



**LIBRARY**  
**Michigan State**  
**University**



This is to certify that the

thesis entitled

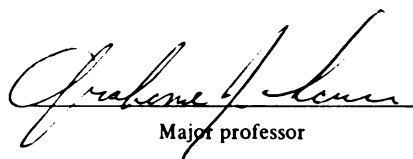
GROUND-WATER FLOW IN A CLAY-RICH TILL  
IN SOUTHEASTERN MICHIGAN: THE ROLE OF  
FRACTURES

presented by

Carol Lee Luukkonen

has been accepted towards fulfillment  
of the requirements for

M.S. degree in Geology

  
Major professor

Date Nov 21, 1997

**PLACE IN RETURN BOX** to remove this checkout from your record.  
**TO AVOID FINES** return on or before date due.  
**MAY BE RECALLED** with earlier due date if requested.

DATE DUE	DATE DUE	DATE DUE
<hr/>	<hr/>	<hr/>
<hr/>	<hr/>	<hr/>
<hr/>	<hr/>	<hr/>
<hr/>	<hr/>	<hr/>
<hr/>	<hr/>	<hr/>

**GROUND-WATER FLOW IN A CLAY-RICH TILL  
IN SOUTHEASTERN MICHIGAN: THE ROLE OF FRACTURES**

**By**

**Carol Lee Luukkonen**

**A THESIS**

**Submitted to  
Michigan State University  
in partial fulfillment of the requirements  
for the degree of**

**MASTER OF SCIENCE**

**Department of Geological Sciences**

**1997**

## **ABSTRACT**

### **GROUND-WATER FLOW IN A CLAY-RICH TILL IN SOUTHEASTERN MICHIGAN: THE ROLE OF FRACTURES**

**By**

**Carol Lee Luukkonen**

**A four layer steady-state ground-water flow model was developed to simulate ground-water flow at the study site near Milan in southeastern Michigan using data collected during this and previous investigations. The fractured clay-rich till units overlying bedrock were treated as equivalent porous media. Particle tracking was used to investigate the observed distribution of tritium at depth and the proposed upward hydraulic gradient beneath the Arkona Road Landfill site. Leakances between layers were systematically varied to simulate the effect of fractures and to observe effects on simulated heads.**

**Particle-tracking results indicate that the model does not accurately represent the fractures which create localized flow systems at a smaller scale than the grid spacing of the model. The minimum travel time for particles from the top of layer one to layer two was 15.2 years, however, the minimum travel time to layer three where tritium was detected in the water was 6,000 years. Particle tracking does indicate that all ground-water flow is downward. Finally simply increasing the leakances between layers does not alone improve the simulated heads.**

## ACKNOWLEDGMENTS

I wish to extend special thanks to my thesis advisor, Dr. Grahame Larson, for the many hours he spent at the study site measuring fractures, for his assistance during model construction and calibration, for his comments that improved this thesis, and for not giving up on me. I also extend special thanks to Dr. Michael Velbel and Dr. William Cambray for taking the time to serve on my committee and for their comments that improved this thesis. I am in debt to all of my committee members for the knowledge I have gained during this study and during coursework. Thanks also go to the U.S. Geological Survey for employing me during this study and for increasing my knowledge of modeling, data analysis, writing, and field work. And last but definitely not least, this study would not have been possible without the support and encouragement of my son, Ben, who kept me company while I worked and often clicked the mouse button for me, and my husband, Dave, who kept me focused on the study and always came up with good suggestions when I needed them the most.

## TABLE OF CONTENTS

List of Tables .....	vi
List of Figures .....	vii
Introduction.....	1
Previous Studies .....	2
Study Area Description.....	5
Geology .....	7
Hydrology.....	10
Fractures .....	14
Simulation of Ground-Water Flow .....	21
Conceptual Model .....	21
Numerical Model .....	23
Model Grid and Layers .....	23
Boundary Conditions .....	24
Sources and Sinks.....	25
Parameter Values .....	25
Model Layers.....	25
Ground-Water Recharge Rates .....	26
Hydraulic Properties .....	26
Model Calibration.....	29

Simulation Results.....	31
Particle Tracking.....	35
Tritium Data .....	37
Proposed Upward Flow .....	38
Analysis of Fractures .....	39
Model Limitations .....	41
Summary.....	42
Conclusions .....	44
Appendix.....	46
List of References .....	68



## LIST OF TABLES

Table 1. Hydraulic Conductivity Values.....	12
Table 2. Hydraulic Conductivities Assigned to Strata Codes.....	27
Table 3. Optimal Parameter Estimates .....	31
Table 4. Effects of Changing Leakances on Simulated Heads .....	40

## LIST OF FIGURES

Figure 1. Location of the Envotech Resource Center Site.....	6
Figure 2. Generalized Cross-Section .....	8
Figure 3. Fracture Orientations Measured by RMT (1992).....	15
Figure 4. Fracture Orientations on the Sloping Surface of the Unit 2 Till .....	18
Figure 5. Fracture Orientations in the Gully of the Unit 2 Till.....	19
Figure 6. Relation Between Measured and Simulated Heads for Layer One.....	32
Figure 7. Relation Between Measured and Simulated Heads for Layer Two .....	33
Figure 8. Relation Between Measured and Simulated Heads for Layer Three .....	34
Figure 9. Relation Between Measured and Simulated Heads for Layer Four.....	36
Figure 10. Model Grid for Layer One.....	46
Figure 11. Model Grid for Layer Two.....	47
Figure 12. Model Grid for Layer Three .....	48
Figure 13. Model Grid for Layer Four.....	49
Figure 14. Land Surface Elevation.....	50
Figure 15. Top of Layer Two.....	51
Figure 16. Top of Layer Three.....	52
Figure 17. Top of Layer Four .....	53
Figure 18. Measured Ground-Water Levels in Layer One .....	54
Figure 19. Measured Ground-Water Levels in Layer Two .....	55

Figure 20. Measured Ground-Water Levels in Layer Three .....	56
Figure 21. Measured Ground-Water Levels in Layer Four .....	57
Figure 22. Estimated Horizontal Hydraulic Conductivity of Layer One .....	58
Figure 23. Estimated Leakance Between Layers One and Two.....	59
Figure 24. Estimated Transmissivity of Layer Two .....	60
Figure 25. Estimated Leakance Between Layers Two and Three .....	61
Figure 26. Estimated Transmissivity of Layer Three.....	62
Figure 27. Estimated Leakance Between Layers Three and Four.....	63
Figure 28. Simulated Ground-Water Levels in Layer One.....	64
Figure 29. Simulated Ground-Water Levels in Layer Two .....	65
Figure 30. Simulated Ground-Water Levels in Layer Three .....	66
Figure 31. Simulated Ground-Water Levels in Layer Four.....	67

## **INTRODUCTION**

The study of fractures in clay and methods of modeling ground-water flow through a fractured media are becoming important areas of research. Studies have shown that the presence of fractures can increase the bulk hydraulic conductivity of till and clay deposits and can provide avenues of ground water and contaminant transport at faster rates than possible through the matrix (Gerber and Howard, 1992; Herzog and others, 1989; Grisak and Cherry, 1975; Grisak and others, 1976; and McKay, 1991). The presence of fractures in many deposits has been confirmed by the detection of tritium or other isotopes at depth beneath older water (Foote, 1989; Hendry, 1982 and 1983; Rudolph and others, 1991; and Ruland and others, 1991), order of magnitude differences in field and laboratory measured values of hydraulic conductivity (Fredericia, 1990; Grisak and Cherry, 1975; Keller and others, 1986 and 1988; McKay and others, 1993; Ruland and others, 1991; Thomson, 1990; and Williams and Farvolden, 1967), or visual observations of fractures at a site (Herzog and others, 1989).

The presence of fractures in two clay-rich till units in southeastern Michigan has been confirmed both by the detection of tritium at depth (Foote, 1989) and by visual observation (RMT, 1992). This site is located in southeastern Michigan approximately 2.5 miles east of the city of Milan in Augusta Township, Washtenaw County. The fractured till units are separated by a lacustrine clay and overlain by a lacustrine sand. Subcropping beneath this area are shale and limestone units. Based on an extensive hydrogeological investigation, RMT predicted that an upward hydraulic gradient exists beneath the Arkona Road Landfill which overlies the fractured

clay-rich till units in this area. RMT developed a ground-water-flow model to evaluate ground-water flow in the upper lacustrine sands at the site, however, their model did not incorporate the underlying till and bedrock units.

This study was undertaken to develop a model to explain the presence of tritium at depth and to investigate the proposed upward hydraulic gradient. This model will include the fractured till units underlying the upper lacustrine sands, as well as the bedrock units underlying the site. Particle tracking, in which hypothetical water particles are tracked as they move through the simulated ground-water-flow system, will be used to determine whether water can move downward at a fast enough rate to allow tritiated water to reach the observed depths and whether there is an upward hydraulic gradient beneath the Arkona Road Landfill.

## **PREVIOUS STUDIES**

The Arkona Road Landfill (ARL), located within the study area, was operated as a waste disposal site from April 1973 until its closure in March 1979 (RMT, 1992). The landfill is located within the upper fractured clay-rich till unit. Subsequent investigations in 1987 led to the conclusion that there was potential for contaminants to migrate beyond the landfill boundaries and that additional work was needed to address the potential for releases (RMT, 1988). Visual observations near the ARL revealed seepage from the landfill cover and some surface water samples near the ARL suggest contributions from the landfill (RMT, 1992).

Although ground-water samples collected by RMT do not clearly demonstrate water chemistry changes due to the ARL, the presence of fractures implies that an effective barrier to contaminant migration from the landfill may no longer exist. A similar conclusion has been suggested at other sites underlain by tills and argillaceous sediments. For example, Herzog and

others (1989) discovered contamination in a monitoring well in Illinois and noted organic chemicals had migrated much faster than expected from a disposal facility. Subsequent studies by Herzog and others revealed that previously undiscovered fractures in the glacial till were responsible for the rapid migration of chemicals. Also, Grisak and Cherry (1975) studied a clay-loam till and lacustrine clay in southeastern Manitoba and found that hydraulic conductivity and storativity of these deposits were primarily controlled by the fractures.

Study of a glacial till in Alberta likewise revealed that pre-bomb ground water overlies tritiated ground water (Hendry, 1982). Hendry suggested that movement of ground water through fractures could explain the presence of tritiated ground water at depth. Rudolph and others (1991) found variations with depth of major ions, oxygen 18, and deuterium at their study site in a fractured lacustrine clay near Mexico City. Ruland and others (1991) observed tritium deeper than expected in tills in southwestern Ontario.

Grisak and others (1976) observed that ground-water velocities in fracture networks were much larger than those in unfractured till masses. The presence of ground-water flow through fractures alone, however, does not completely account for the observed concentrations of chlorides and other soluble salts in much of the till waters in the Plains Region. Diffusion must be considered also (Grisak and others, 1976). Day (1977) found that diffusional exchange with pore water could explain the absence of tritium and oxygen 18 at depth observed in a fractured till in Manitoba. Grisak and others (1980) studied solute transport through a cylindrical column of fractured clayey glacial till. The breakthrough curves indicated that calcium and chloride were affected by diffusion from the fractures into the porous matrix of the till. Thus, "analyses of contaminant migration through fractured till and of ground water origin and age based on the distribution of isotopes such as  $^{18}\text{O}$ , D,  $^3\text{H}$ , and  $^{14}\text{C}$  in fractured till should account for the effect of matrix diffusion" (Grisak and others, 1980).

Methods of modeling fracture systems have been developed by many researchers (Berkowitz and Braester, 1991; Grisak and Pickens, 1980; Hull and others, 1987; Moreno and others, 1990; Rowe and Booker, 1990 and 1991; Snow, 1969; Sudicky and McLaren, 1992; Sudicky and Frind, 1982; Thoma and others, 1992; and Zimmerman and others, 1992). Fracture systems can be modeled using (1) equivalent porous media, (2) discrete fracture network, or (3) dual porosity models (Anderson and Woessner, 1992). Harrison and others (1992) observed that the discrete network approach ignores diffusion, and that equivalent porous media and dual porosity model approaches have questionable results when extended to greater depths where the fracture frequency is lower. Long and others (1982), Long and Witherspoon (1985), and Long and Billaux (1987) have investigated treating a fractured network as an equivalent porous media and Long and others (1982) found that a fractured system behaves more like a homogeneous, anisotropic material with an increase in fracture density, nonuniform orientations, uniform apertures, and constant gradients for each representative elementary volume. Subsequent studies by Long and Witherspoon (1985) observed that "systems with longer but less dense fractures behave more like porous media than systems with shorter, but more dense fractures". Systems with longer fractures tended to have a higher degree of interconnection which Long and Witherspoon found to affect fracture permeability. Long and Billaux (1987) concluded that an equivalent porous media approach was generally not valid for their two-dimensional fracture network due to the low degree of fracture interconnection. However, Long and Billaux's analyses indicated that a three dimensional system may be well connected. Other researchers doubt that equivalent porous media models adequately represent fractured networks (Cacas and others, 1990a and 1990b). Gale (1982) found that systems with a low matrix hydraulic conductivity and a low fracture density could not be appropriately modeled as an equivalent porous media. Berkowitz and

others (1988), however, observed that if field estimates of hydraulic parameters were available, an equivalent porous media model could be constructed.

A problem in representing a fractured system as an equivalent porous media lies in determination of the effective hydraulic parameters. Keller and others (1986) showed that the bulk permeability of a clayey till near Saskatoon, Saskatchewan exceeded the matrix permeability by two orders of magnitude. Fredericia (1990) observed that laboratory measured values probably only represent the hydraulic conductivity of the matrix material between the fractures. Keller and others (1988) concluded that bulk permeability was greater in fractured till compared to unfractured till. Grisak and others (1976) observed that ground-water velocities were many orders of magnitude larger in fracture networks than in unfractured till masses.

Additional problems result since field-measured values of hydraulic conductivity can be influenced by smearing during installation of measuring equipment (McKay and others, 1993). McKay and others (1993) found that use of specially designed augers that minimize smearing produced higher estimates of hydraulic conductivity. Measurements of hydraulic conductivity are further affected by the physical scale (McKay and others, 1993; and Bruner, 1993). Bruner (1993) found that the bulk hydraulic conductivity increases as larger volumes of till are tested.

## **STUDY AREA DESCRIPTION**

Approximately 2.5 miles east of the city of Milan, Envotech Resource Center (ERC) has proposed locating a hazardous waste management facility in Augusta Township, Washtenaw County, Michigan (Figure 1). The ARL site is located approximately three-quarters of a mile west of the proposed waste management facility and an abandoned limestone quarry is located approximately a quarter mile south of the ARL site. Data on the geology and hydrogeology of the



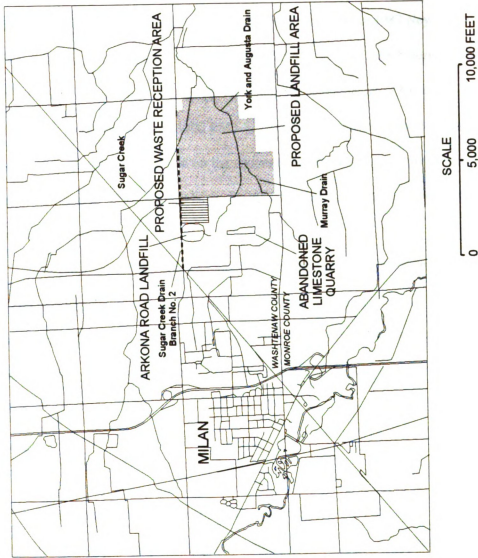


Figure 1. Location of the Envotech Resource Center Site.

proposed facility site and surrounding area is available from numerous investigations (RMT, 1992; Neyer, Tiseo, and Hindo, 1987; Hunttec, Ltd., 1967; and McNamee, Porter, and Seeley, 1965).

In 1965, McNamee, Porter, and Seeley advanced 29 soil and rock borings and 11 test holes for Martin-Marietta Company who was considering developing the site as a limestone quarry. In 1967, Hunttec, Ltd. investigated the elevation and stratigraphy of the bedrock using resistivity and seismic surveys with borings into the bedrock and in 1987 Neyer, Tiseo, and Hindo (NTH) advanced 50 borings to depths ranging from 55 to 125 feet with 5 borings to the bedrock for NTH who was assessing the property's potential for development of hazardous waste facilities for Envotech. Between 1987 and 1990 RMT advanced 278 monitoring wells and soil borings throughout the proposed study area for the Augusta Development Corporation, a corporation related to Envotech. These borings have provided detailed information on the subsurface stratigraphy of the area.

The proposed landfill area includes 518 acres and an adjacent waste reception area includes an additional 40 acres. The land surface slopes gently towards Lake Erie. Sugar Creek crosses the northeast corner of the site. The York and Augusta Drains cross in the south and the Murray Drain crosses the southwest corner of the site (RMT, 1992).

## **Geology**

At the study site, glacial deposits were deposited during the Wisconsin glacial (Dorr and Eschman, 1970). The sequence of deposits at the site, which includes two till units separated by a lacustrine clay, indicates the presence of multiple advances of ice. At the Milan study site the glacial deposits range from 84 to 119 feet thick (RMT, 1992) and overlie shale and limestone bedrock units of Devonian age (Figure 2). Rocks of Mississippian, Pennsylvanian, Permian, Triassic, Jurassic, Cretaceous, and Tertiary age are missing in this area.

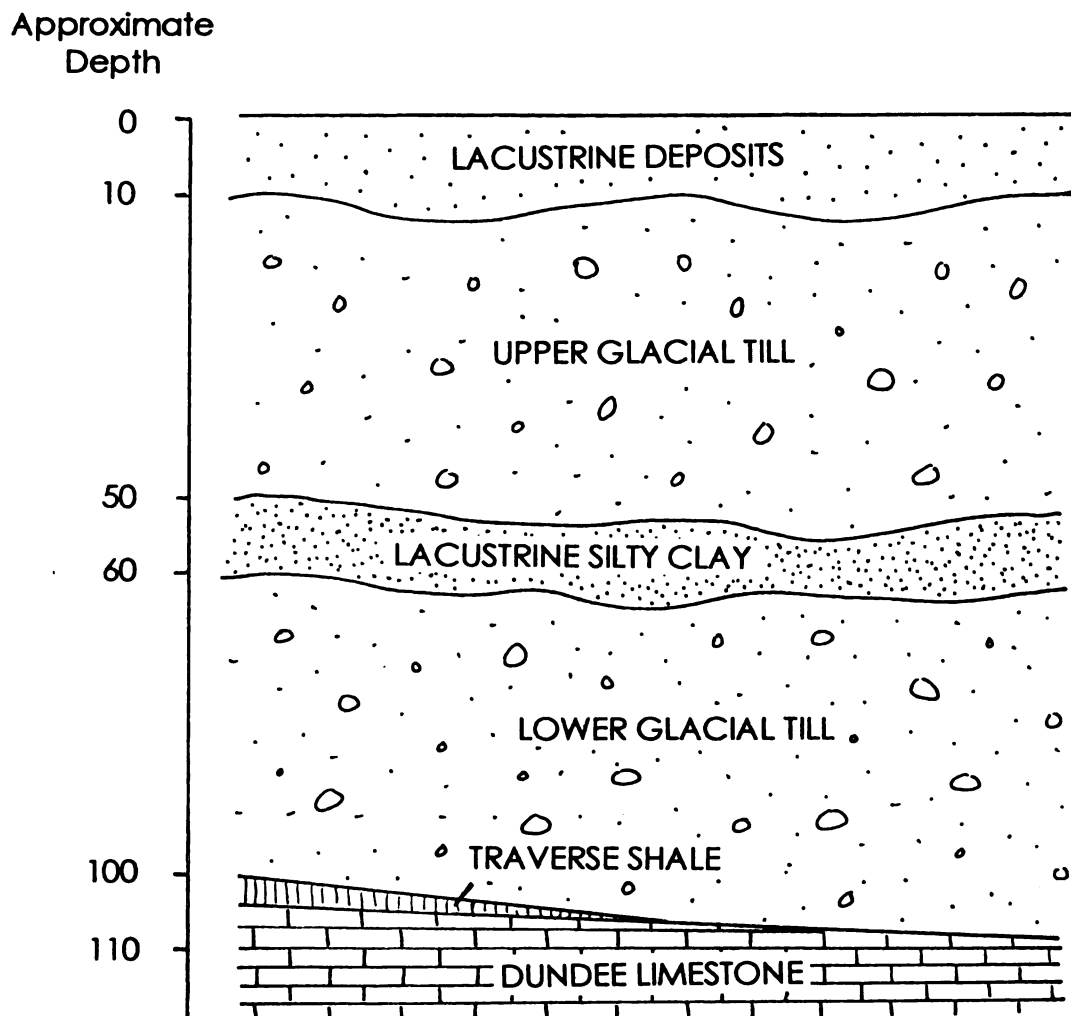


Figure 2. Generalized Cross-Section.

