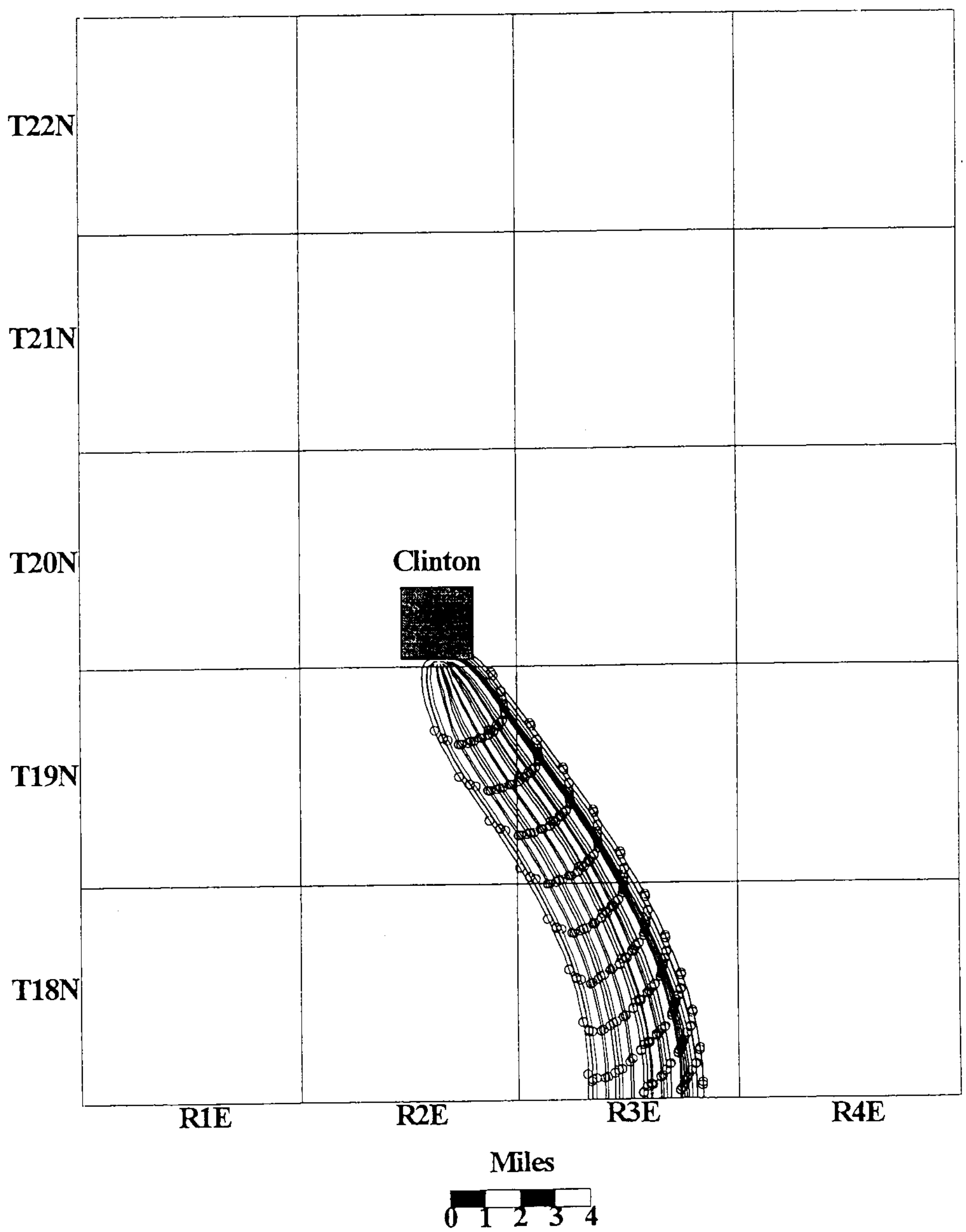


Figure 22. Map showing the 50 year time-of-travel capture zone for the city of Clinton's municipal water supply wells after adjustment of the row to column anisotropy by plus 10 percent. (Circles represent 50 year time markers.)

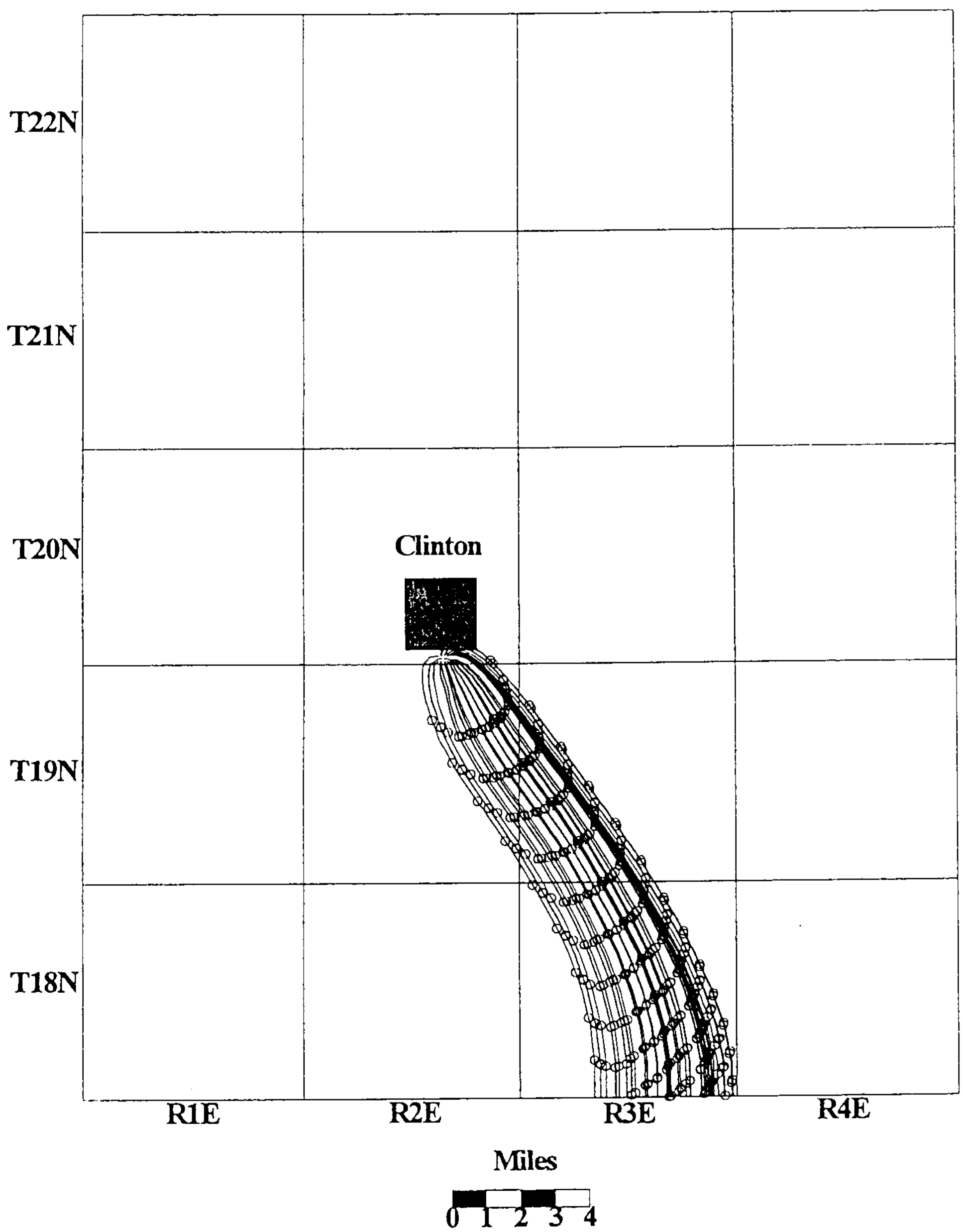


Figure 23. Map showing the 50 year time-of-travel capture zone for the city of Clinton's municipal water supply wells after adjustment of the row to column anisotropy by minus 10 percent. (Circles represent 50 year time markers.)