The glacial deposits underlying the proposed facility site have been divided into four units (RMT, 1992). These units include: 1) surficial lacustrine deposits, 2) upper glacial till unit, 3) lacustrine silty clay deposits, and 4) lower glacial till unit. Lacustrine/outwash lenses are found within the glacial till units. Surface exposures reveal that the glacial till units are weathered and fractured.

The upper lacustrine deposits, unit 1, range from 5 to 15 feet thick and consist primarily of sand and silt. Unit 1 was deposited at the bottom and on the shore of a glacial lake (RMT, 1992). According to RMT (1992) a melting glacier occupying the Lake Erie Basin blocked drainage to the east and caused the formation of a glacial lake in front of the ice margin. Lake level changes, shoreline location changes and different sediment sources, as well as more recent reworking by wind and streams, have introduced some variability into this deposit (RMT, 1992).

The upper glacial till, unit 2, ranges from 20 to 50 feet thick and consists primarily of a silty clay or clay. The till is relatively homogeneous but does contain some sand and sand and gravel lenses. This upper till unit was deposited by the ice of the Erie-Huron Lobe (Kunkle, 1961, as referenced in RMT, 1992) and extends to the east into the present Lake Erie Basin (RMT, 1992). The upper till unit is visibly weathered and fractured in surface exposures. These fracture surfaces show geochemical changes, including iron oxide and possible manganese oxide staining. Calcite and gypsum precipitation is also visible. The number of fractures decreases with depth. At about 35 feet below the surface of this till unit, secondary mineral deposition is rare (RMT, 1992).

Underlying the upper till unit is a lacustrine clay, unit 3, which averages 10 feet thick over the site and consists primarily of a silty clay. This lacustrine clay was deposited at the bottom of a pro-glacial lake and was later over-run by the glacier that deposited the overlying till unit (RMT, 1992).

The lower glacial till, unit 4, is approximately 55 feet thick over the area and consists of multiple till units. Unit 4 is slightly coarser-grained than the upper till, unit 2. Multiple earlier advances of the ice in the Erie-Huron Lobe deposited this unit (RMT, 1992).

The two Devonian bedrock units subcrop beneath the Milan study site and are, on the average, 110 feet below the ground surface. The contact between the Dundee Formation and the overlying Traverse Shale crosses the study area from southwest to northeast. These units dip gently towards the northwest. The Traverse Shale is very fine grained with numerous fossils and some pyrite. This shale ranges from 0 feet thick in the southeast portion of the site to 40 feet thick in the northwest portion of the site (RMT, 1992). This bedrock unit is permeable in the northwest section of the study area, possibly due to bedding plane fractures (Snow, 1967). The Traverse Shale unconformably overlies the Dundee Limestone. The Dundee Limestone is a fine to coarse grained dolomitic limestone and dolomite with fossils (RMT, 1992). Snow (1967) reported that the Dundee is about 100 feet thick.

## **Hydrology**

RMT's (1992) investigations at the Envotech proposed facility site reveal that ground-water-flow directions are towards the southeast and northeast. Wetlands lie on top of the unit 2 clay and within the unit 1 sand. Their hydrology is probably influenced most by recharge from precipitation, ground-water flow in the sand, and ground water discharge to adjacent surface water bodies (RMT, 1992). Water from the unit 1 sand is occasionally used for residential water supply. Other limited sources of water to wells include the discontinuous sand or sand and gravel lenses within the unit 2 and unit 4 tills, however, these are not regionally continuous (RMT, 1992).

Kunkle (1961, as referenced in RMT, 1992) found that regionally the water table dips slightly towards the southeast to Lake Erie. The creeks and drains within the Milan study site control the shape of the water table surface and serve as sites for discharge of water from the shallow portions of the flow system (RMT, 1992). During both high and low water conditions measured by RMT (1992), the creeks and drains formed an east-west trending ridge on the water table surface with the highest elevations beneath the waste reception area and the northwest corner of the landfill area. Generally, ground water flows northeast to Sugar Creek and Branch No. 2 of Sugar Creek and southeast to the York and Augusta Drain. RMT (1992) observed that the York and Augusta Drains and Sugar Creek form hydrogeologic divides to horizontal flow in the unit 1 sand.

Ground water flow is primarily horizontal through unit 1, the surficial lacustrine deposits, and is generally towards the surface drains, subsurface drains, and streams (RMT, 1992). Flow is primarily vertical in units 2, the upper glacial till, 3, lacustrine silty clay, and 4, the lower glacial till. RMT (1992) observed an exception to the downward flow conditions that occurred near the former quarry operation where ground water flow discharged to the surface or to the quarry lake, and beneath the ARL site and part of the proposed facility site where ground water flow was upward and controlled by the hydraulic head in the limestone. RMT (1992) also found that the lacustrine and outwash lenses within the tills "have little effect on the overall pattern of downward flow across the site. The exceptions to this are the thick (10 to 20 feet) sandy deposits at the surface of the bedrock where strong horizontal flow components are found".

Within the Traverse Shale in the western part of the area, ground water flow is vertical. Ground water flow is towards the south in the Dundee Limestone (RMT, 1992). Water is available to wells in the Dundee Limestone when a significant number of joints and fractures are present (Twenter and others, 1976, as referenced in RMT, 1992). Solution-enlarged fractures produce the permeable zones in part of the bedrock below the site (Snow, 1967, as referenced in

RMT, 1992). The piezometric surface in the Dundee Limestone shows an increase in head away from the center of the ERC towards the north, west, and east. McNamee, Porter, and Seeley (1965) and Twenter and others (1976), as referenced in RMT (1992) reported some flowing wells, which suggest the presence of localized upward gradients, within three miles of the ERC. Review of 682 well logs collected by RMT reveal that 7 wells, of which 4 are completed in bedrock, had static water levels at or above the ground surface. These flowing wells were located north and west of the site. Of the bedrock wells, the closest is approximately 2/3 mile west of the ARL site and the farthest is 1 mile north of the ARL site.

RMT (1992) measured hydraulic conductivities in each of the units at the site (Table 1). Laboratory values were determined using a permeameter on undisturbed samples. Field values were determined using bail-down or slug tests in which the recovery rate of the well was measured after a predetermined amount of water was removed from the well. RMT interpreted the recovery rate data using analytical solutions developed by Hvorslev (1951) or Bouwer and Rice (1976).

Table 1. Hydraulic Conductivity Values.  
( (f) denotes field value and n denotes number of measurements )

UNIT	MEASURED VALUES FOR HYDRAULIC CONDUCTIVITY, feet/day (RMT, 1992)	ESTIMATED VALUES FOR HYDRAULIC CONDUCTIVITY, feet/day (this study)
1	SE 3.4 e-03 to 1.53 [(f), n=13] NW 0.964 to 7.65 [(f), n=5]	6.07 to 22.6
2	8.5 e-05 to 4.82 e-03 [(f), n=24]	4.0 e-04 to 1.5 e-04
4	2.55 e-03 [(f), n=1]	4.3 e-07 to 9.8 e-04
bedrock	3.12 e-05 to 1.93 [(f), n=6]	0.134 to 13.39

For unit 1, hydraulic conductivity values determined from field tests ranged from  $3.4 \times 10^{-3}$  to 1.53 ft/d in the southeast (n=13) and from 0.964 to 7.65 ft/d in the northwest (n=5). The higher values were in the area of the proposed waste reception area and reflect the coarser grained deposits in this area. The geometric means of these measurements were  $7.37 \times 10^{-2}$  in the southeast and 3.4 in the northwest.

For unit 2, hydraulic conductivity values determined from field tests ranged from  $8.5 \times 10^{-5}$  to  $4.82 \times 10^{-3}$  ft/d. The geometric mean using these 24 measurements was  $2.58 \times 10^{-4}$ . For both field and laboratory determined values RMT calculated 95 % confidence intervals. For unit 2, the upper limit of the 95 % confidence interval calculated from field values, which RMT interpreted to be an effective hydraulic conductivity for the unit, was  $2.83 \times 10^{-4}$  ft/d. The lower limit of the 95 % confidence interval calculated from laboratory values, which RMT interpreted to be the matrix hydraulic conductivity, was  $4.25 \times 10^{-5}$  ft/d. For unit 3, the geometric mean using 194 laboratory measurements was  $4.34 \times 10^{-5}$  ft/d.

For unit 4, a hydraulic conductivity value of  $2.55 \times 10^{-3}$  ft/d was determined from one field test. RMT interpreted the matrix hydraulic conductivity to be  $2.83 \times 10^{-5}$  ft/d which is within the 95 % confidence interval calculated from 149 laboratory measurements. Finally, for the limestone RMT determined hydraulic conductivity values from field tests that ranged from  $3.12 \times 10^{-5}$  to 1.93 ft/d. The geometric mean using these 6 measurements was  $8.22 \times 10^{-3}$  ft/d. Snow (1967) also determined a mean hydraulic conductivity value using airlift data of 5.67 ft/d. RMT estimated the hydraulic conductivity of the Traverse Shale to range from  $2.83 \times 10^{-5}$  to  $2.83 \times 10^{-8}$  ft/d.



## Fractures

RMT (1992) observed fractures in the unit 2 till (Figure 3). After excavating an area for cover for the Arkona Road Landfill, an approximately 2.5 acre sloping surface of unit 2 was exposed to a depth of 35 feet below the unit 1 sand. Six test pits were dug with two each at 10, 20, and 35 foot depths. At the two deeper depths the 2 to 4 foot deep test pits were oriented approximately north-south and east-west, while the shallow pair were both oriented north-south. Smeared clay surfaces were removed and the orientations of fractures measured.

RMT observed a frequency of 6 to 7 fractures per foot in the top 10 feet of unit 2 with a spacing of about 0.15 foot in horizontal exposures. The fractures in vertical exposures appeared to be spaced at about 0.67 foot but these were less visible and may have been underestimated. These fractures showed a predominant strike of  $80^{\circ}$  and a possible second set striking  $150^{\circ}$  with both sets generally dipping within  $10^{\circ}$  of vertical ( $n=66$ ). Observed products of geochemical changes on fracture surfaces included a dark mineral (possibly manganese oxide), iron oxide, gypsum, and calcite precipitates. The unfractured matrix was slightly oxidized near fracture surfaces (RMT, 1992).

At a depth of 20 feet below the unit 1 sand, RMT (1992) observed a frequency of 3 to 4 fractures per foot with a spacing of about 0.30 feet in horizontal exposures. The frequency of fractures in vertical exposures was 2 to 3 per foot with a spacing of about 0.40 foot. Three fracture sets were observed with strikes of  $90^{\circ}$ ,  $130^{\circ}$ , and  $20^{\circ}$  with the majority of fractures near vertical ( $n=48$ ). Observed products of geochemical changes on fracture surfaces included iron oxide, gypsum, and calcite precipitates. Some oxidation of the unfractured clay matrix was observed near fracture surfaces (RMT, 1992).

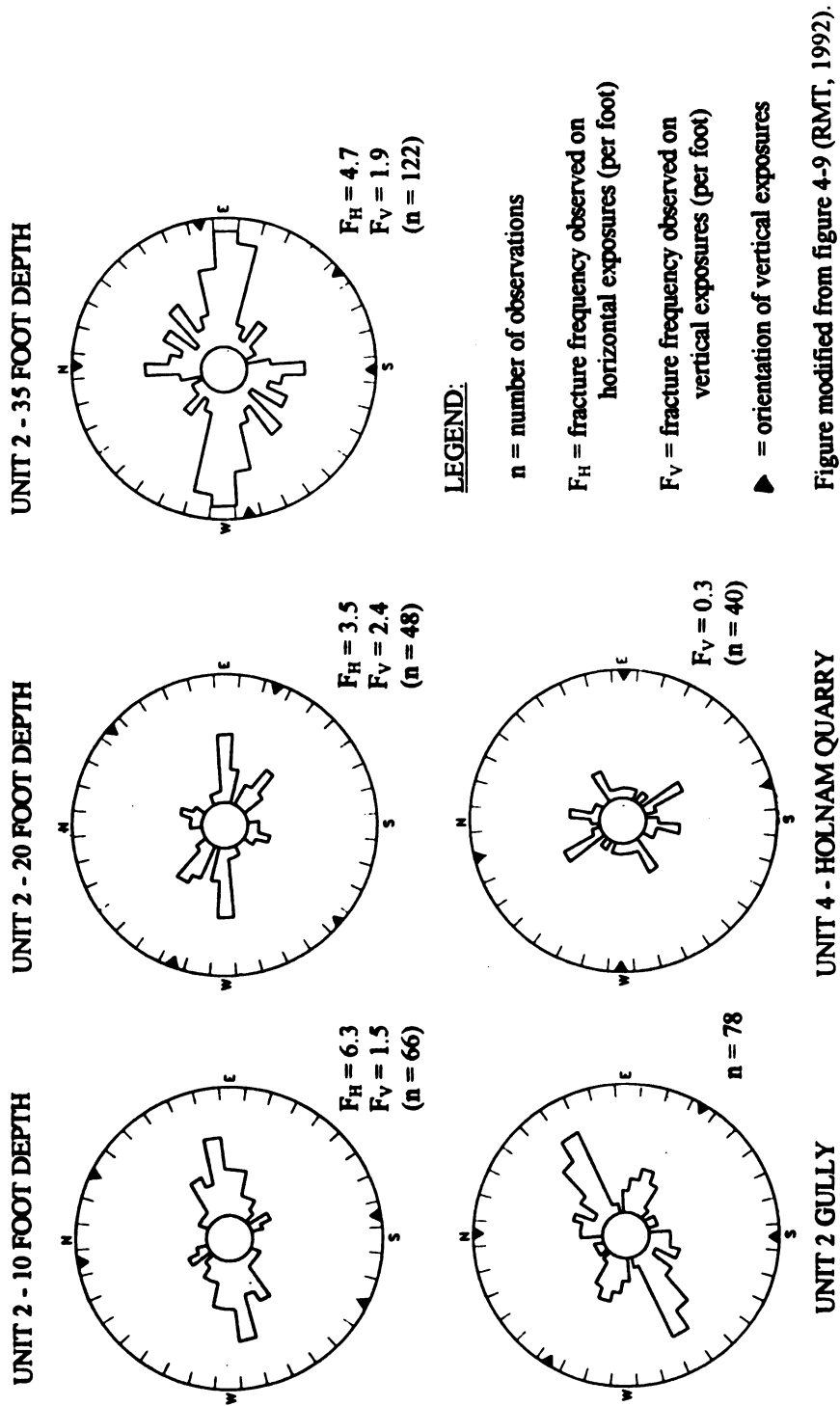


Figure 3. Fracture Orientations Measured by RMT (1992).

At the 35 foot depth the frequency and orientations of fractures was nearly identical to those at the 20 foot depth (n=122). Fracture surfaces rarely showed secondary mineral deposition, although the unfractured clay matrix was oxidized near fracture surfaces (RMT, 1992).

RMT made additional observations of the fracturing in the unit 2 clay in a gully eroded into the west wall of the quarry where approximately 20 to 25 feet of unit 2 was exposed. Fracture set orientations were observed striking 60°, 110°, and 15° (n=78). Thus these appear to be rotated somewhat from those in the test pits. Due to weathering, any precipitation on fracture surfaces or oxidation of the matrix could not be determined. Between 10 to 20 feet deep, fractures were spaced about 0.5 to 1.0 foot. Below 10 feet fractures were observed ranging from several feet to greater than 5 feet in length.

The unit 4 till is not visible in surface exposures at the ERC site. RMT (1992) observed exposures of this unit at a quarry approximately 10 miles to the south operated by Holman, Inc. near Dundee, Michigan. Near-vertical fractures were observed to have a frequency of 0.3 to 1.0 per foot with a spacing of about 1 to 3 feet. These fractures were observed to be up to 5 to 6 feet long. Fracture set orientations were observed striking 145°, 60°, and 5° (n=40). This unit was also weathered so any geochemical changes on fracture surfaces could not be determined.

Errors observed during measurement of fracture frequency and orientation data from other nearby quarries was reported by Chaivre (1972). Chaivre investigated measurement of fractures in Upper Silurian and Devonian rocks by different operators and methods. His results indicated that the size of the sample or number of fractures measured was important. In Chaivre's observations large fractures trended the same as smaller ones thus the more obvious ones could be measured exclusively as long as a sufficient number was available to measure. Also, he observed that some error was introduced due to operator variability in measurements and in selecting what to measure. Chaivre accounted for these sources of error and presented results of fracture set orientations for

jointing in the Dundee Limestone from three different quarries. Fractures generally strike 121 - 180° and 46 - 75° with near vertical dips.

Since Chaivre's results indicated that operator variability introduced error into the fracture measurements and the number and experience level of RMT personnel who measured the fractures is unknown, additional measurements were made during this study. Along the sloping exposed surface of unit 2, fracture measurements were made at 10, 20 and 35 foot depths (Figure 4). Along the vertical walls of eroded channels in the surface at each depth, a shovel was used to excavate the upper weathered material exposing unweathered portions of unit 2. In these unweathered sections visible fractures were measured. The criteria for selecting which fractures to measure was based on the partings along planar surfaces in the clay and on visible staining and oxidation along fracture surfaces.

Fractures were observed at varying orientations at the 10 foot depth with most having strikes ranging from 20 - 140° with a major group at 85° (n=23). These fractures were near vertical and most showed visible oxidation of the clay matrix along fracture surfaces. At the 20 foot depth two preferred orientations were evident (n=32). One fracture set ranged from 60 - 120° and the other near 10° with all fractures having near vertical dips. Most of these fractures showed visible oxidation of the clay matrix near fracture surfaces. Finally at the 35 foot depth most fractures were observed to strike around 35°, 90° or 125° (n=30). Measurements at this depth were made from two separate excavations, one oriented north-south and the other oriented east-west. Fractures at this depth ranged in dip from 57° to 90°.

In an eroded gully located to the west of the slope additional fractures were measured (Figure 5). Strikes of the near vertical fractures were measured at four depth intervals which included 0 - 10, 15 - 20, 20 - 25, and 25 - 30 feet. At the 0 - 10 foot depth fracture strikes are oriented almost randomly with small groups at 18 to 32° and 92 to 112° (n=15). At the 15 - 20

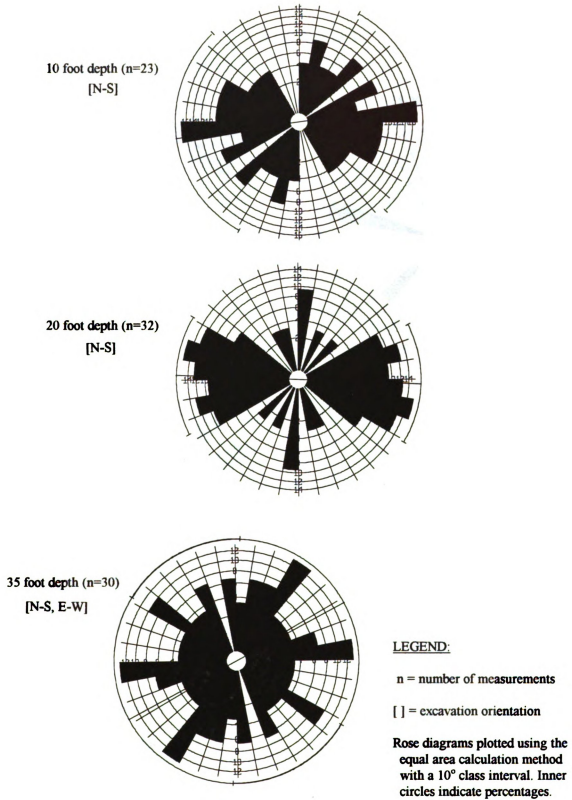


Figure 4. Fracture Orientations on the Sloping Surface of the Unit 2 Till.

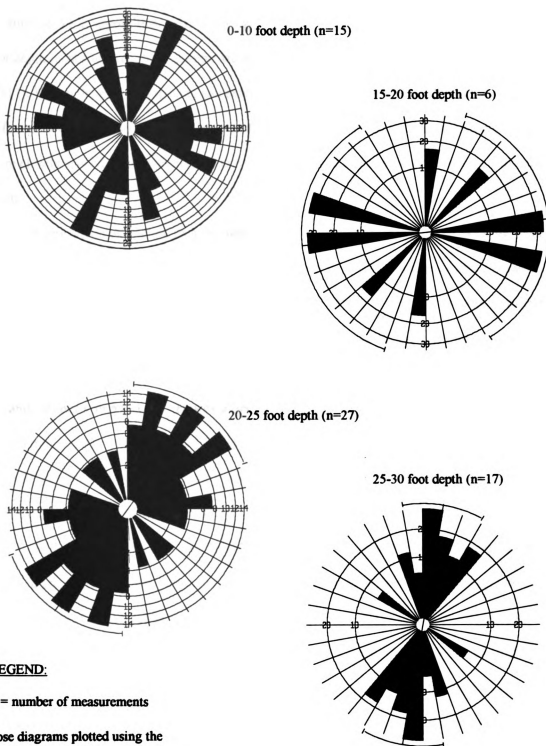


Figure 5. Fracture Orientations in the Gully of the Unit 2 Till.

foot depth most fractures strike at approximately  $5^{\circ}$  or  $100^{\circ}$  ( $n=6$ ). At the 20 - 25 foot depth most fractures strike at approximately  $32^{\circ}$  with a grouping ranging from  $2^{\circ}$  to  $70^{\circ}$  ( $n=27$ ). At the 25 - 30 foot depth most fractures strike at approximately  $10^{\circ}$  with a grouping ranging from  $350^{\circ}$  to  $32^{\circ}$  ( $n=17$ ). Within the gully the spacing and extent of the fractures could be determined. A larger set of fractures was spaced 1.5 to 2 feet apart and extended vertically up to 15 feet in length. A second more closely spaced set was observed 2 to 6 inches apart and extended vertically from 1 to 5 feet in length.

Comparison of fracture measurements made during this study with those made by RMT (1992) reveal that the orientations generally match. Along the sloping surface of unit 2 at the 10 foot depth both measurements indicate a major group near  $85^{\circ}$  and a grouping ranging from  $20^{\circ}$  to  $140^{\circ}$ . The wide range of these measurements is probably due to desiccation and weathering of the upper portions of the unit. At the 20 foot depth, both measurements indicate a major group near  $90^{\circ}$  and a minor group near  $10^{\circ}$ . However, measurements made during this study do not show a second minor group at  $130^{\circ}$ . At the 35 foot depth, both measurements show groups near  $90^{\circ}$ ,  $30^{\circ}$ , and  $130^{\circ}$ . Possibly more directions are evident in measurements made during this study since both north-south and east-west orientations were measured.

In the gully, RMT apparently combined measurements made from different depths, thus it is difficult to directly compare those measurements with ones made during this study. However, the major group RMT observed at  $60^{\circ}$  falls within the range observed at to 20-25 foot depth. The group RMT observed at  $110^{\circ}$  falls close to the measurements obtained at the 0-10 and 15-20 foot depths. Finally, the group observed at  $15^{\circ}$  closely matches the average of the measurements obtained at the 25-30 foot depth. The fracture spacings observed during this study generally agree with those made in the gully by RMT.

Overall the measurements made along the sloping surface of unit 2 indicate a general east-west trend in fracture orientations. The measurements made in the adjacent gully do not show this same trend. However, the orientation of the exposed surfaces in the gully may have contributed to the absence of an east-west group of fracture orientations. For example, at the 25-30 foot depth the gully wall trended  $300^{\circ}$ , thus, an east-west trending set of fractures would have likely been missed.

## **SIMULATION OF GROUND-WATER FLOW**

### **Conceptual Model**

The conceptual model is the first step in model design and includes (1) definition of units, (2) water budget, and (3) definition of flow system. The purpose of a conceptual model is to organize the available data in a way that represents the field situation as closely and as simply as possible, since the actual field situation can not be duplicated exactly. The model boundaries include the ARL site and most of the proposed hazardous waste management facility area. Since no natural hydrologic boundaries exist around this area the boundaries must be extended enough away from the main area of interest so as not to affect simulation results in the central model area.

The layers of the model consist of the units described by RMT (1992). The upper layer will consist of the unit 1 sand. Water can enter or exit this layer from the boundaries, creeks, drains, and the underlying layer. Water can also enter in the form of precipitation. The second layer consists of the unit 2 till and the unit 3 lacustrine clay. These two units were combined due to their similar hydraulic conductivities. Water can enter or exit this layer from the overlying and underlying layers. The third layer consists of the unit 4 till. Water can enter or exit this layer from



the overlying and underlying layers. The fourth layer consists of the bedrock limestone unit. Water can enter or exit this layer from the boundaries and the overlying layer. Water can also enter this layer in the form of precipitation at the quarry location.

Ground-water flow in the unit 1 sand is primarily towards Sugar Creek and the York, Augusta, and Murray Drains. Ground-water flow is primarily vertical in the clay units 2, 3, and 4. Ground-water flow is primarily towards the south in the Dundee Limestone.

Ground-water flow is presumably faster within the fractures than within the intervening matrix material as indicated by the presence of tritium at depth. To use a standard finite difference code such as MODFLOW (McDonald and Harbaugh, 1988), a fractured material must be represented as an equivalent porous media in which primary and secondary hydraulic conductivities are replaced with an effective hydraulic conductivity. With an appropriate representative elementary volume of material, the values for effective parameters can be determined using aquifer tests, water balances or inverse models, or field descriptions of fracture apertures and interconnections (Anderson and Woessner, 1992). However, utilization of these techniques at the Milan study site was not possible during this study.

At this site, fracture frequency and orientations have been measured, however, Long and Witherspoon (1985) found in their studies that this information alone was inadequate to determine permeability or whether the system behaved as a porous media. Field and laboratory measurements of hydraulic conductivity were conducted at this site in each unit by RMT (1992) and can be used to estimate effective hydraulic conductivities. Knowledge of these values and the selection of a cell size much larger than the fracture spacing will be assumed to be adequate to represent this system as an equivalent porous media. The accuracy of this assumption will be indicated by how well simulated heads match measured heads.

## **Numerical Model**

### **Model Grid and Layers**

The grid spacing used in the model must be large enough to prevent excessive computer storage requirements and computation time, yet small enough to represent the system accurately (Anderson and Woessner, 1992). Within most of the study area, the large number of soil borings and monitoring wells located approximately 200-300 feet apart provides good information on lithologic characteristics and water levels. However, these soil borings and monitoring wells are concentrated within the ARL and proposed waste reception and landfill areas. Outside of these areas lithologic and hydrologic information is limited with available borings 800 or more feet apart. Based on the high and low data densities, a grid spacing of 150 feet was chosen to represent flow conditions within this area.

The axes in the model need to be aligned with the principal directions of hydraulic conductivity ( $K_x$ ,  $K_y$ , and  $K_z$ ). If the study site shows some trend other than east-west and north-south, the axes of the model need to be rotated. Since fracture measurements made during this study and by RMT indicate a general east-west trend, the model grid does not need to be rotated. Therefore the model grid consists of 33 rows and 50 columns and covers 1.33 square miles approximately 2 miles east of the city of Milan. Vertically the model consists of four layers with layer 1 representing the upper unit 1 sand, layer 2 representing the upper unit 2 till and the unit 3 lacustrine clay, layer 3 representing the lower unit 4 till, and layer 4 representing the bedrock limestone unit. The bedrock shale unit is implicitly included in the leakance term between layers 3 and 4.

## **Boundary Conditions**

Boundaries of ground-water-flow systems can be physical or hydraulic. Physical boundaries are formed by an impermeable body of rock or a body of surface water. Hydraulic boundaries include ground-water flow divides and streamlines. These boundaries are represented in a mathematical model by the following types of conditions: 1) specified head boundaries where the head in the cell is given, 2) specified flow boundaries where the flux across the cell boundary is given, and 3) head-dependent flow boundaries where flux across a cell boundary is determined using a specified head in the cell (Anderson and Woessner, 1992). External boundaries for the model were chosen based on the conceptual model outlined above. External boundaries for the model area were chosen to be distant from the main area of interest to remove effects of the specified boundary conditions. The boundaries of the model extend approximately 4,800 feet east of ARL, 600 feet west of ARL, 1,050 feet north of ARL, and 1,950 feet south of ARL.

Layer 1 boundaries were specified head on all sides except where Sugar Creek intercepted the north and east boundaries and along the south boundary at the quarry location. The river cells were assigned head-dependent flow boundaries. The cells at the quarry were assigned specified flow boundaries with flow equal to zero, therefore these were no-flow boundaries. The quarry excavation extends through units 1, 2, and 3, thus no flow is possible across this excavation. The upper boundary of layer 1 was assigned as specified flow equal to the average recharge rate for the area. Layer 2 and 3 boundaries were specified flow on all sides with flow equal to zero. Since flow in these units is primarily vertical it is assumed that no flow is possible in the horizontal direction across the external boundary. Layer 4 boundaries were specified head boundaries on all sides. The lower boundary of layer 4 was assumed to be a no-flow boundary.

## **Sources and Sinks**

Sources and sinks are another avenue for water movement into and out of the model area. Sources and sinks are represented by the same types of boundary conditions described above and can be considered as internal boundary conditions. Specified head, specified flow, with flow equal to zero, and head-dependent flow boundaries were used to define interior sources and sinks in the model area. For layer 1 no-flow cells were assigned to the quarry location. Head-dependent flow cells were assigned to the locations representing Sugar Creek, and the York, Augusta, and Murray Drains. For layer 2 and 3 no-flow cells were assigned to the quarry location. For layer 4 specified head cells were assigned to the quarry location.

## **Parameter Values**

Input parameters required for the model include 1) the geometry of model layers, 2) ground-water recharge rates, and 3) the aquifer hydraulic properties. Each of these will be described in the following paragraphs.

## **Model Layers**

Information on unit thicknesses was taken from the well and boring logs prepared during earlier site investigations (RMT, 1992; Neyer, Tiseo and Hindo, 1987; and McNamee, Porter and Seeley, 1965). The top of layer 1 was taken to be the water table. This surface was defined using data from water level measurements in 41 wells, as well as, 23 river and 59 drain elevations. Well data was averaged from seven measurements taken between 12/10/87 and 6/1/88. This range was chosen since it bracketed March 16, 1988 when a large number of monitoring wells at the site were measured. An average of head measurements over a range of time more accurately represents

steady-state conditions than a single point in time. The measurements for any well installed immediately prior to or during this range were inspected for the point at which equilibrium was reached. Only those measurements for the well at equilibrium were included in the initial estimate of the water table.

The bottom of layer 1 was defined using 454 measurements from well and boring logs. The bottom of layer 2 was defined using 296 measurements from well and boring logs. The bottom of layer 3 was defined using 140 measurements, of which 24 were from well and boring logs and 116 were taken from Figure 4-13 (RMT, 1992). The bottom of layer 4 was taken to be 100 feet beneath the bottom of layer 3 based on Snow's (1967) observations.

### **Ground-Water Recharge Rates**

RMT (1992) estimated a recharge value of 4.5 inches per year based on mass balance calculations for the site and on literature values for similar soils in similar climatic regimes. This constant value was used for layer 1. This value is very close to the range of 5.0 to 5.2 inches per year predicted for this area using the analysis relating base flow characteristics of streams to land use and basin characteristics in the Lower Peninsula of Michigan determined by Holtschlag (1994).

### **Hydraulic Properties**

The hydraulic properties, including hydraulic conductivity, transmissivity, leakance, and streambed and drain conductances, control simulated ground-water flow through and between model layers. These properties were calculated as the product of a matrix containing initial estimates and a constant determined during model calibration. The methods and information used to determine the initial estimates are described in the following paragraphs.

The hydraulic conductivity of layer 1 and the transmissivities of layers 2 and 3 were determined by assigning hydraulic conductivities to each lithology described in the well and boring

logs for each layer (Table 2). Using the procedures described by McDonald and Harbaugh (1988, p. 5-2), effective hydraulic conductivities were computed for each location. These values were then contoured over the model area. For layers 2 and 3, these values were multiplied by the layer thickness to determine transmissivity. Initial estimates of horizontal hydraulic conductivity for layer 1 range from 9.5 to 35.3 ft/d. The initial estimate for transmissivity of layer 2 ranges from  $2.8 \times 10^{-4}$  to  $2.03 \times 10^{-2}$  ft<sup>2</sup>/d. The initial estimate for transmissivity of layer 3 ranges from  $1.905 \times 10^{-5}$  to  $3.276 \times 10^{-2}$  ft<sup>2</sup>/d.

Table 2. Hydraulic Conductivities Assigned to Strata Codes.

HYDRAULIC CONDUCTIVITY (feet per day)	STRATA CODE	LITHOLOGIC DESCRIPTION
0.00028	13	sandy clay / sandy, silty clay
	16	clay and sand / silty, clay
	19	till
	40	top soil
0.0028	15	silt / sandy silt
0.28	28	sand with clay
28	20	sand / sandy fill
	21	fine sand / silty sand
280	25	sand and gravel

The initial estimate for transmissivity of layer 4 was taken from Figure 4-14 (RMT, 1992). This figure shows bedrock hydraulic conductivity derived from Snow (1967). These values were multiplied by the assumed 100 foot thickness of the layer. The initial estimate for transmissivity of layer 4 consisted of zones equaling 1.42, 14.2 and 142 ft<sup>2</sup>/d.

Leakances were determined using a similar method. Hydraulic conductivities were assigned to each lithology described in the well and boring logs for each layer. An effective vertical hydraulic conductivity was computed for each location using the equation described by Freeze and Cherry (1979, p. 34).

$$K_z = d / ((d_i / K_i) + (d_{i+1} / K_{i+1}))$$

where  $K_z$  = effective vertical hydraulic conductivity,

$d$  = thickness of layered system,

$d_i$  = thickness of layers above and below contact, and

$K_i$  = hydraulic conductivity of layers above and below contact.

The leakance equals the vertical hydraulic conductivity divided by the thickness of the layered system ( $d$ ) and has units of  $1/T$ . Thus, for example for layer 1, the leakance equaled:

$$1/((d_1/K_1) + (d_2/K_2))$$

The leakance for layer 3 included vertical hydraulic conductivity and thickness values for the Traverse Shale. There was none for layer 4 since this was the bottom layer of the model. The initial estimate of leakance for layer 1 ranged from  $4.14 \times 10^{-6}$  to  $2.8 \times 10^{-4} / d$ . The initial estimate of leakance for layer 2 ranged from  $5.17 \times 10^{-9}$  to  $5.27 \times 10^{-6} / d$ . The initial estimate of leakance for layer 3 ranged from  $5.16 \times 10^{-9}$  to  $2.91 \times 10^{-5} / d$ .

In the model, streambed conductance is the product of the hydraulic conductivity of the streambed materials, stream length, and stream width, divided by the streambed thickness (McDonald and Harbaugh, 1988, p. 6-5). These values were assumed to be constant within the model area. Stream width, as measured by RMT (1992) in December 1987, was approximately 10.5 ft. Stream length is equal to the length of the cell (150 ft) and streambed thickness is arbitrarily assumed to be 1 ft. Hydraulic conductivity of the streambed materials was assumed to be 0.5 ft/d. Drain conductances are calculated in the same way as for streams. The drain width, as measured by RMT (1992) in December 1987, was approximately 7.8 ft. Drain length is equal to

the length of the cell (150 ft) and drain thickness is arbitrarily assumed to be 1 ft. Hydraulic conductivity of the drain was assumed to be 0.2 ft/d. Streambed conductances equaled 800 ft<sup>2</sup>/day and drain conductances equaled 200 ft<sup>2</sup>/day.

### **Model Calibration**

Model calibration requires adjustments to input parameters to reduce the difference between measured and simulated hydraulic heads. The nonlinear regression method, MODFLOWP, developed by Cooley and Naff (1990) and modified by Hill (1992) was used with MODFLOW to calibrate the model. In MODFLOWP, optimal parameter values are calculated that minimize the sum of squared errors. Scaled sensitivities are also computed by MODFLOWP and give an indication of how much a change in the parameter value will affect the simulated heads. A low sensitivity indicates little effect on the simulated heads and that the parameter can not be accurately estimated by regression.

Parameter estimation was used to determine the optimal estimates for the multiplicative constants for matrices containing hydraulic conductivity of layer 1, transmissivity of layer 4, and leakances for layers 1, 2, and 3. The transmissivities of layers 2 and 3, as well as the streambed and drain conductances had very low sensitivities and could not be estimated by MODFLOWP. Initially the multiplicative constants were assigned a value of one.

Weights were assigned to the head measurements for each layer. In general more weight was assigned to measurements whose measurement variances were low. A standard deviation, which when squared equals the variance, was calculated for each well from the measurements collected from 12/10/87 to 6/1/88. A total of 41 wells were included for layer 1, 26 for layer 2, 6 for layer 3, and 14 for layer 4. An additional 8 measurements for cells at the quarry location for layer 4 were included and assigned a standard deviation of 0.22 which was the lowest standard



deviation calculated for the wells in each unit. As an example, water levels for well 152 B measured on 10-Dec-87, 5-Jan-88, 22-Feb-88, 16-Mar-88, 4-Apr-88, 11-May-88, and 1-Jun-88 were 672.72, 673.33, 673.62, 673.52, 673.64, 672.31, and 671.67 feet respectively (RMT, 1992). The calculated standard deviation for these measurements is 0.70. The weight, which is the inverse of this value squared, was 2.04 for well 152 B in layer 2.

Optimal parameter estimates are given in Table 3. MODFLOWP indicated that all of the leakances were correlated. Correlation between parameters complicates the estimation and interpretation of parameter values. Coordinated changes in parameter values would produce identical results in terms of the calibration criteria (Hill, 1992). Thus the leakances can not be uniquely estimated.

The estimated values for the hydraulic conductivity of layer 1, the transmissivity of layer 4, and the leakances for layers 1, 2, and 3 were computed as the matrix of initial estimates times the optimal parameter value determined by nonlinear regression. The resulting range in hydraulic conductivity for layer 1 is 6.07 to 22.6 ft/d, in transmissivity for layer 4 is 13.4 to 1339 ft<sup>2</sup>/d, in leakance for layer 1 is  $1.1 \times 10^{-5}$  to  $8.02 \times 10^{-4}$  /d, in leakance for layer 2 is  $1.08 \times 10^{-10}$  to  $1.1 \times 10^{-7}$  /d, and in leakance for layer 3 is  $1.53 \times 10^{-10}$  to  $8.6 \times 10^{-7}$  /d (Table 1).