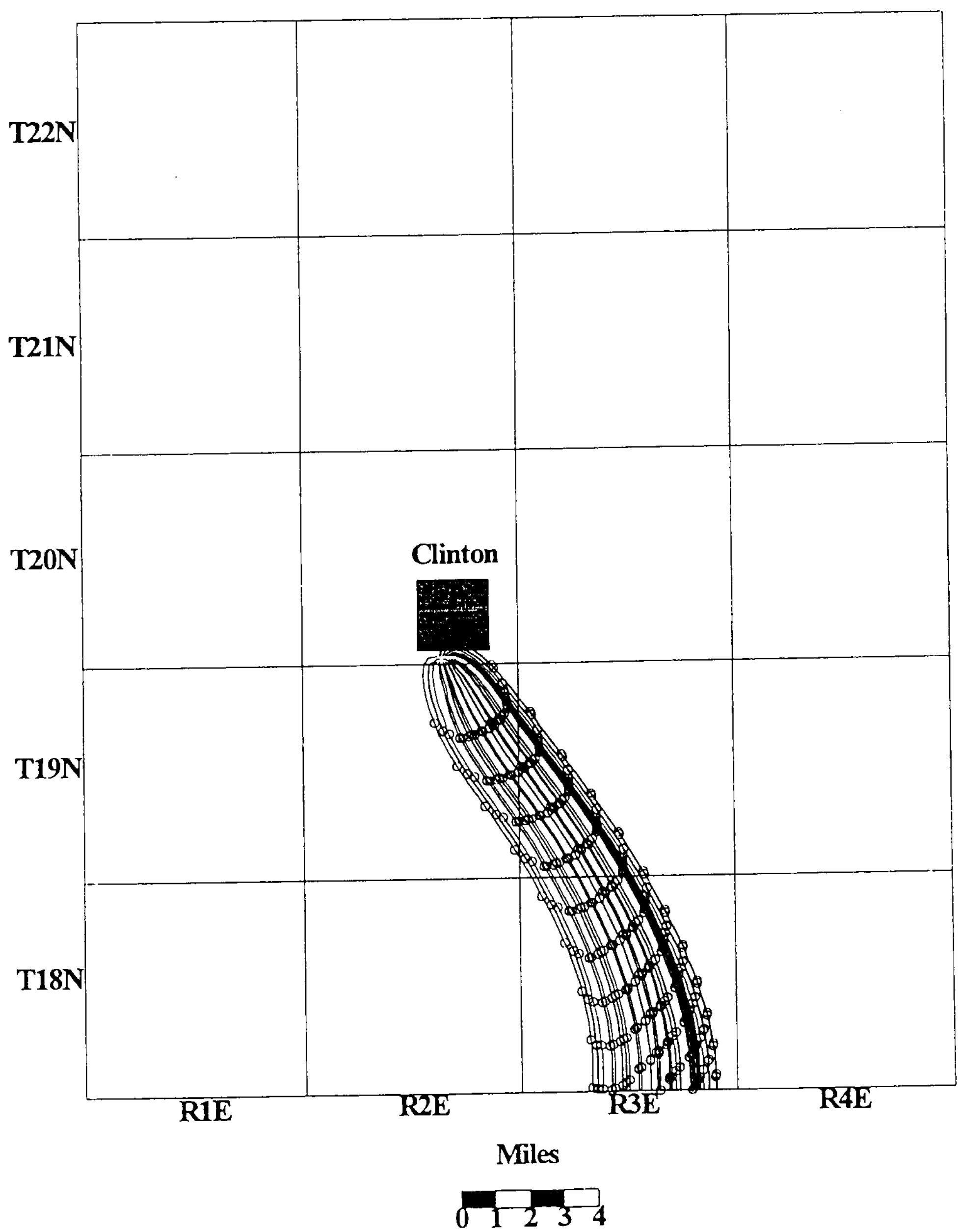


Figure 24. Map showing the 50 year time-of-travel capture zone for the city of Clinton's municipal water supply wells after adjustment of layer one's hydraulic conductivity by plus 10 percent. (Circles represent 50 year time markers.)

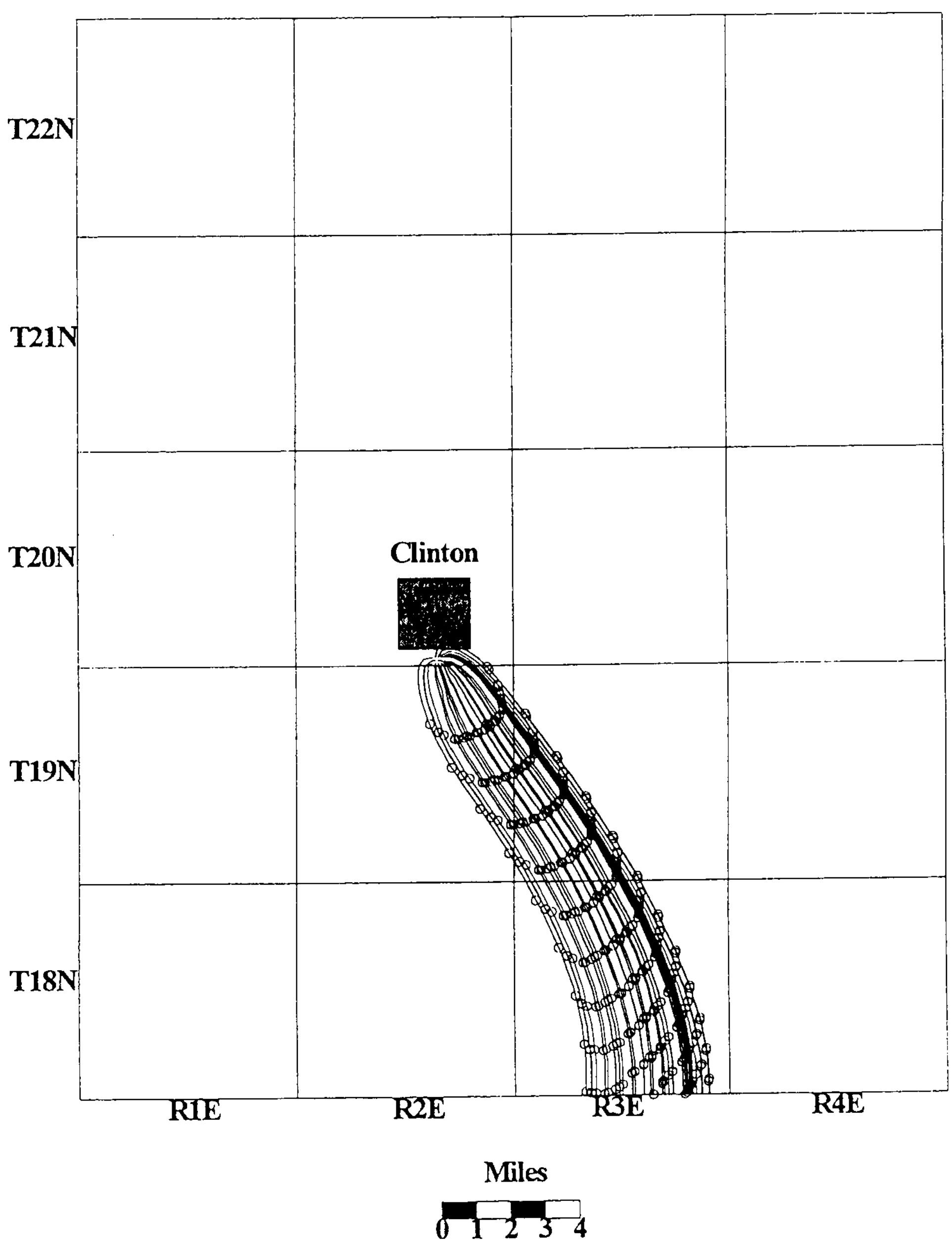


Figure 25. Map showing the 50 year time-of-travel capture zone for the city of Clinton's municipal water supply wells after adjustment of layer one's hydraulic conductivity by minus 10 percent. (Circles represent 50 year time markers.)

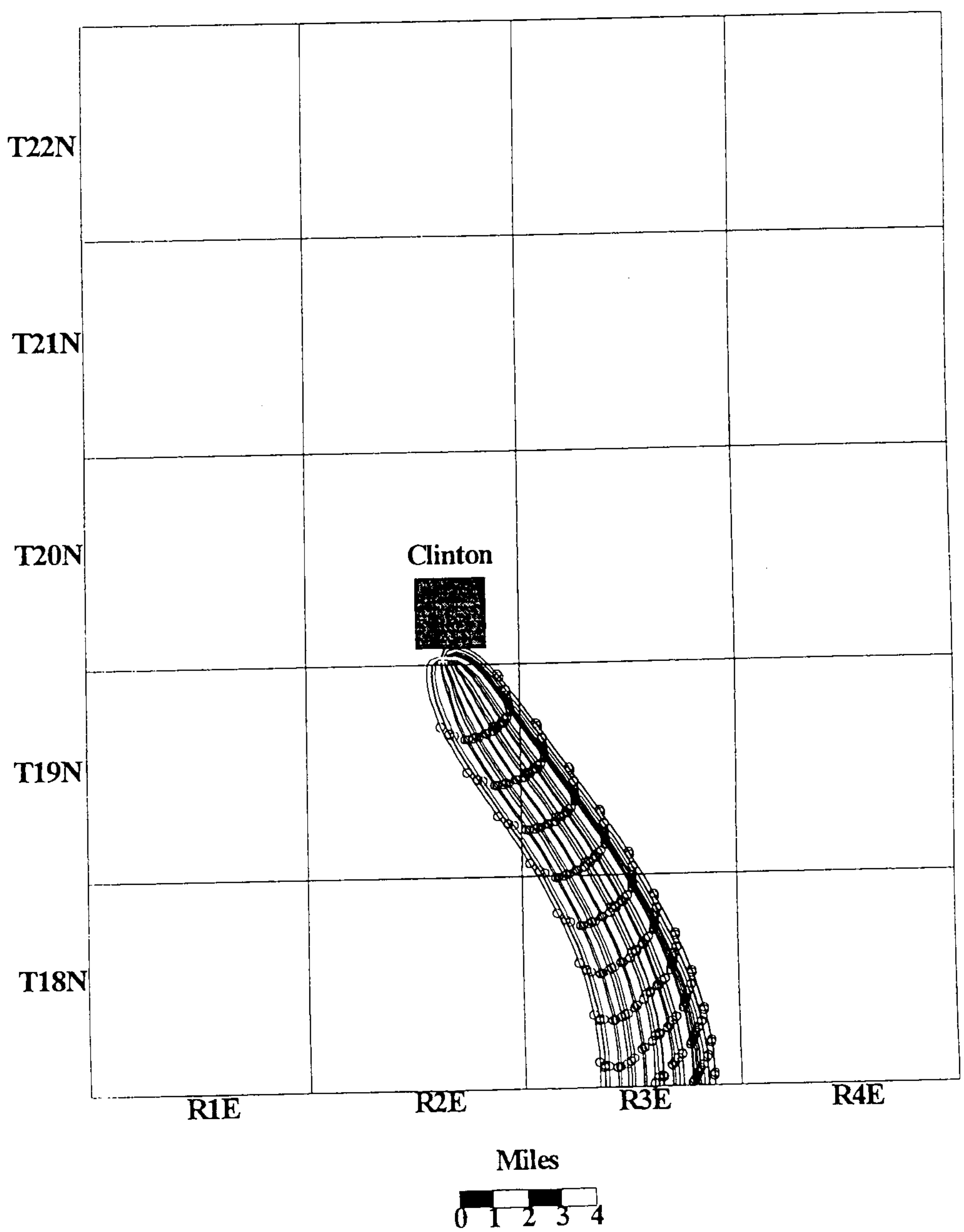


Figure 26. Map showing the 50 year time-of-travel capture zone for the city of Clinton's municipal water supply wells after adjustment of layer two's hydraulic conductivity by plus 10 percent. (Circles represent 50 year time markers.)