Table 3. Optimal Parameter Estimates.

PARAMETER	INITIAL ESTIMATE	OPTIMAL ESTIMATE
Hydraulic Conductivity of Layer One	1.0	0.639
Transmissivity of Layer Four	1.0	9.43
Leakance for Layer One	1.0	0.0395
Leakance for Layer Two	1.0	0.0209
Leakance for Layer Three	1.0	0.0296

### Simulation Results

Generally, simulated heads were consistent with measured heads. Near the model boundaries where no water level data was available, initial heads were estimated. In layer 1 the greatest differences between simulated and estimated heads (-27 to 10 ft) are near the model boundaries and mostly to the west. Within most of the central model area simulated heads are within 4 feet of measured values (Figure 6). In layer 2 the greatest differences between simulated and estimated heads (-20 to 29 ft) are near the model boundaries. Within most of the central model area simulated heads are within 5 feet of measured values (Figure 7). In layer 3 the greatest differences between simulated and measured heads (-28 to 10 ft) are near wells 204, 501, and 502. Within most of the central model area simulated heads are within 8 feet of measured values (Figure 8). In layer 4 the greatest differences between simulated and estimated heads (-66 to 51 ft) are near

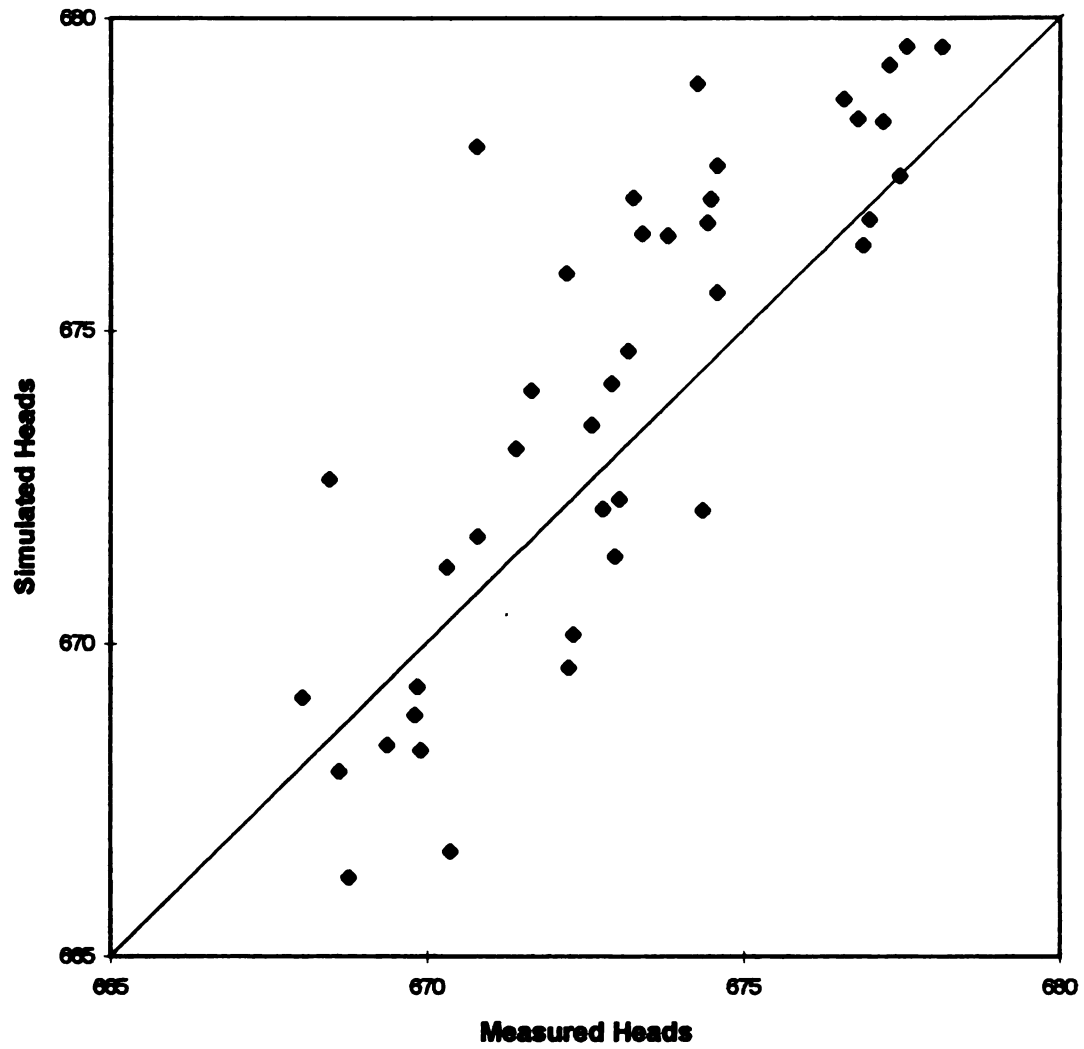


Figure 6. Relation Between Measured and Simulated Heads for Layer One.

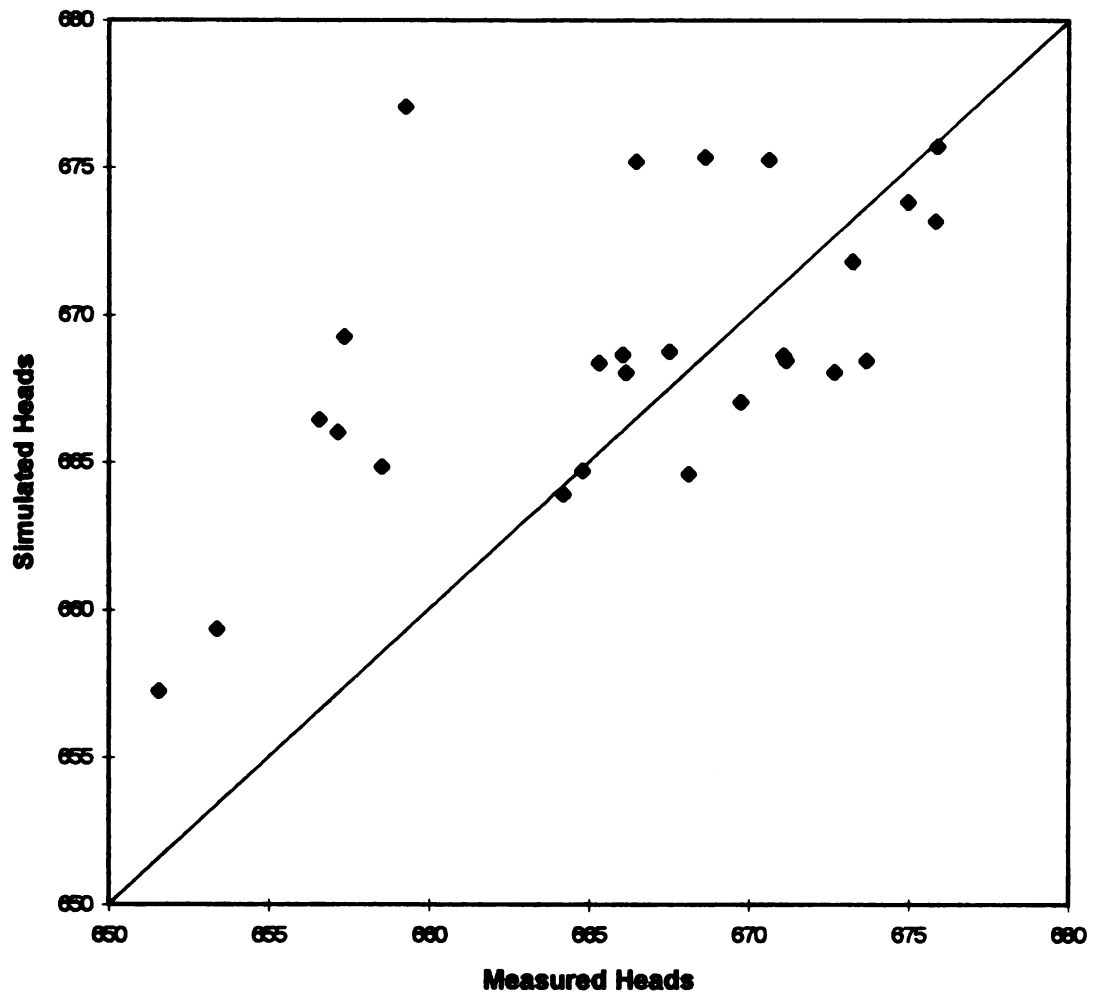


Figure 7. Relation Between Measured and Simulated Heads for Layer Two.

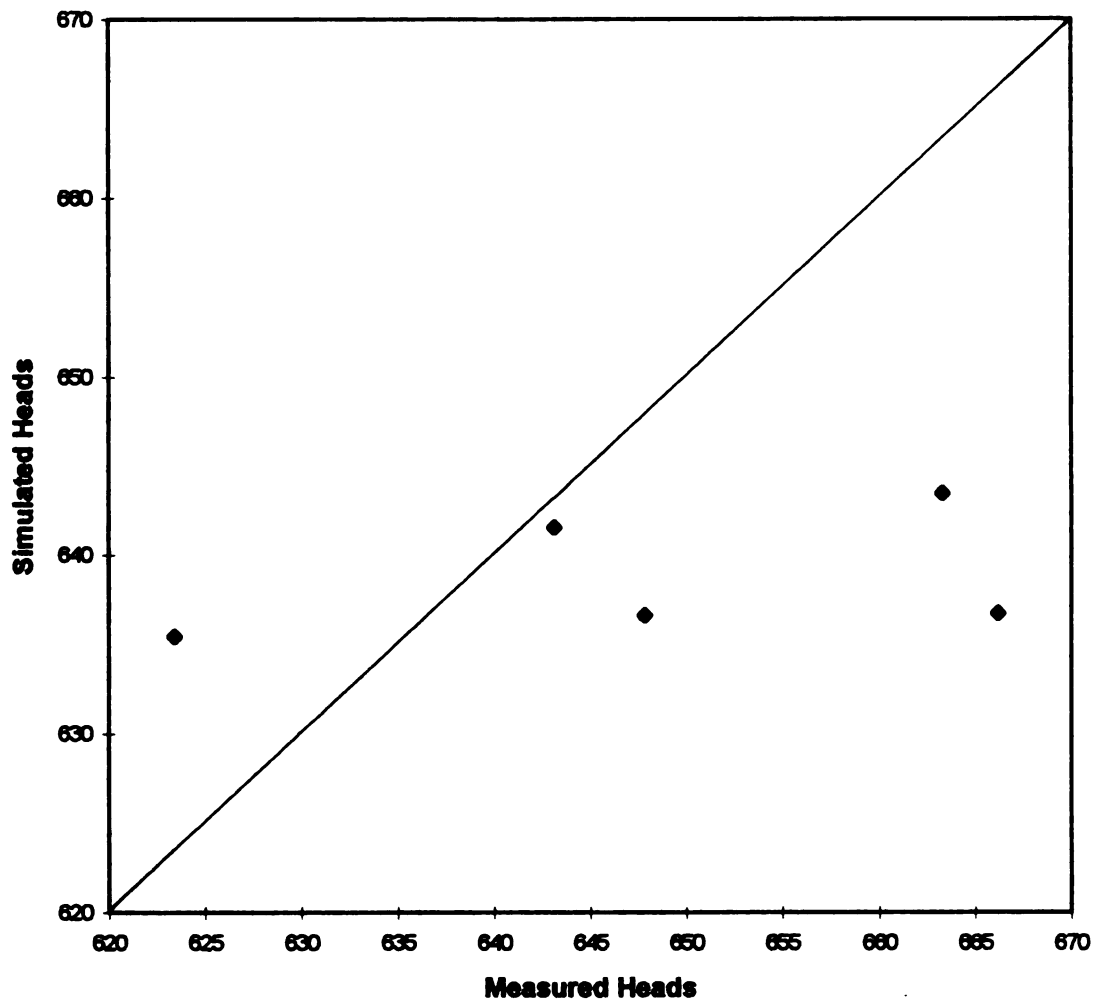


Figure 8. Relation Between Measured and Simulated Heads for Layer Three.

the model boundaries and mostly to the east. Within most of the central model area simulated heads are within 10 feet of measured values (Figure 9).

Generally, estimated ranges for the hydraulic parameters are consistent with measured field values (Table 1). Estimated values for the layer 1 sand were higher than the field measured values, however, when compared to literature values (Freeze and Cherry, 1979) the estimated values seem reasonable for a unit that is primarily sand. Estimated values for layer 2 are within the range of field measured values. Estimated values for layer 3 are lower than the field measured value. However, only one field measurement was collected and it is not known whether this value is representative of the unit or not. Comparison of these estimated values with literature values (Freeze and Cherry, 1979) show that they seem reasonable for a unit that is primarily glacial till. Finally, estimated values for layer 4 are higher than the field measured values. However, Snow (1967) estimated an average hydraulic conductivity value of 5.67 ft/d for the limestone which is in closer agreement with the model estimated values.

### **Particle Tracking**

Particle tracking provides a way to investigate the ground-water flow directions. Cell-by-cell flows are output from MODFLOW and used as input for the particle tracking program, MODPATH, documented by Pollock (1989). MODPATH was used to track the particles as they moved from cell to cell throughout the steady-state three-dimensional flow system. In a particle tracking simulation, hypothetical particles are placed on the faces of a cell or within a cell and tracked for a specified amount of time or until they leave the ground-water flow system. The path of the particle as well as the stopping location can be determined as it moves through the system. Particles can leave the ground-water flow system at the boundaries or at sinks such as rivers.

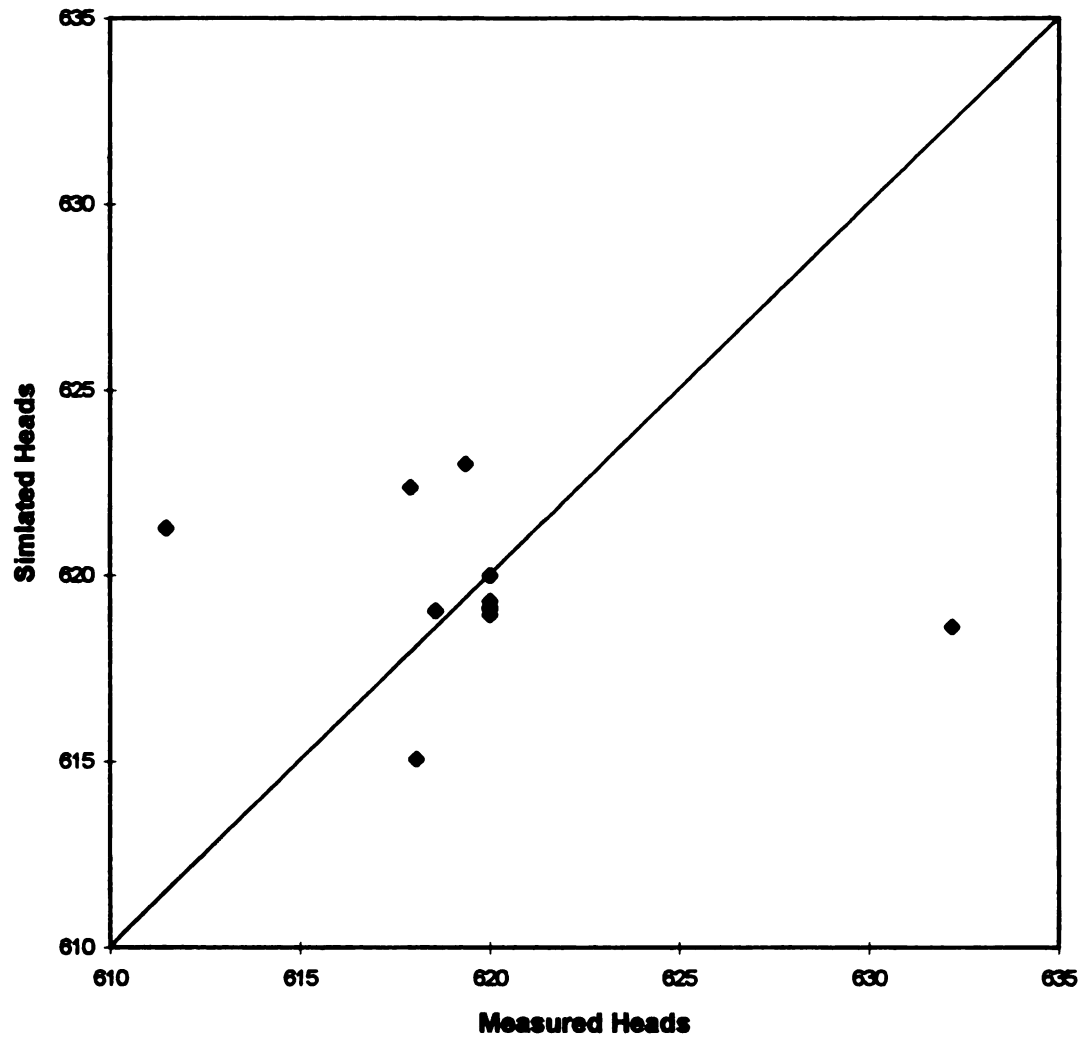


Figure 9. Relation Between Measured and Simulated Heads for Layer Four.

Particle tracking was used to investigate the presence of tritium at depth and the proposed upward flow directions at the ARL site.

### **Tritium Data**

Large amounts of tritium, a radioactive isotope of hydrogen, were first released into the atmosphere around 1952 during a period of atomic testing. Before that date, Payne (1972) estimated that natural tritium concentrations in precipitation ranged from 5 to 20 tritium units. Using the half-life of tritium of 12.3 years, ground water that is older than 45 years old would now have a tritium concentration less than 2.0 tritium units (TU). Ground water (tritiated water) that has been recharged since that date would be expected to have tritium concentrations greater than 2.0 TU.

At the study site in southeastern Michigan, Foote (1989) collected samples from 17 different elevations in a soil boring and from 15 nested wells. In the extracted water samples from the soil boring tritiated water was found at depths exceeding 22 m, while non-detectable values were found as shallow as 8 m depth. In the ground-water samples from the nested wells, tritiated water was found at depths of at least 25 m in the glacial sediments, while non-detectable values were found as shallow as 14 m depth (Foote, 1989).

Particle tracking was used to determine whether the model could account for fractures in the clay units and explain the presence of tritium at depth. For this simulation four particles were placed on the upper face of each active cell not including constant head cells in layer 1 and tracked forward until they left the ground-water flow system. Thus, pathlines and ending locations were determined for 5,944 particles. Of these particles, 19 % were removed from the ground-water flow system in layer 4. The rest were removed at the boundaries, drains, and river of layer 1. That most



particles leave the ground-water flow system in layer 1 is expected due to the evidence that ground-water flow in the upper sand unit is primarily towards the surface and subsurface drains and river.

For those particles that traveled through layers 2 and 3 before being removed from the ground-water flow system in layer 4, the travel times were determined. The minimum travel time to layer 2 was 15.2 years, while the minimum travel time to layer 3 was 6000 years. Thus the model does allow for recent water to move to the upper till unit and lacustrine clay unit. However, it does not allow for recent water to move down to the lower till unit as was observed to be the case with Foote's (1989) measured tritium concentrations. These particle-tracking results show that the model does not adequately account for the local flow systems created by fractures in the till units.

### **Proposed Upward Flow**

To investigate the proposed upward ground-water flow direction at the ARL site, three particle tracking simulations were run. Twenty-five particles were placed on the upper face of each cell not including constant head cells in layers 2, 3, and 4. In each simulation particles were tracked forward to determine whether they moved upward or downward. In the first simulation with particles on the upper face of layer 2 which is also the lower face of layer 1, 2 % stop in layer 1 at the boundary, drain, and river cells. The rest stop in layer 4. In the second simulation with particles on the upper face of layer 3 all particles travel downward and stop in layer 4. In the third simulation with particles on the upper face of layer 4, all particles stop in layer 4. Thus particle tracking indicates that the ground water is flowing downward within all of the model area.

## **Analysis of Fractures**

The presence of fractures complicates the interpretation of ground-water flow in this area. Fractures allow ground water movement at faster rates than possible through the clay matrix. The above ground-water flow model treats the fractured clay units as equivalent porous media. At a large enough scale the effect of fractures is minimized and an effective hydraulic conductivity can be determined for the fractured matrix. However, the above particle tracking results indicate that the model does not adequately represent the fractured units since water can not get to the depth that tritium has been detected in a short enough time. An additional series of runs were done to examine the effect of increasing the hydraulic conductivity of the fractured units by allowing greater leakage between them. After increasing the leakage, these new simulated heads were compared to the simulated heads calculated by parameter estimation.

In seven groups of runs, the following leakages were modified to determine the effect: 1) leakage between layer 1 and layer 2 ( $k_{v1}$ ), leakage between layer 2 and layer 3 ( $k_{v2}$ ), and leakage between layer 3 and layer 4 ( $k_{v3}$ ); 2)  $k_{v1}$ ; 3)  $k_{v2}$  and  $k_{v3}$ ; 4)  $k_{v3}$ ; 5)  $k_{v1}$  and  $k_{v3}$ ; 6)  $k_{v2}$ ; 7)  $k_{v1}$  and  $k_{v2}$ . In each group the leakages were multiplied by 0.01, 0.1, 5.0, 10.0, and 50.0. The runs using 0.01 and 0.1 were done in order to determine the effect of decreasing the leakage. The results are shown in Table 4. The values were calculated by taking the simulated head value minus the measured value for the well and squaring the result.

The last column shows the value using simulated heads determined by parameter estimation. In each case except for group two, layer 1 heads were improved by increasing the leakage. Layer 2 simulated heads were improved in group four. Layer 3 heads were improved in groups one, two, and part of group six. Layer 4 heads were only improved when the leakage was

Table 4. Effects of Changing Leakances on Simulated Heads.

LEAKANCE CHANGED	LAYER NUMBER	LEAKANCE MULTIPLIER OF 0.01	LEAKANCE MULTIPLIER OF 0.10	LEAKANCE MULTIPLIER OF 5.0	LEAKANCE MULTIPLIER OF 10.0	LEAKANCE MULTIPLIER OF 50.0	FINAL MODEL
kv1,kv2,kv3	1	5.84	5.83	5.75	5.67	5.19	5.82
	2	70166.63	36.78	41.52	42.55	45.54	38.39
	3	2927.72	322.15	297.25	285.84	243.47	307.46
	4	22.81	22.83	25.58	29.91	95.85	23.21
kv1	1	5.84	5.83	5.82	5.82	5.82	5.82
	2	1601.38	416.49	84.97	96.09	106.25	38.39
	3	833.94	524.83	278.85	275.21	272.25	307.46
	4	22.82	22.99	23.26	23.26	23.27	23.21
kv2,kv3	1	5.84	5.83	5.78	5.76	5.72	5.82
	2	104.10	93.39	165.16	396.34	1123.82	38.39
	3	338.21	290.14	418.79	505.54	684.34	307.46
	4	22.79	22.83	24.55	25.67	28.66	23.21
kv3	1	5.83	5.83	5.81	5.81	5.81	5.82
	2	100.31	74.04	34.41	34.20	34.11	38.39
	3	876.03	486.63	687.34	784.53	876.38	307.46
	4	22.81	22.92	23.32	23.34	23.35	23.21
kv1,kv3	1	5.84	5.83	5.81	5.81	5.81	5.82
	2	83.98	60.61	79.66	92.46	105.30	38.39
	3	312.53	239.54	660.30	764.20	867.99	307.46
	4	22.80	22.88	23.40	23.43	23.46	23.21
kv2	1	5.84	5.83	5.80	5.80	5.79	5.82
	2	103.58	89.69	50.89	67.91	91.52	38.39
	3	901.25	780.56	230.39	278.76	354.97	307.46
	4	22.80	22.84	23.72	23.88	24.05	23.21
kv1,kv2	1	5.84	5.83	5.79	5.78	5.77	5.82
	2	37.60	31.31	62.37	76.75	99.64	38.39
	3	903.37	796.77	326.43	523.95	861.46	307.46
	4	22.79	22.84	23.99	24.33	24.79	23.21

decreased. These results indicate that simply increasing the leakage to better represent the increased flow possible through the fractures does not improve the model.

## **MODEL LIMITATIONS**

The ground-water flow model simulates steady-state conditions within the model area. All inputs are assumed to be constant throughout the simulation. Changes in recharge or other parameters over time can not be represented by this model. The model combines primary and secondary hydraulic conductivities by treating the fractured units as equivalent porous media. To more accurately represent this area and the small-scale localized flow systems a model that includes fractures should be considered.

The model boundaries were simulated as constant head cells for layers 1 and 4 and determined on the basis of water level measurements in nearby wells. The solution is constrained by and dependent upon the values chosen for these boundaries. More detailed water level measurements should be obtained to more accurately represent the boundaries. To investigate the effect of these boundaries on the interior of the model these values should be changed and moved. An even better technique would be to first model a larger area using natural ground-water flow divides and physical boundaries. Then successively smaller areas could be modeled using output from the larger model to determine the boundary conditions where natural and physical boundaries do not exist. Additionally modeling a larger area would enable inclusion of pumping wells as stresses on the ground-water system in the area and improve the calibration.

The model cells are assumed to represent homogeneous hydraulic properties. Local flow systems smaller than the cell dimensions can not be represented. The hydraulic properties of the layers were determined using existing well and soil boring data. The estimates for the layers could

be further improved by collection of more lithologic data. Determination of effective hydraulic conductivities for the fractured units could be improved by more aquifer tests and more detailed fracture measurements.

The accuracy of the particle tracking results depend on the assumptions and accuracy of the ground-water flow model and the estimate of effective porosity of the flow system. The particle tracking assumes no dispersion or diffusion. Similarly the results of the analysis of decreasing and increasing leakage to simulate the presence of fractures depend on the accuracy of the ground-water flow model.

## **SUMMARY**

Fractures provide a means for ground water movement and contaminant migration at faster rates than possible through the matrix alone. At the study site, Augusta Development Corporation has proposed locating a hazardous waste management facility overlying a fractured clay till unit. Investigation of the role of fractures on ground-water flow is necessary to ensure the protection of water quality in this area. A four layer steady-state ground-water flow model was developed to simulate the ground-water flow system in this area.

The glacial deposits underlying the proposed facility site can be divided into four units (RMT, 1992). These units include: 1) surficial lacustrine deposits, 2) upper glacial till unit, 3) lacustrine silty clay deposits, and 4) lower glacial till unit. Lacustrine/outwash lenses are found within the glacial till units. Surface exposures reveal that the glacial till units are weathered and fractured. These glacial units overlie the Traverse Shale and the Dundee Formation. The contact between the Dundee Formation and the overlying Traverse Shale crosses the study area from southwest to northeast.

RMT's (1992) investigations reveal that ground-water flow directions are towards the southeast and northeast. Wetlands lie on top of the unit 2 clay and within the unit 1 sand. Their hydrology is probably influenced most by recharge from precipitation, ground-water flow in the sand, and ground-water discharge to adjacent surface water bodies. Ground-water flow is primarily horizontal through unit 1 and is generally towards the surface drains, subsurface drains, and streams. Flow is primarily vertical in units 2, 3, 4, and the Traverse Shale. Ground-water flow is towards the south in the Dundee Limestone.

The ground-water flow model developed for this area consists of four layers with layer 1 representing the upper unit 1 sand, layer 2 representing the upper unit 2 till and the unit 3 lacustrine clay, layer 3 representing the lower unit 4 till, and layer 4 representing the bedrock limestone unit. The bedrock shale unit is implicitly included in the leakance term between layers 3 and 4. The model area is a rectangular grid covering 1.33 square miles approximately 2 miles east of the city of Milan in southeastern Michigan. This area is divided into a grid of equally spaced cells in 33 rows and 50 columns with each cell 150 feet on a side.

The model was calibrated using nonlinear regression. The estimated values for the hydraulic conductivity of layer 1, the transmissivity of layer 4, and the leakances for layers 1, 2, and 3 were computed as the matrix of initial estimates times the optimal parameter. The resulting range in hydraulic conductivity for layer 1 is 6.07 to 22.6 ft/d, in transmissivity for layer 4 is 13.4 to 1339 ft<sup>2</sup>/d, in leakance for layer 1 is  $1.1 \times 10^{-5}$  to  $8.02 \times 10^{-4}$  /d, in leakance for layer 2 is  $1.08 \times 10^{-10}$  to  $1.1 \times 10^{-7}$  /d, and in leakance for layer 3 is  $1.53 \times 10^{-10}$  to  $8.6 \times 10^{-7}$  /d.

Generally, simulated heads were consistent with measured heads. Within most of the central model area simulated heads are within 4 feet of measured values for layer 1, within 5 feet of measured values for layer 2, within 8 feet of measured values for layer 3, and within 10 feet of measured values for layer 4.

Particle tracking was used to investigate the observed distribution of tritium at depth. Foote (1989) collected samples from within a soil boring and from nested wells and found tritiated water at depth beneath non-tritiated water. The particle tracking results indicate that water can not reach layer 3 where tritium was detected within a reasonable amount of time. Particle tracking was also used to investigate the upward hydraulic gradient beneath the Arkona Road Landfill proposed by RMT (1992). The results show that all ground water movement is downward within the model area. Finally, leakances between layers were systematically varied to simulate the effect of fractures and to observe effects on simulated heads. However the results indicate that simply increasing the leakances between layers is not sufficient to improve the simulated heads.

## CONCLUSIONS

At the Milan study site, approximately 2.5 miles east of the city of Milan in southeastern Michigan, a four layer steady-state ground-water-flow model was developed to simulate ground water flow in an attempt to explain the presence of tritium at depth observed by Foote (1989) and the upward hydraulic gradient beneath the Arkona Road Landfill proposed by RMT (1992). Simulation results using particle tracking indicate that water recharging this area can not travel from the land surface to the depth where tritium was detected within a reasonable amount of time. Simulation results also indicate that all ground water movement is downward within the model area.

The fact that this model can not reproduce the results observed by Foote (1989) is not surprising. The model described in this study does not explicitly account for the presence of fractures, rather, fractures are implicitly included in the effective hydraulic conductivities determined for each layer. Furthermore movement of water through fractures would occur at a

much smaller scale than represented by the cell dimensions. Fractures would allow local movement of water at faster rates than indicated by the effective hydraulic conductivity for the layer.

Therefore, the presence of fractures near the sampled wells would allow water containing tritium to reach the observed depths.

The fact that this model does not show an upward hydraulic gradient beneath the Arkona Road Landfill is also explained by the fact that the model can not represent small-scale flow systems. The wells beneath the Arkona Road Landfill showing the upward gradient are screened in localized outwash units within the glacial till and likely do not represent gradients present within the surrounding till. Additionally, water levels taken from well logs within a three mile radius of the area show that in only 4 logs out of 682 are heads in the Dundee Limestone at or above the land surface. These wells likely intersect a joint or fracture in the limestone. These isolated locations where the gradient is upward would occur at a much smaller scale than represented by the cell dimensions.



## **APPENDIX**

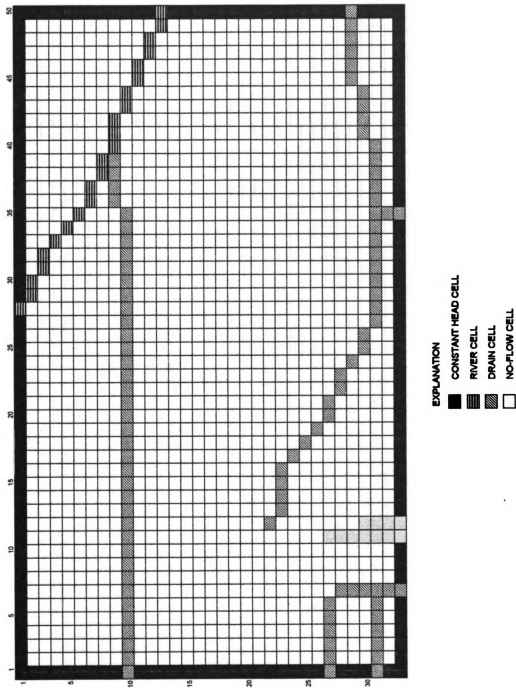


Figure 10. Model Grid for Layer One.

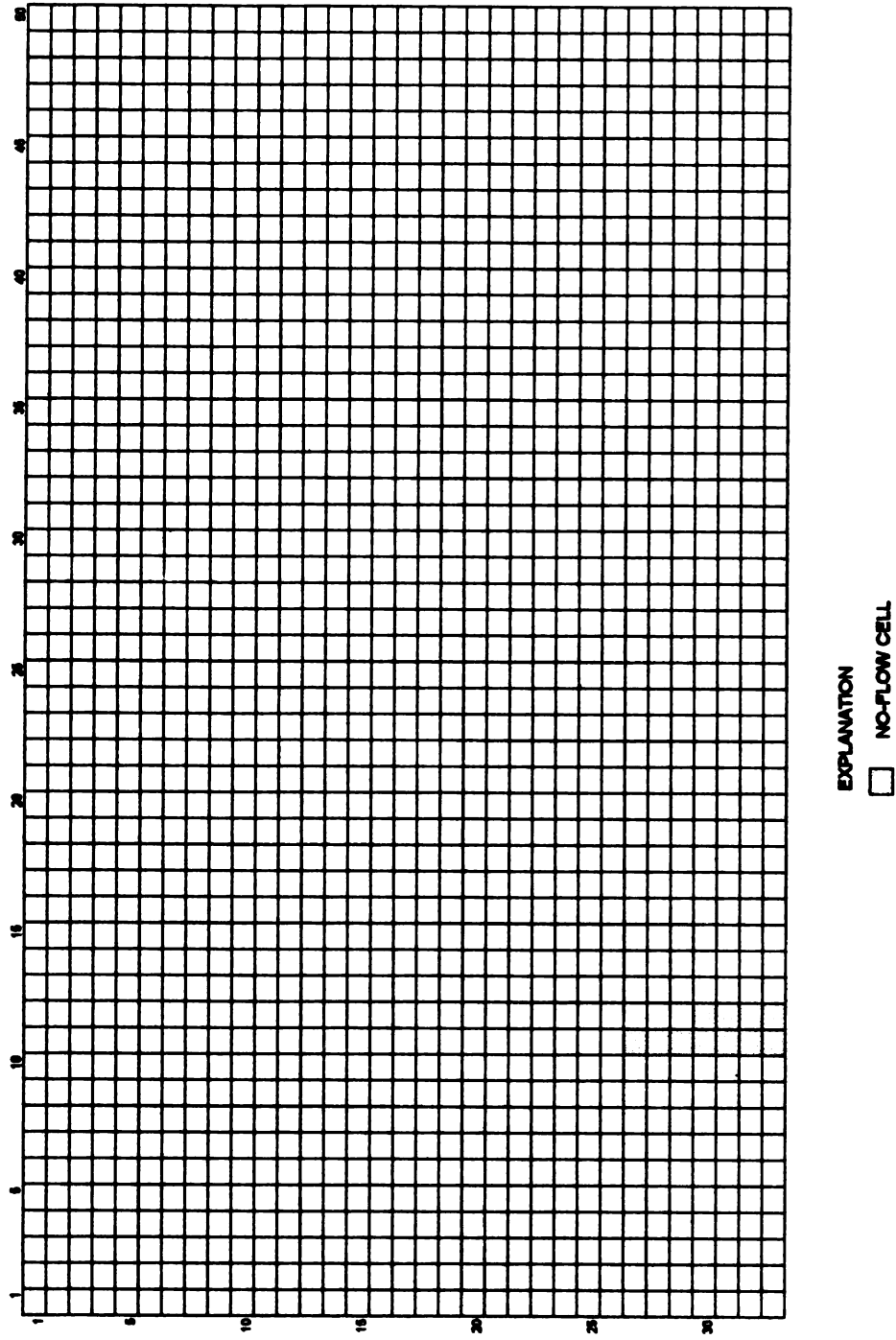


Figure 11. Model Grid for Layer Two.

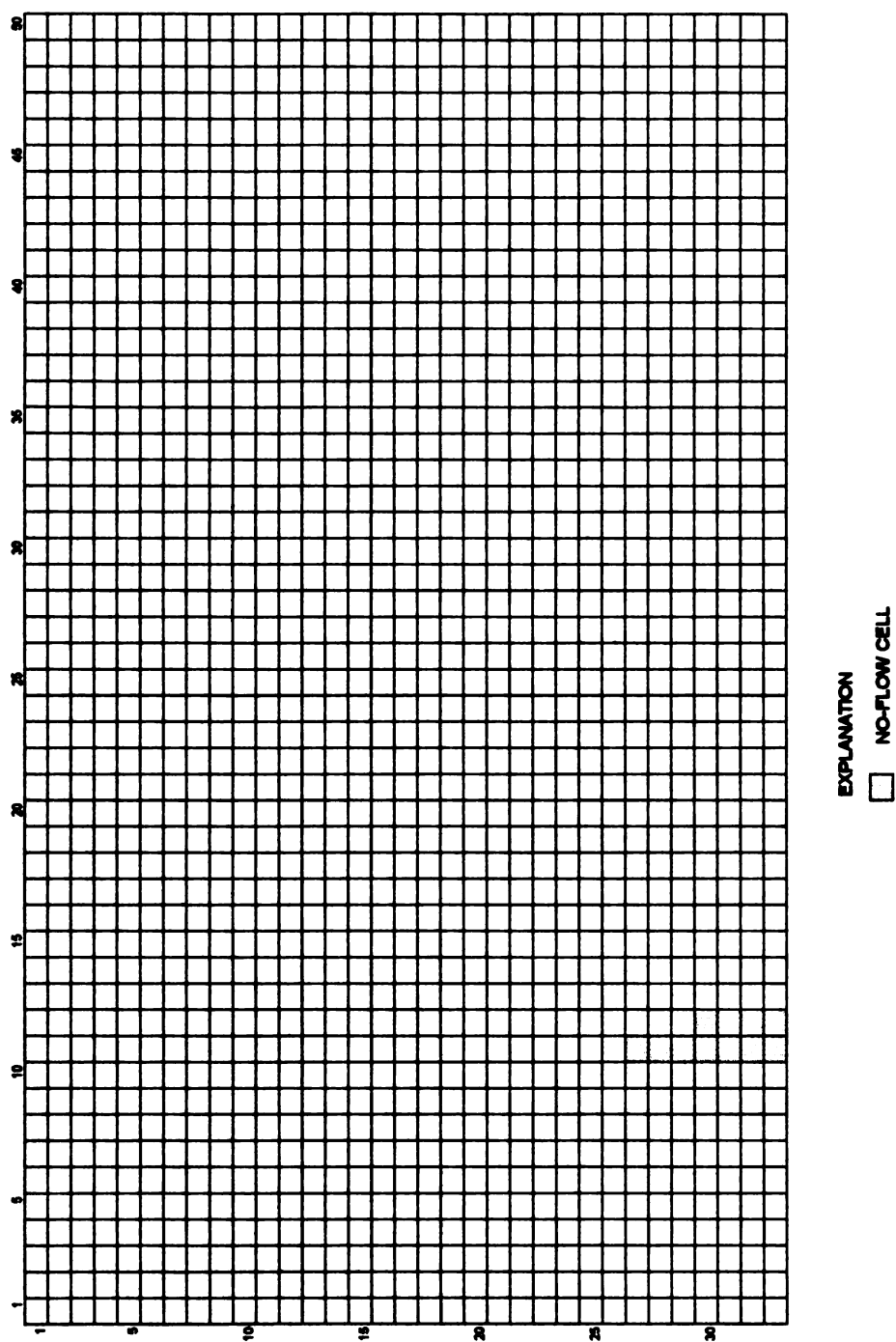


Figure 12. Model Grid for Layer Three.