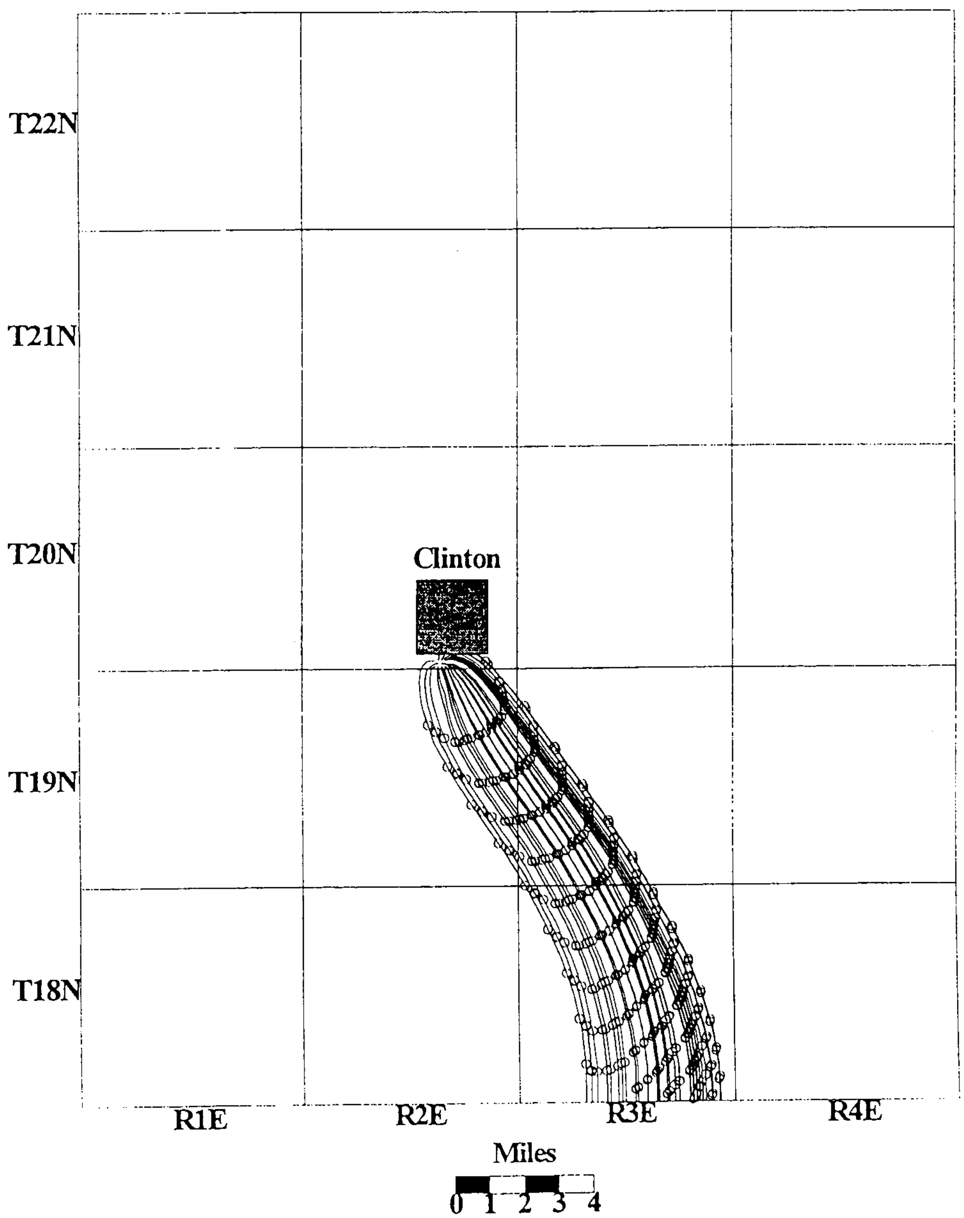


Figure 27. Map showing the 50 year time-of-travel capture zone for the city of Clinton's municipal water supply wells after adjustment of layer two's hydraulic conductivity by minus 10 percent. (Circles represent 50 year time markers.)