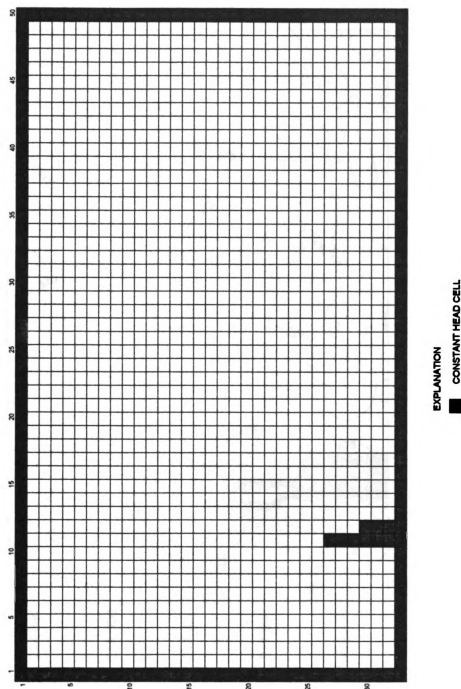


Figure 13. Model Grid for Layer Four .

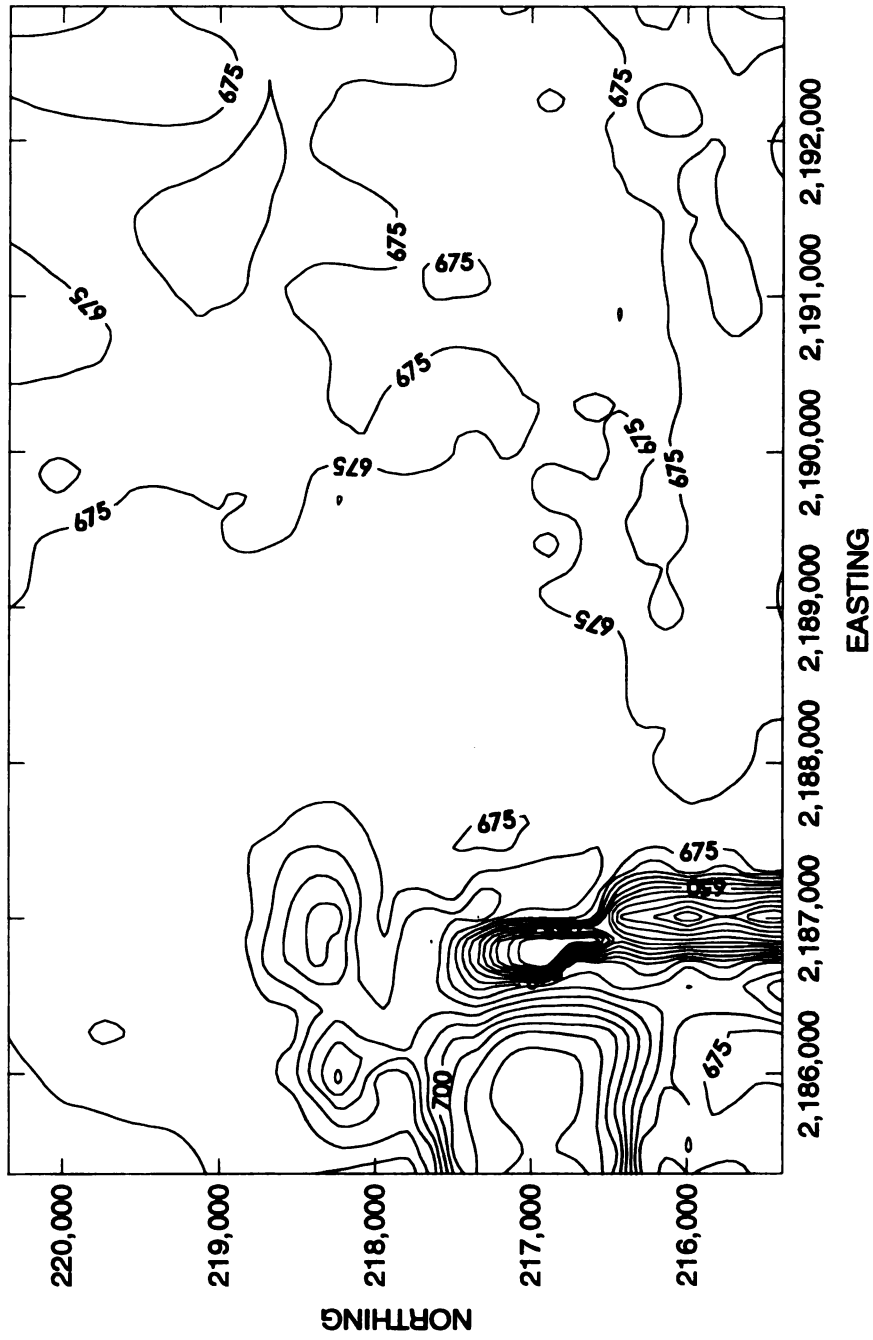


Figure 14. Land Surface Elevation.

**Figure 15. Top of Layer Two.**

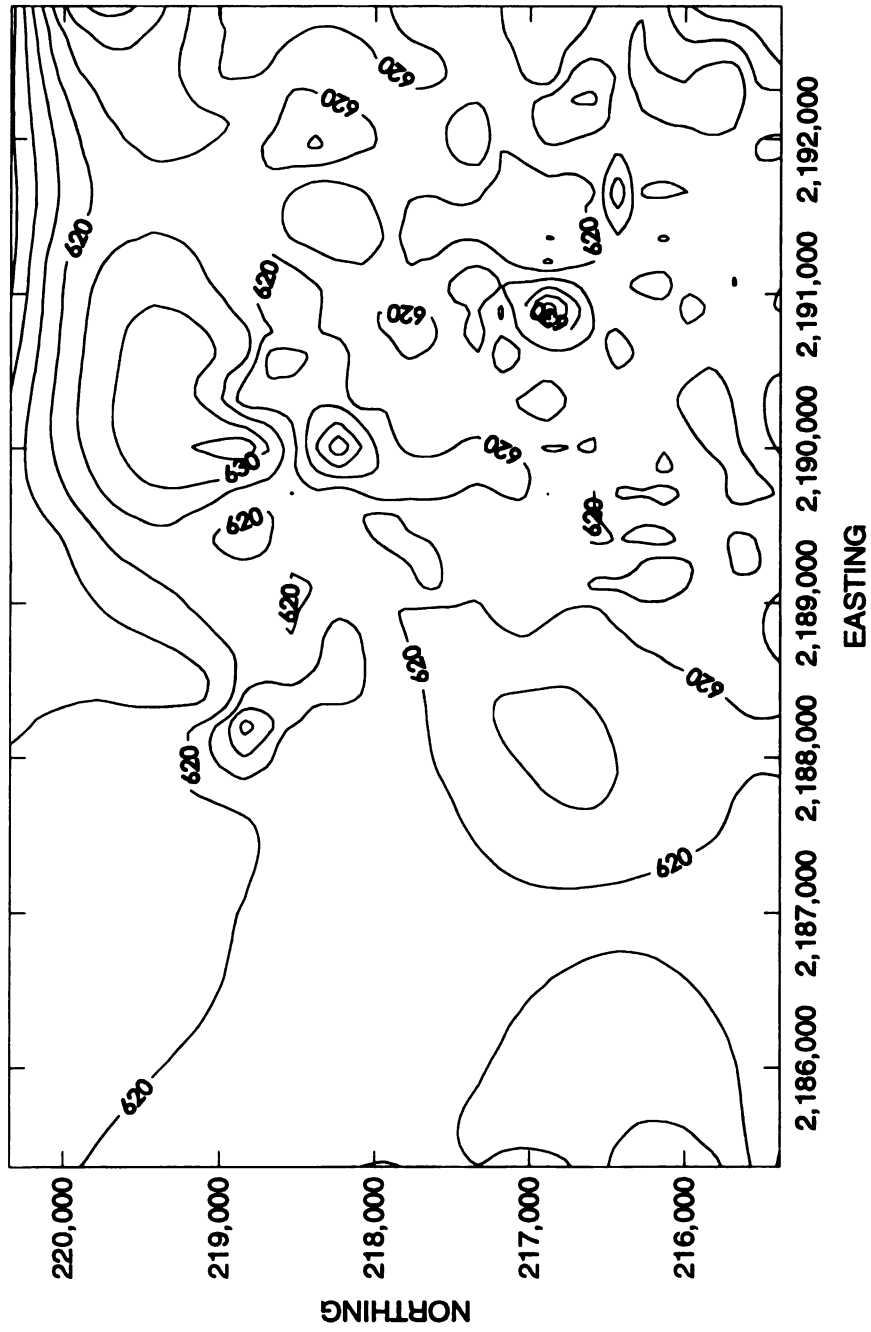


Figure 16. Top of Layer Three.



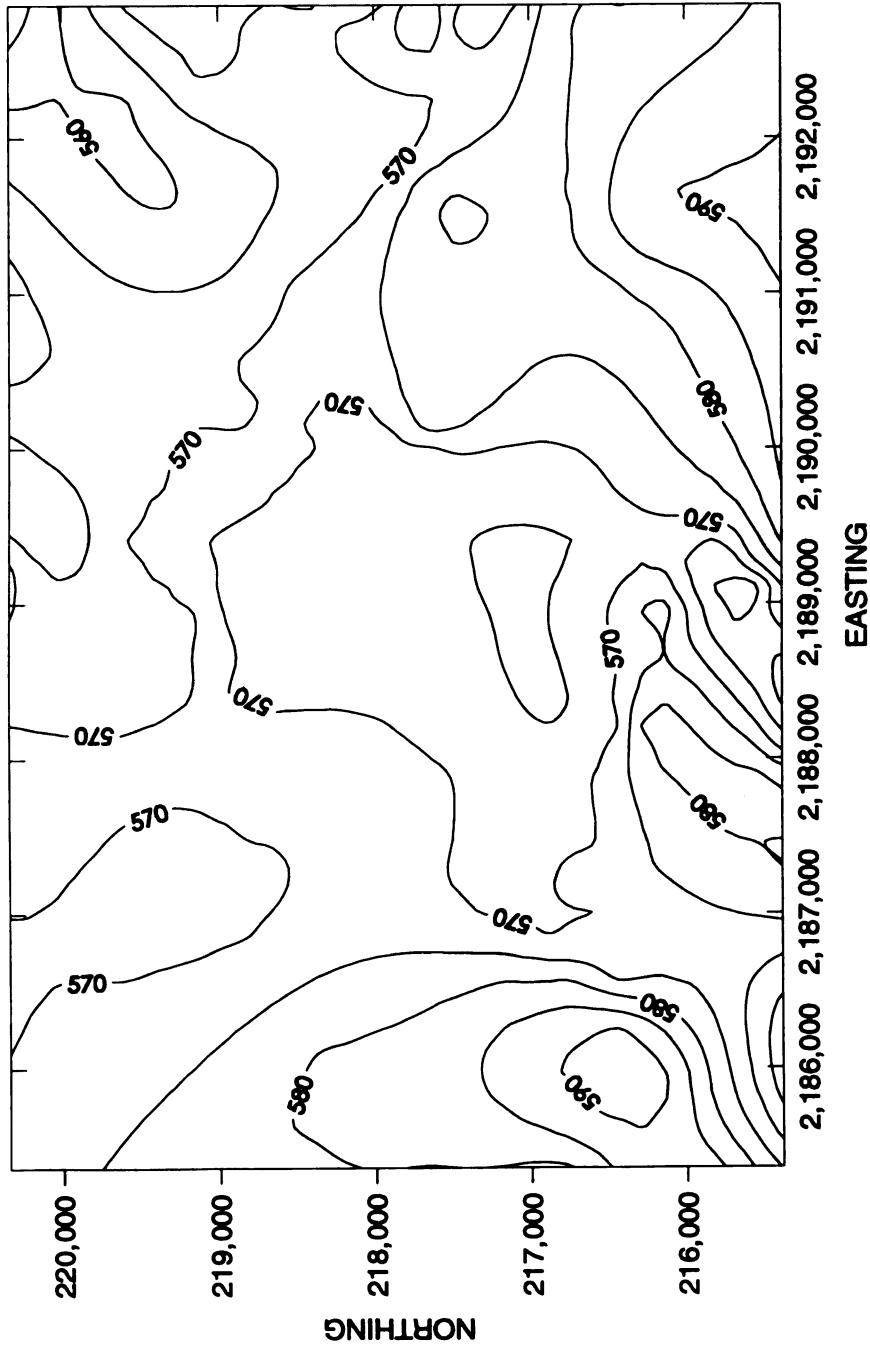
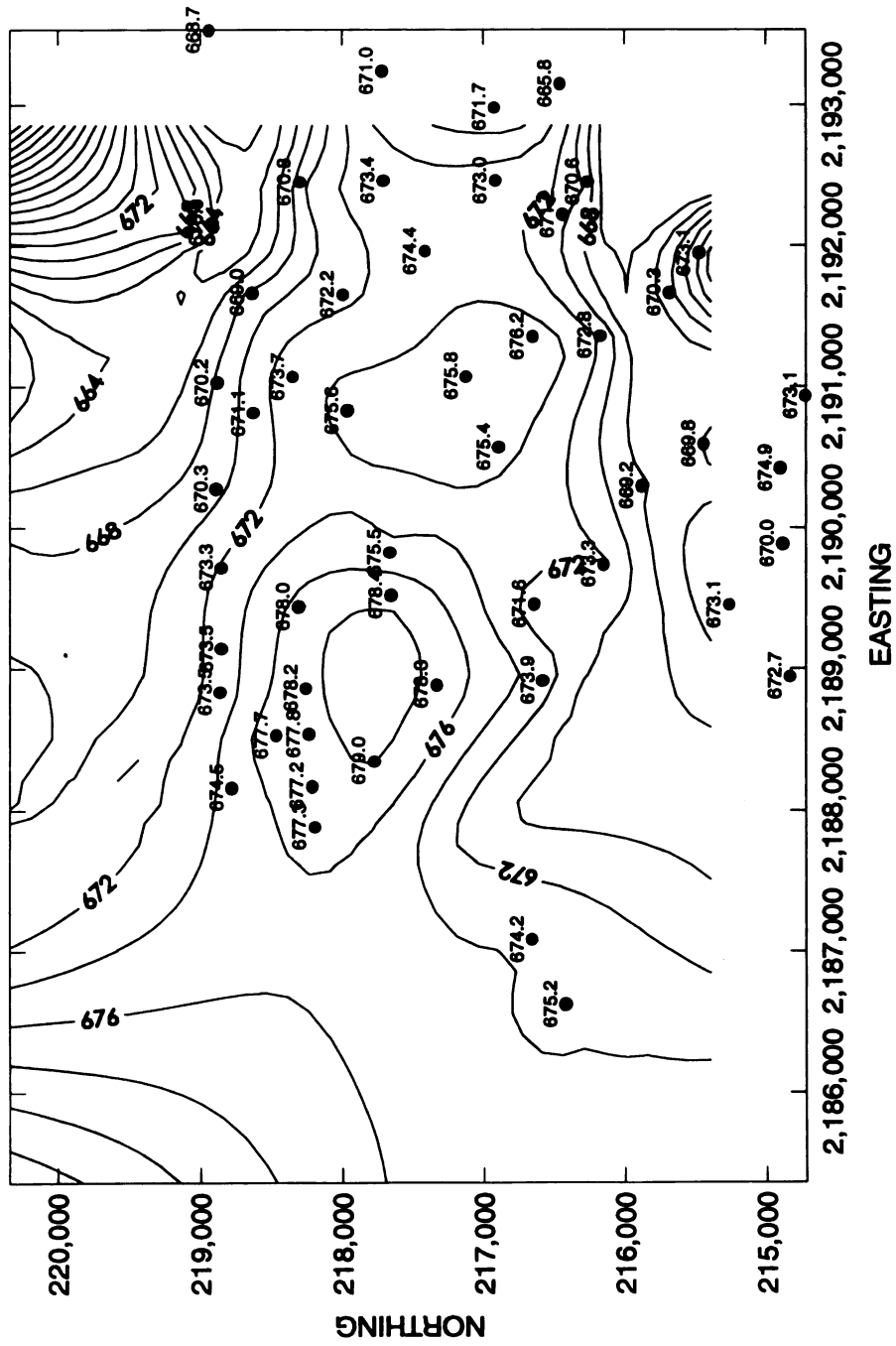


Figure 17. Top of Layer Four.



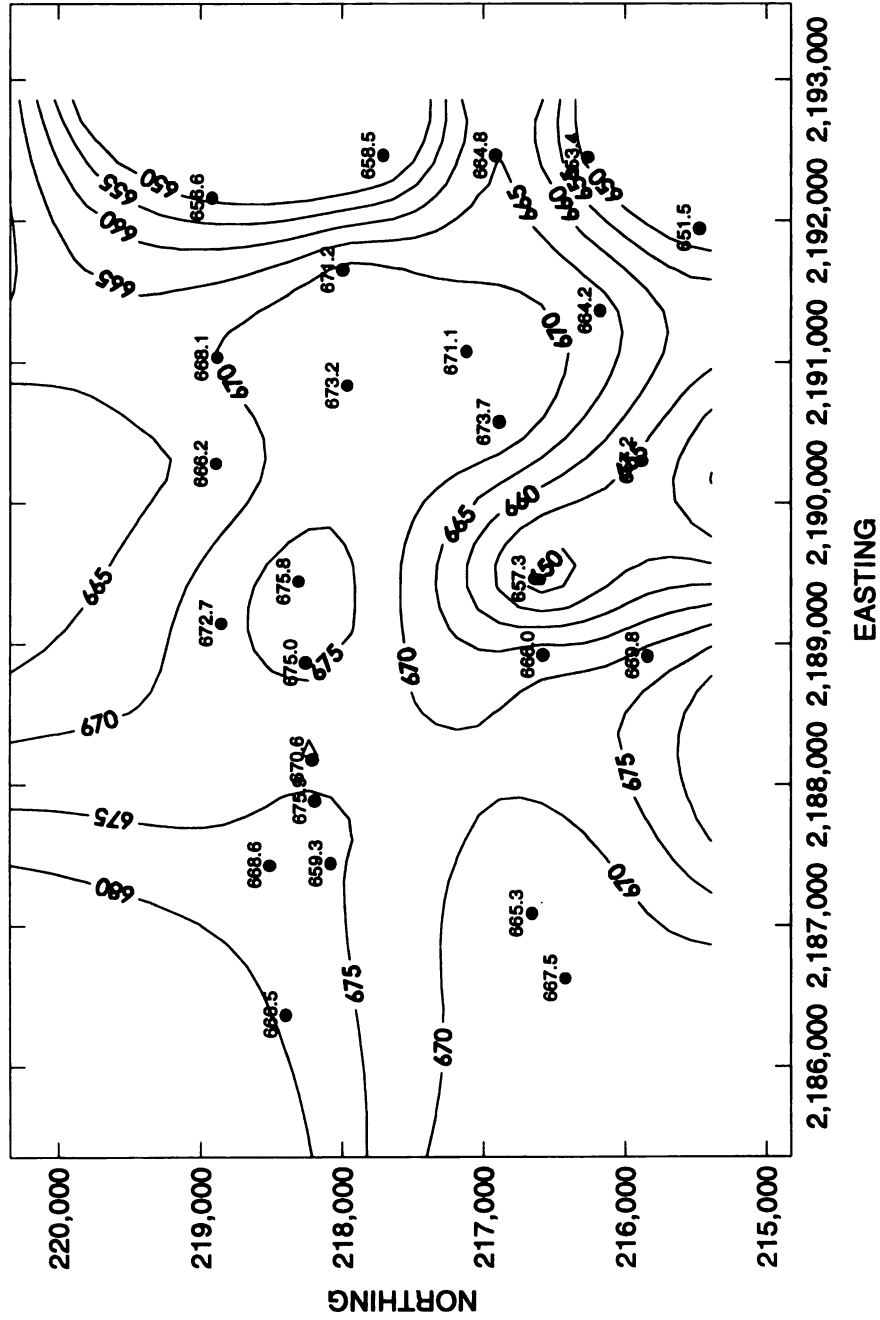


Figure 19. Measured Ground-Water Levels in Layer Two.