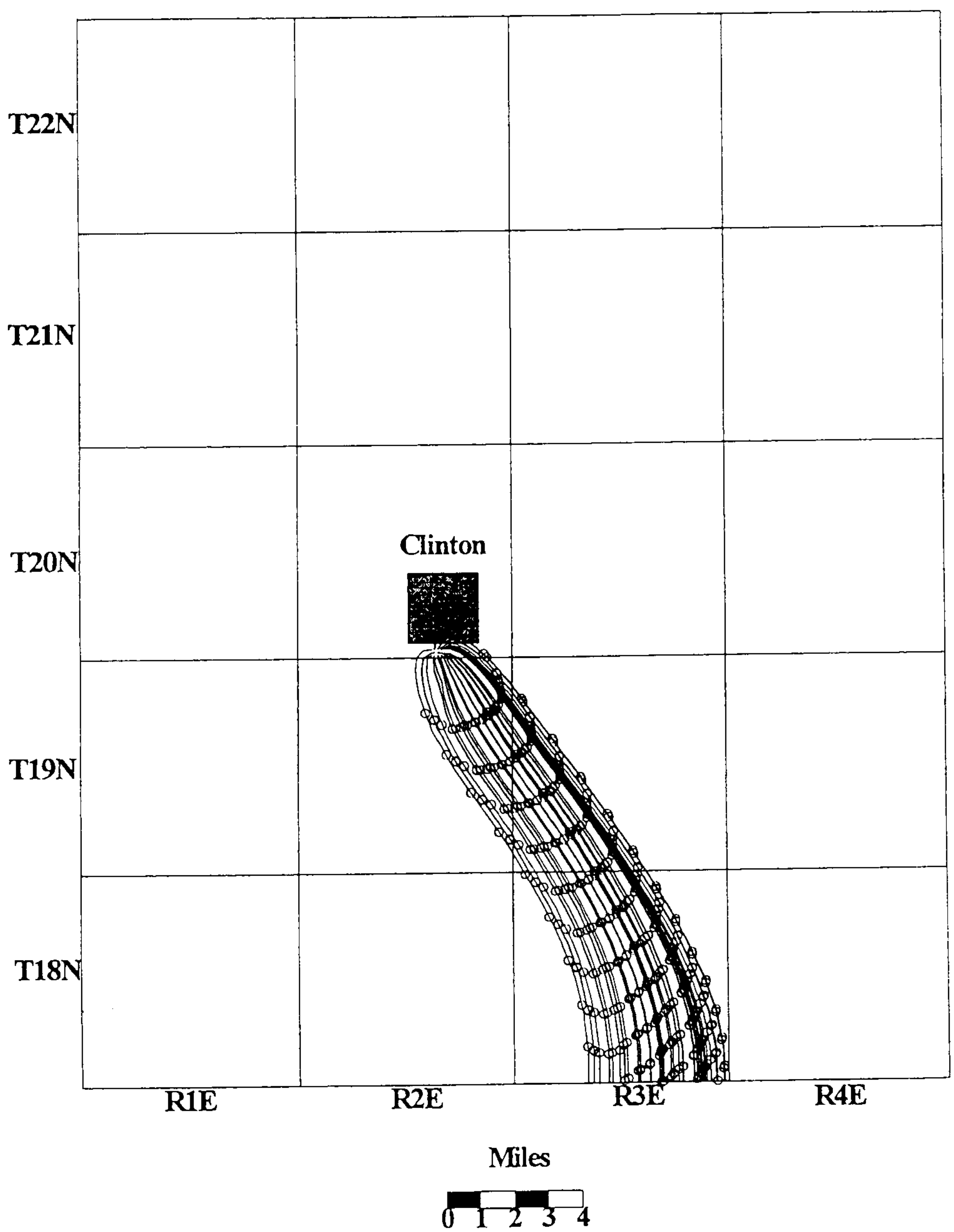


Figure 28. Map showing the 50 year time-of-travel capture zone for the city of Clinton's municipal water supply wells after adjustment of the recharge rate by plus 10 percent. (Circles represent 50 year time markers.)

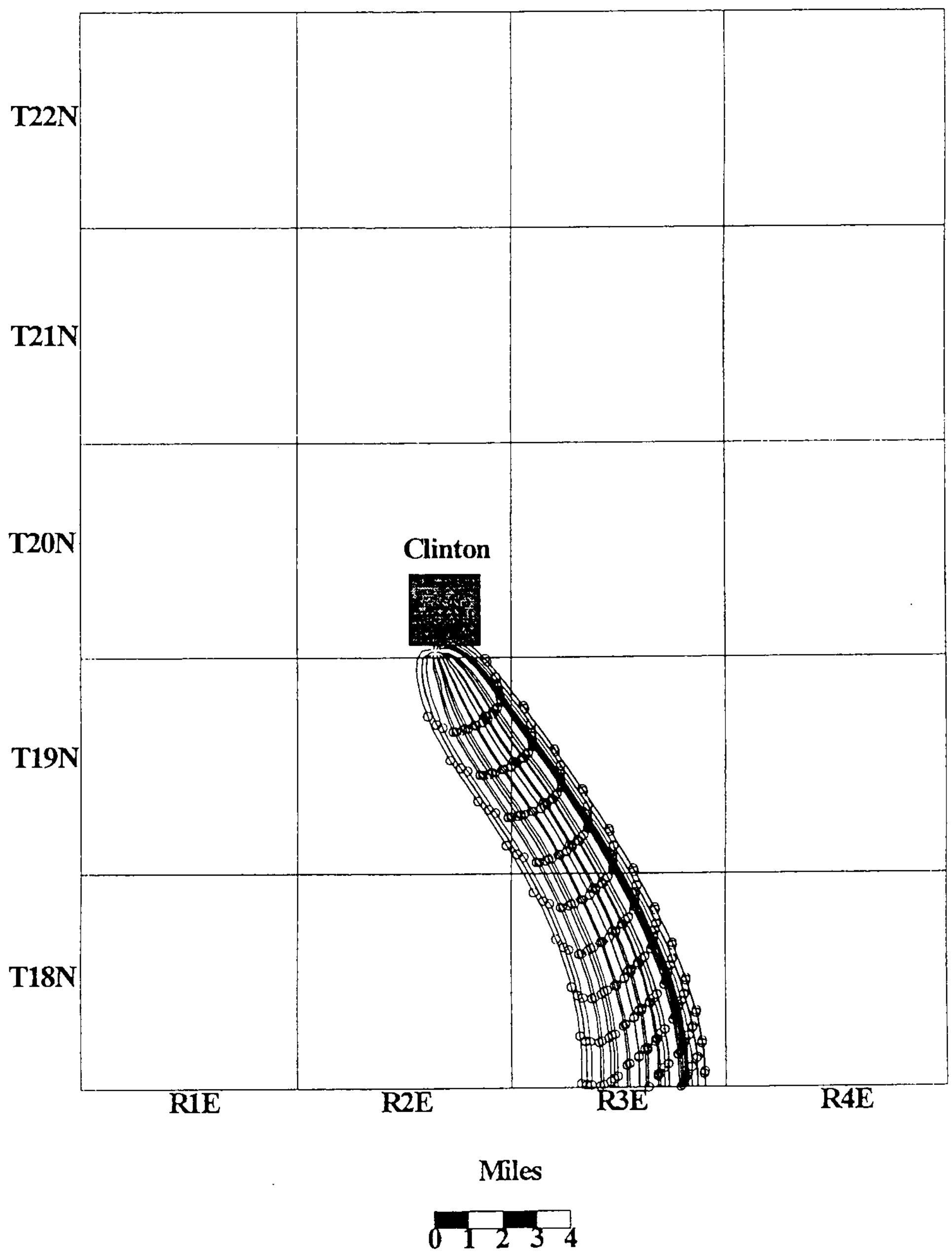


Figure 29. Map showing the 50 year time-of-travel capture zone for the city of Clinton's municipal water supply wells after adjustment of the recharge rate by minus 10 percent. (Circles represent 50 year time markers.)

Table 1. Volumetric budget for sensitivity analysis (ft^3/day).

Parameter	Base Model	ANP	ANM	RCP	RCM	KL1P	KL1M	KL2P	KL2M
IN									
Recharge	$1.51x10^{+6}$	$1.51x10^{+6}$	$1.51x10^{+6}$	$1.66x10^{+6}$	$1.35x10^{+6}$	$1.51x10^{+6}$	$1.51x10^{+6}$	$1.51x10^{+6}$	$1.51x10^{+6}$
River	$1.04x10^{+5}$	$1.04x10^{+5}$	$1.03x10^{+5}$	$1.03x10^{+5}$	$1.04x10^{+5}$	$1.04x10^{+5}$	$1.03x10^{+5}$	$1.04x10^{+5}$	$1.04x10^{+5}$
Head Dependent Boundary	$1.09x10^{+7}$	$1.09x10^{+7}$	$1.08x10^{+7}$	$1.08x10^{+7}$	$1.09x10^{+7}$	$1.09x10^{+7}$	$1.08x10^{+7}$	$1.09x10^{+7}$	$1.08x10^{+7}$
OUT									
Evapotranspiration	$1.15x10^{+7}$	$1.15x10^{+7}$	$1.15x10^{+7}$	$1.16x10^{+7}$	$1.14x10^{+7}$	$1.15x10^{+7}$	$1.15x10^{+7}$	$1.15x10^{+7}$	$1.15x10^{+7}$
River	$2.34x10^{+5}$	$2.40x10^{+5}$	$2.27x10^{+5}$	$2.42x10^{+5}$	$2.25x10^{+5}$	$2.40x10^{+5}$	$2.27x10^{+5}$	$2.34x10^{+5}$	$2.34x10^{+5}$
Well	$1.27x10^{+5}$	$1.27x10^{+5}$	$1.27x10^{+5}$	$1.27x10^{+5}$	$1.27x10^{+5}$	$1.27x10^{+5}$	$1.27x10^{+5}$	$1.27x10^{+5}$	$1.27x10^{+5}$
Head Dependent Boundary	$6.02x10^{+5}$	$6.30x10^{+5}$	$5.72x10^{+5}$	$6.03x10^{+5}$	$6.01x10^{+5}$	$6.09x10^{+5}$	$5.95x10^{+5}$	$6.44x10^{+5}$	$5.60x10^{+5}$
IN - OUT	-812.00	-828.00	-817.00	-839.00	-861.00	-815.00	-811.00	-866.00	-775.00
Percent Difference	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01

Key to above model abbreviations:

ANP = Row to column anisotropy adjusted by +10%.
ANM = Row to column anisotropy adjusted by -10%.
RCP = Recharge adjusted by +10%.
RCM = Recharge adjuxted by -10%.
KL1P = Hydraulic conductivity of layer 1 adjusted by +10%.
KL1M = Hydraulic conductivity of layer 1 adjusted by -10%.
KL2P = Hydraulic conductivity of layer 2 adjusted by +10%.
KL2M = Hydraulic conductivity of layer 2 adjusted by -10%.