**Figure 20. Measured Ground-Water Levels in Layer Three.**

**Figure 21. Measured Ground-Water Levels in Layer Four.**

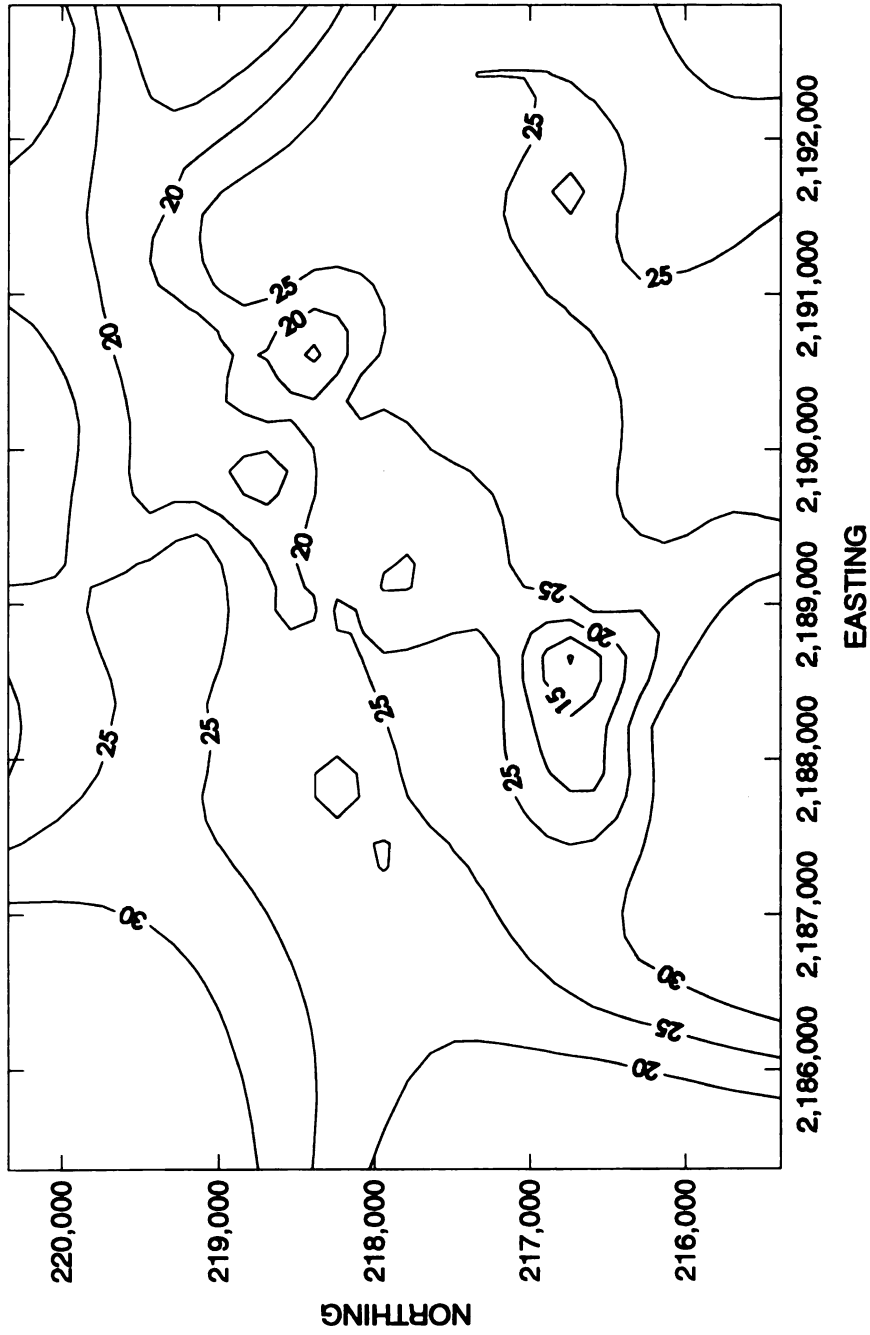


Figure 22. Estimated Horizontal Hydraulic Conductivities of Layer One

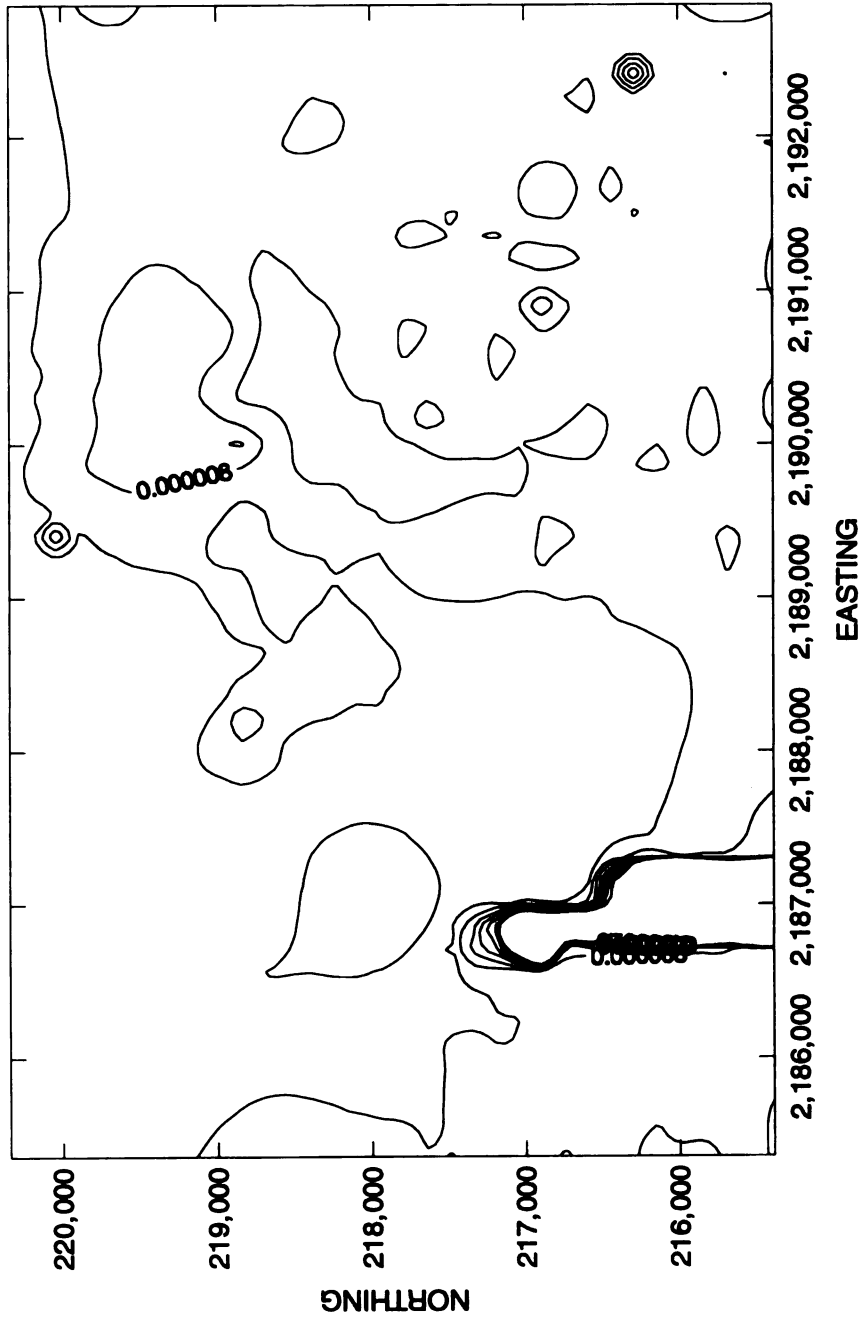


Figure 23. Estimated Leakance Between Layers One and Two.

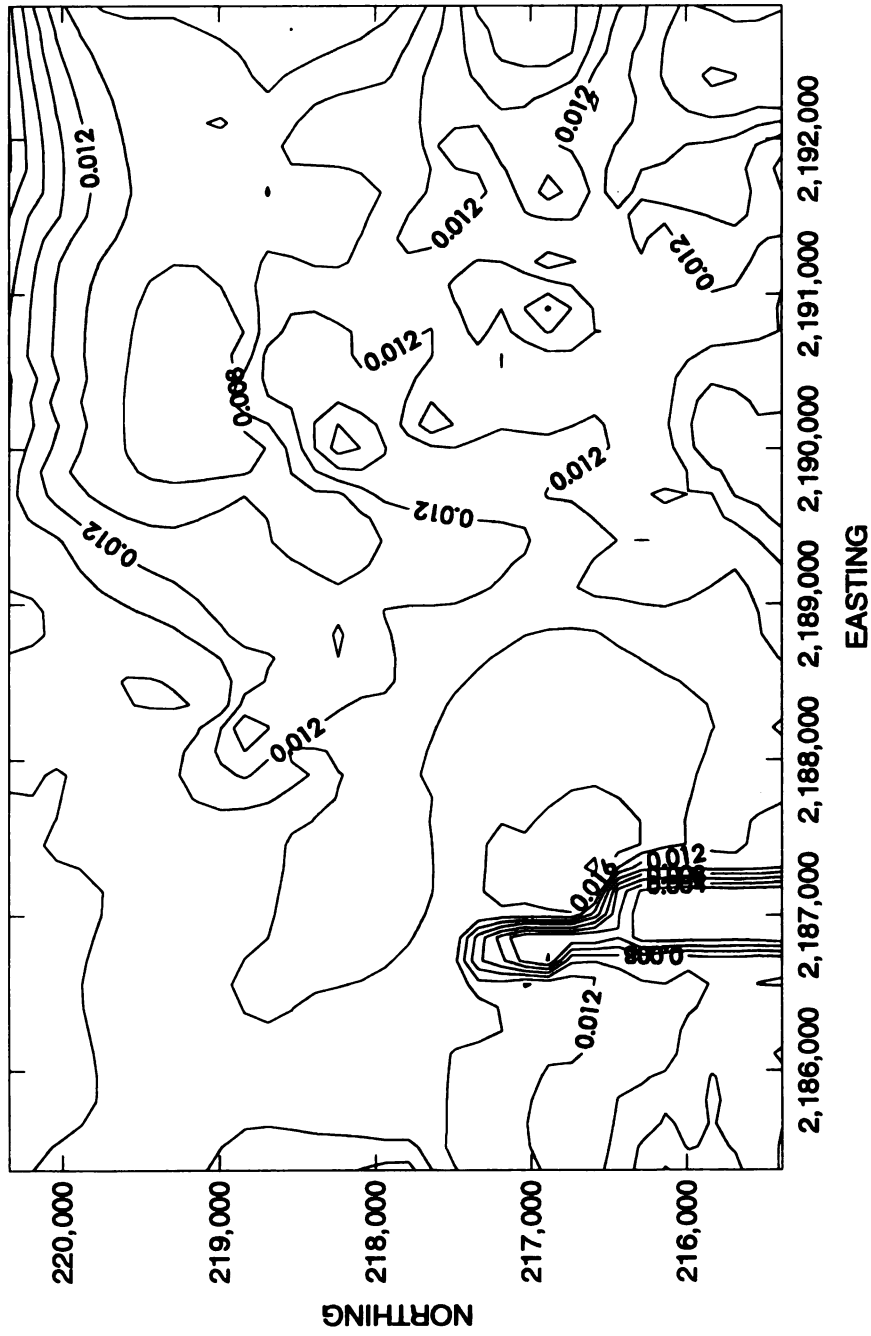


Figure 24. Estimated Transmissivity of Layer Two.



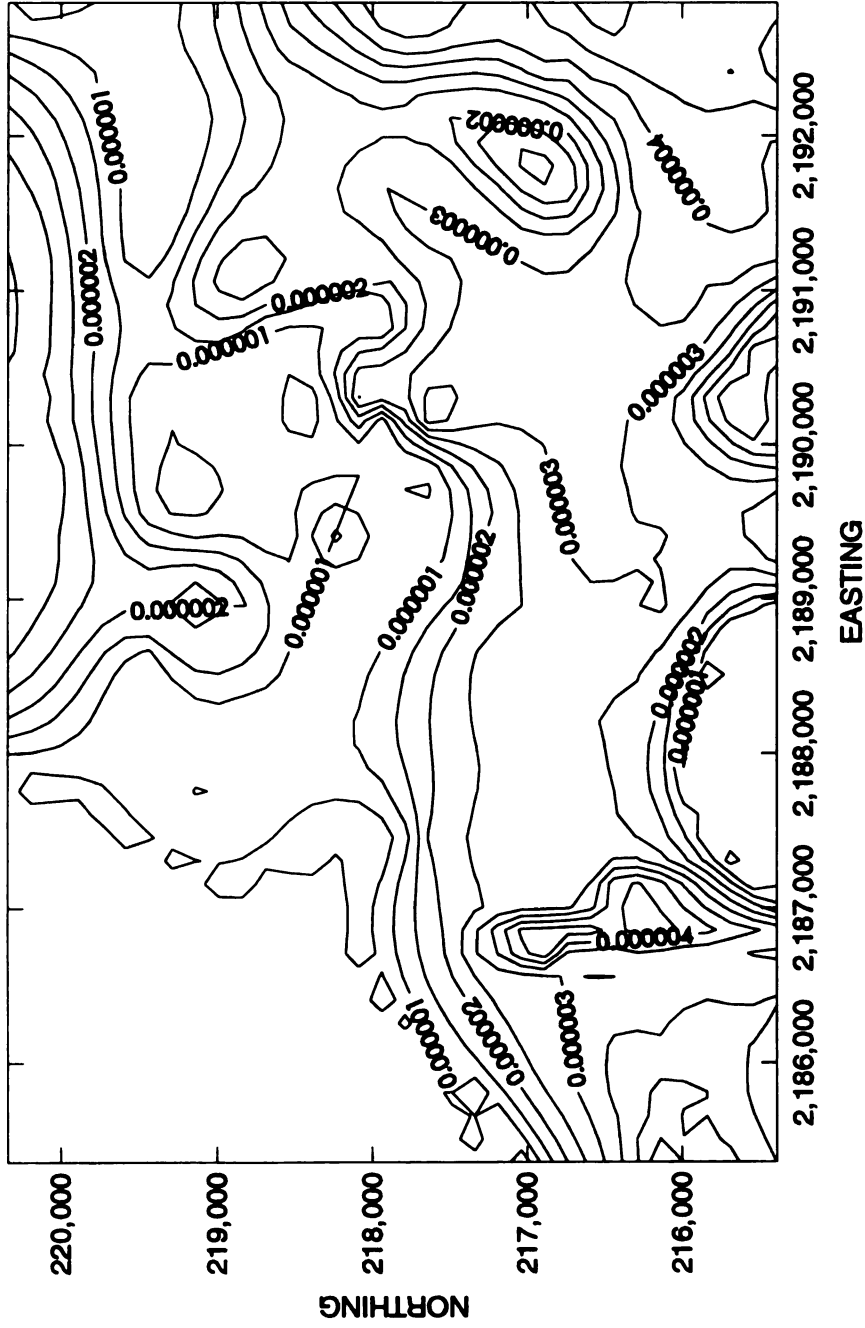


Figure 25. Estimated Leakance Between Layers Two and Three.

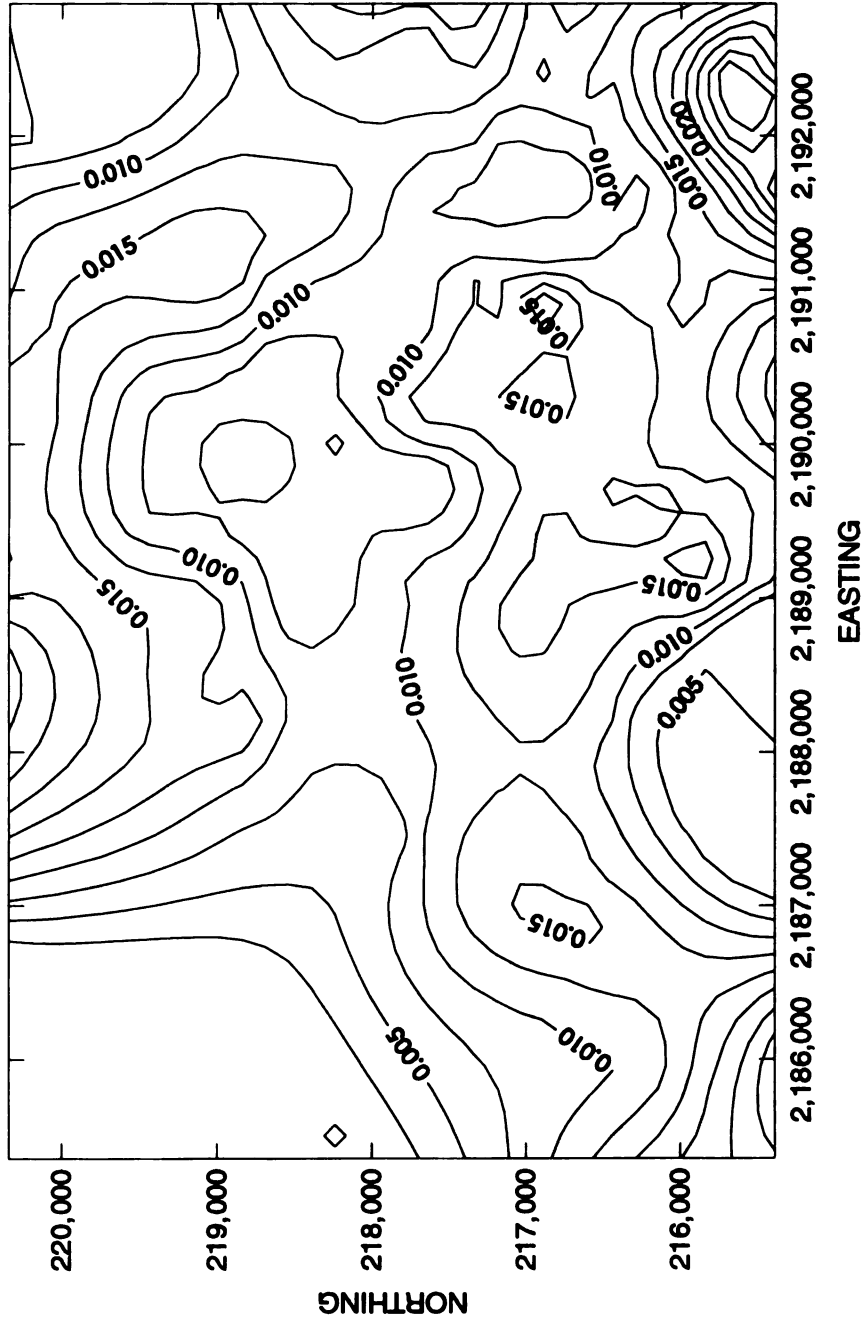


Figure 26. Estimated Transmissivity of Layer Three.