Table 2. Summary of particle travel times from sensitivity analysis (values in years).

Parameter	**Base Model**	**ANP**	**ANM**	**RCP**	**RCM**	**KL1P**	**KL1M**	**KL2P**	**KL2M**
Minimum Travel Time	451.75	418.89	487.33	451.75	451.75	451.75	451.75	418.89	487.33
Maximum Travel Time	624.23	575.95	678.99	626.97	626.97	624.23	624.23	569.47	692.68
Average Travel Time	514.72	481.86	564.00	517.45	517.45	517.45	517.45	476.39	564.00
%P*	53.5	57.8	56.7	53.3	53.3	53.3	53.3	52.2	53.3

* Percentage of particles with less than the average travel time.

average particle travel-time for the base model was 514.72 years. After adjusting the row to column anisotropy by plus 10 percent the average travel-time was reduced to 481.86 years, a change of approximately 6.38 percent. Average travel-times are therefore 6.38 percent shorter than those of the base model. Adjustment of the same parameter by minus 10 percent yielded an average travel-time of 564.00 years, a change of approximately 9.57 percent. Therefore, average travel times in this case are 9.57 percent longer than those of the base model. Adjustment of the hydraulic conductivity of layer 2 by plus 10 percent yielded an average particle travel-time of 476.39 years, a change of approximately 7.45 percent. Average travel-times are therefore 7.45 percent shorter than those of the base model. An adjustment of layer two's hydraulic conductivity by a factor of minus 10 percent yielded an average travel-time of 564.00 years, a change of approximately 9.57 percent. The average particle travel-times are therefore 9.57 times longer than those of the base model. Adjustments to the recharge and layer one's hydraulic conductivitie showed an average change of only one-half of one percent in the average particle travel-times. It can therefore be concluded that the model is most sensitive to the row to column anisotropy and the hydraulic conductivity in layer two.

CHAPTER V

CONCLUSIONS

The delineation of time-dependent surface recharge areas and time-of-travel capture zones for water supply wells is a labor-intensive, complex problem. The input data required for a groundwater model are numerous and their accuracy ultimately determines the accuracy of the final results. Many of the values for specific model parameters are at best known to perhaps an order of magnitude and therefore a certain degree of guesswork is involved in any modeling endeavor. The values the geohydrologist assigns to model parameters can have great effects on the resultant time-dependent surface recharge area and time-of-travel capture zones. For these reasons, a sensitivity analysis should be an integral part of a wellhead protection study.

The 5 year time-of-travel capture zones for the city of Clinton's six municipal water supply wells are located in close proximity to the wells themselves. The 50 year capture zones are located approximately 2.5 miles southeast of the wells. None of the particles tracked in the model entered the flow system within the modeled study area. This indicates that the time-dependent surface recharge areas for the wells are not located within the modeled study area. However, based upon the model's results, it can be said that the recharge areas are located at *least* 12 miles to the southeast of or up-gradient from he wells. According to the model, the average particle travel-time associated with this 12 mile minimum distance is approximately 515 years.

According to the results from the sensitivity analysis, the model is most sensitive to the row to column anisotropy and the hydraulic conductivity of layer two. Varying theses parameters by 10 percent caused a variance ranging from approximately 6.4 percent to 9.6 percent in the average travel-time. The model was less sensitive to variations in the hydraulic conductivity of layer one and the recharge rate.

Based on the results from these three-dimensional groundwater models, it can be concluded that Clinton's municipal water supply wells do not appear to be threatened by contamination.

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APPENDIX A

MODFLOW AND MODPATH

INPUT FILES

Directory A:\Clinton	MODFLOW Packages
cq.bas	Basic
cq.oc	Output Control
cq.bcf	Block Centered Flow
cq.rch	Recharge
cq.wel	Well
cq.evt	Evapotranspiration
cq.riv	River
cq.ghb	General Head Boundary
cq.sip	Strongly Implicit Procedure
cq.cbc	Cell-by-cell Flow
cq.hds	Head Save
cq.out	Output
	MODPATH Packages
cq.sp	Starting Point
name.dat	Name File
main.dat	Main Data File
summary.pth	Pathline Summary File

APPENDIX B

CROSS SECTION WELL

IDENTIFICATION

Table 3. Cross section well identification.

From	Identification Number	Penetrates	Total Depth (ft.)
A-A'	120390002000	Br	266.1
	120392095500	Br	229.0
	120392100200	Br	274.0
	120392103800	Br	286.1
	120393103600	Br	289.1
	120392111200	Br	370.1
	120390052000	Ms	347.1
B-B'	120392079400	Ms	270.0
	120392103900	Ms	279.9
	120392075600	Ms	259.9
	120392103600	Br	289.1
	120392111200	Br	370.1
	120392104300	Ms	335.0
	120390057800	Ms	335.0

Ms = Mahomet Sand

Br = Bedrock