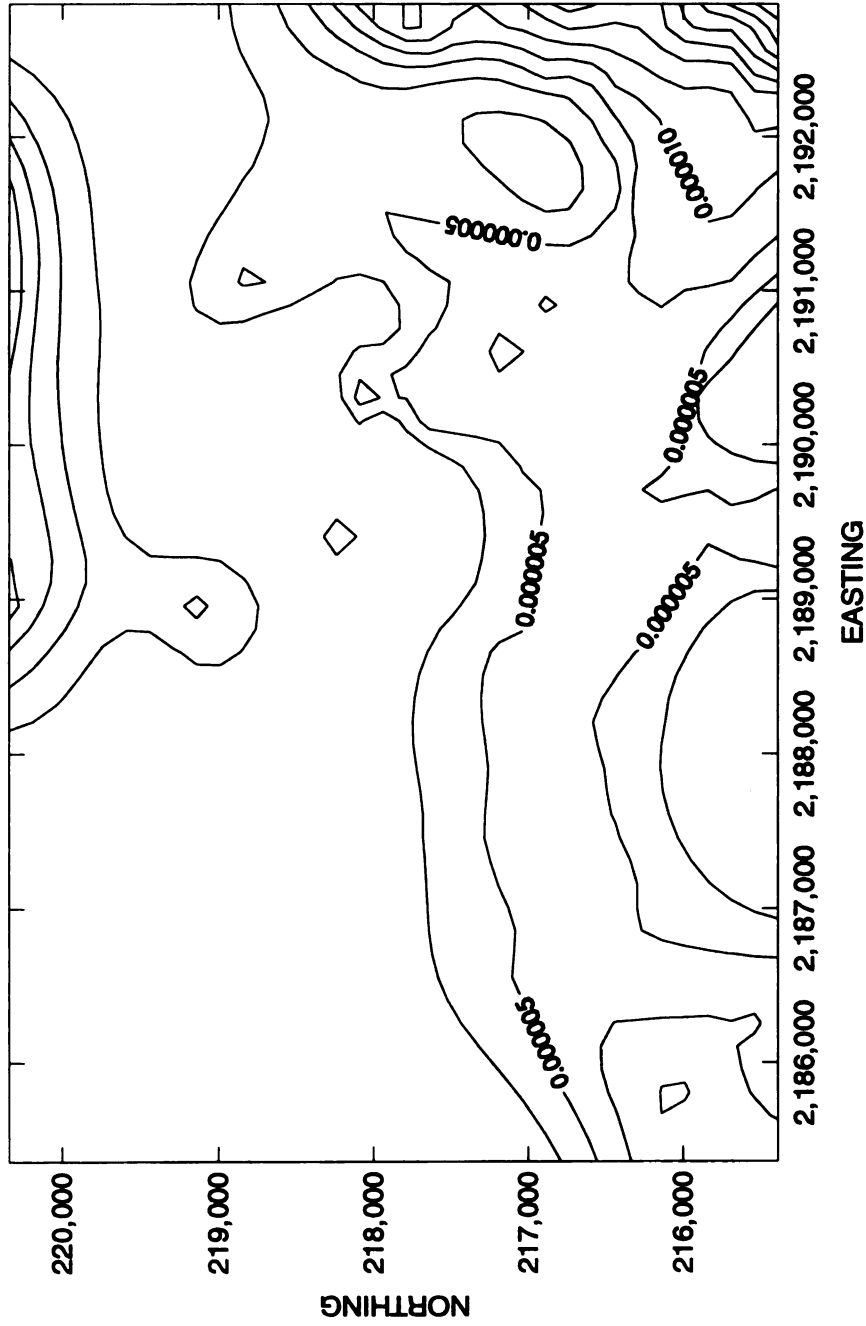


Figure 27. Estimated Leakance Between Layers Three and Four.

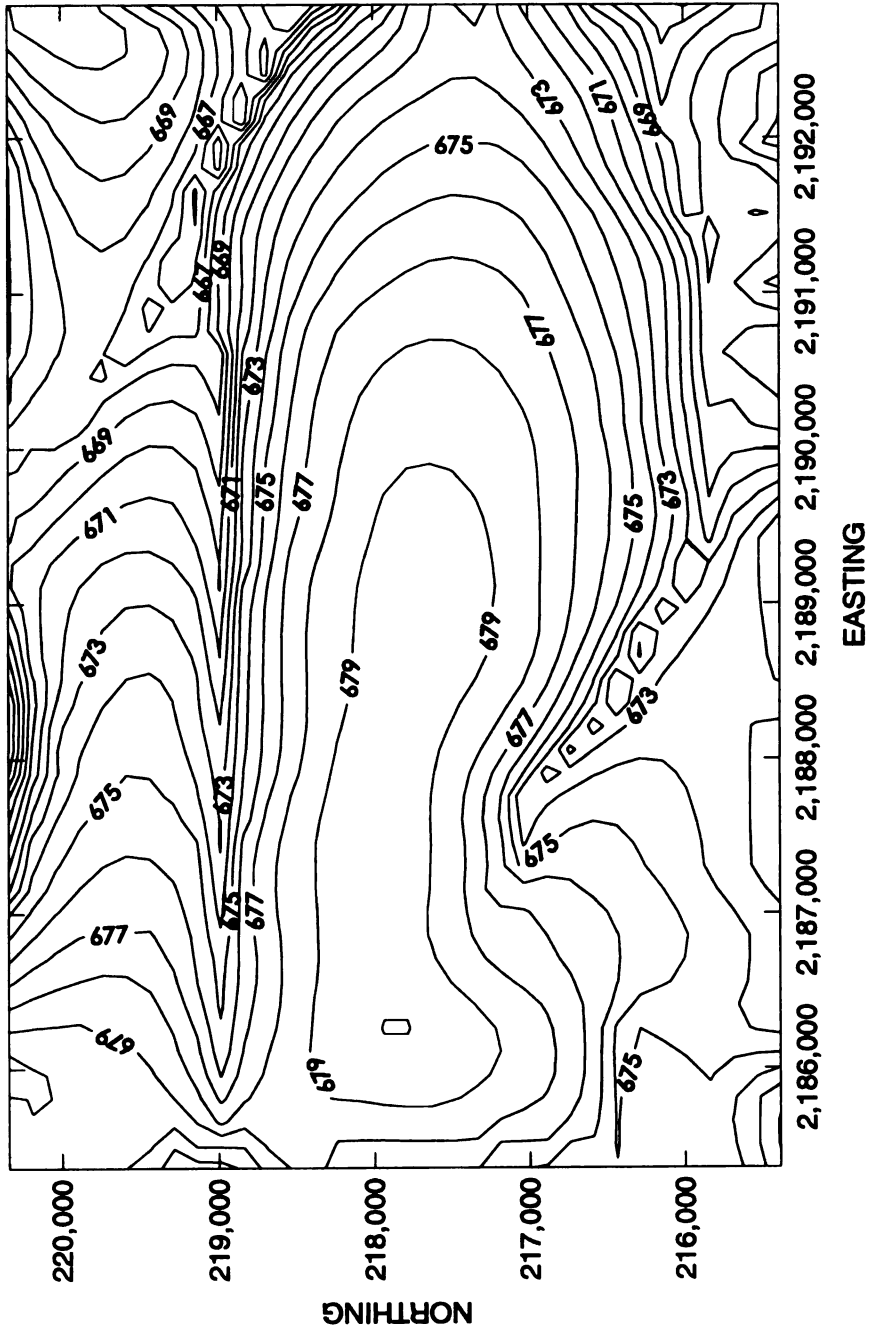


Figure 28. Simulated Ground-Water Levels in Layer One.

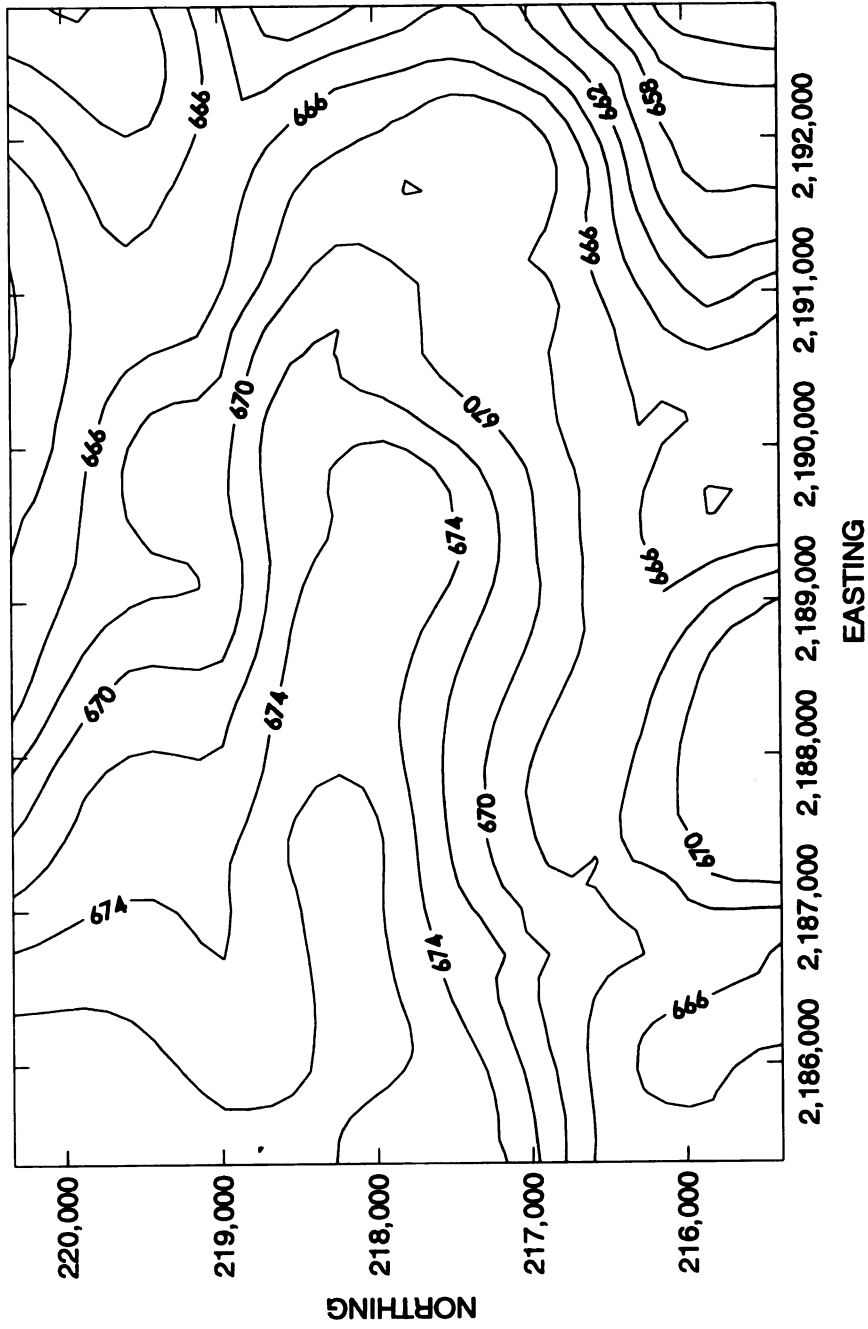


Figure 29. Simulated Ground-Water Levels in Layer Two.

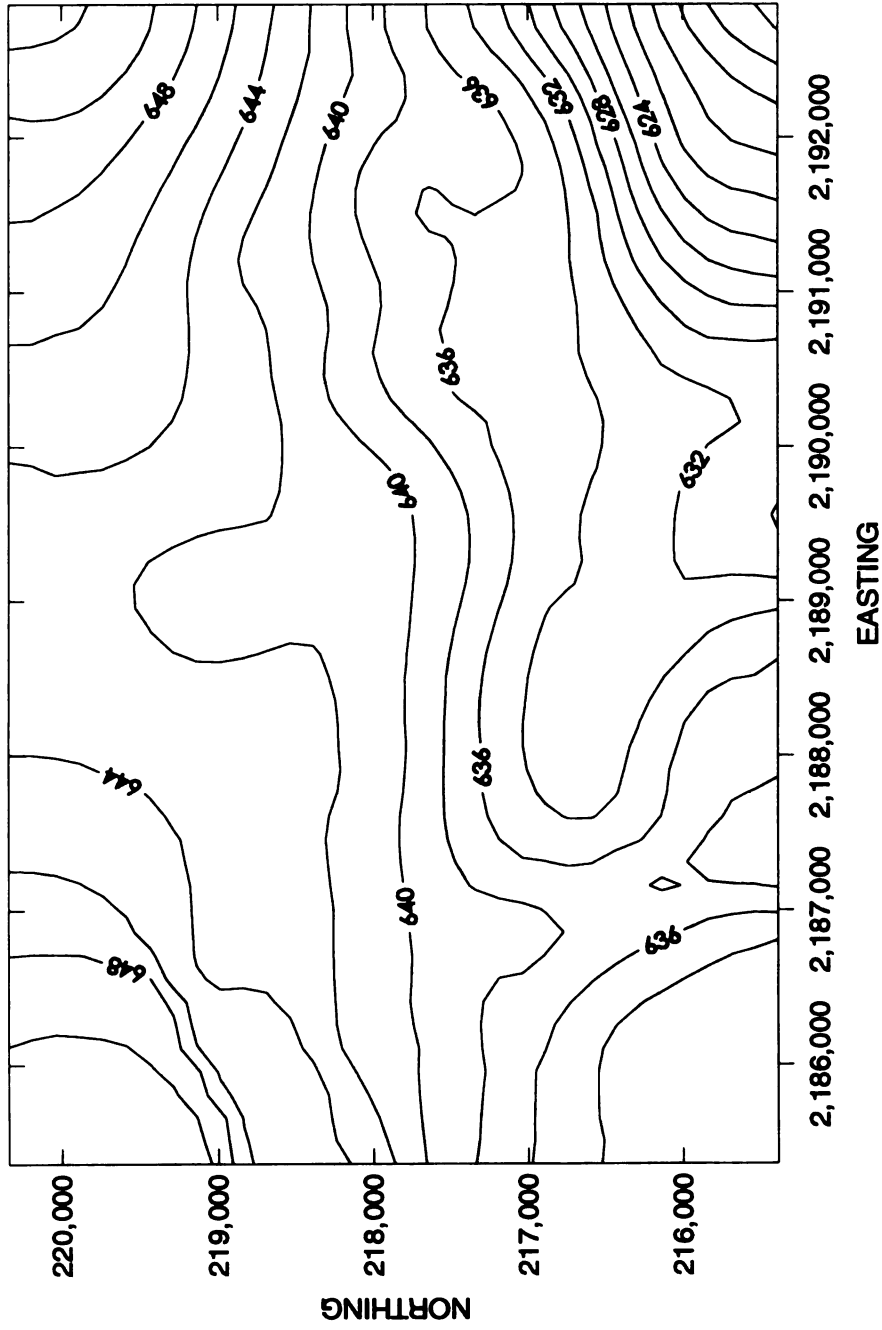


Figure 30. Simulated Ground-Water Levels in Layer Three.

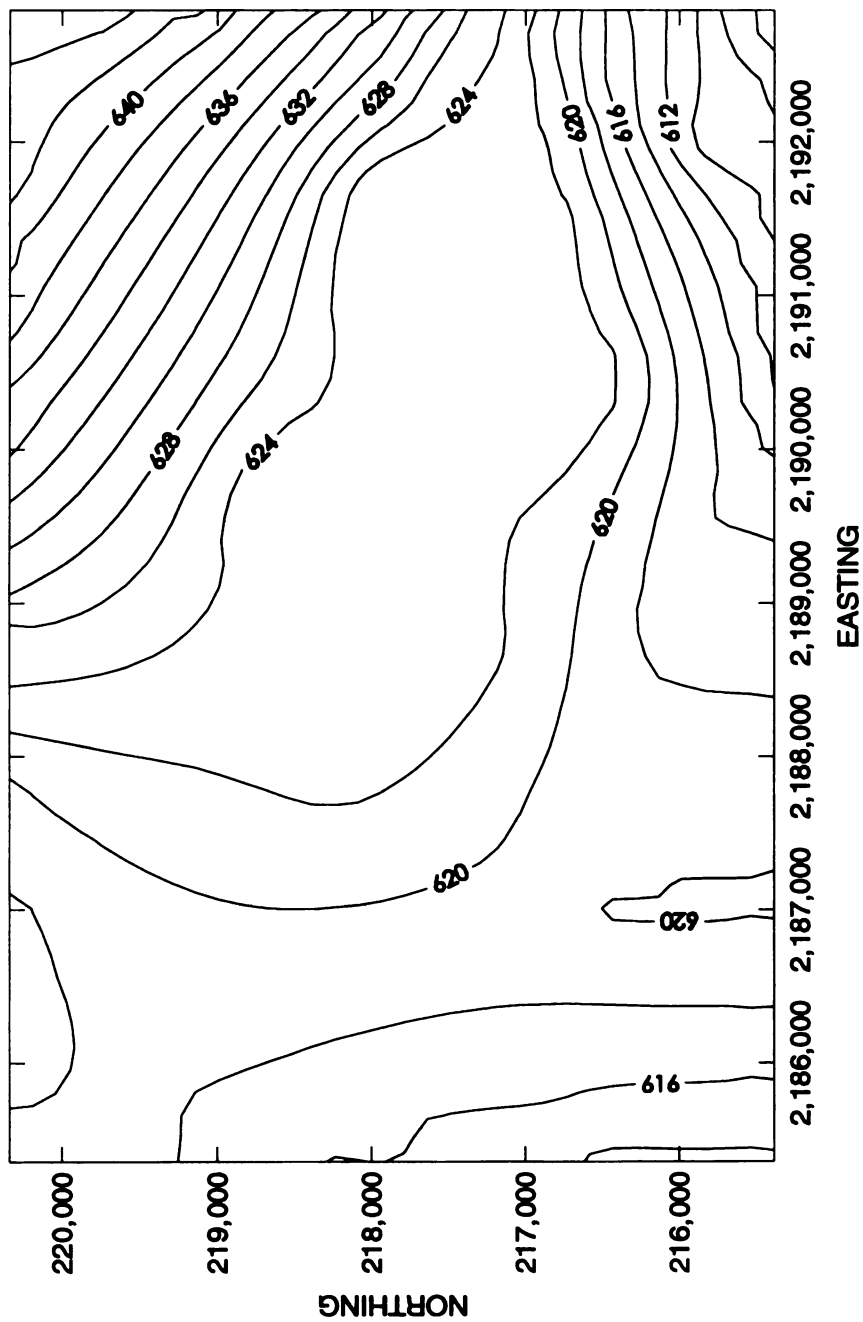


Figure 31. Simulated Ground-Water Levels in Layer Four.

## **LIST OF REFERENCES**



## LIST OF REFERENCES

- Anderson, M. P. and Woessner, W. W., 1992. *Applied Groundwater Modeling*: San Diego: Academic Press, Inc., 381 p.
- Berkowitz, B., Bear, J., and Braester, C., 1988. Continuum models for contaminant transport in fractured porous formations. *Water Resources Research*, v. 24, no. 8, p. 1225-1236.
- Berkowitz, B. and Braester, C., 1991. Solute transport in fracture channel and parallel plate models. *Geophysical Research Letters*, v. 18, no. 2, p. 227-230.
- Bouwer, H. and Rice, R.C., 1976. A slug test for determining hydraulic conductivity of unconfined aquifers with completely or partially penetrating wells. *Water Resources Research*, v. 12, no. 3, p. 423-428.
- Bruner, D.R., 1993. Scale effect of hydraulic conductivity measurements in pre-Illinoian and Wisconsinan tills in Iowa. *Geological Society of America Abstracts with Programs*, v. 25, no. 3, p. 9.
- Cacas, M.C., Ledoux, E., de Marsily, G., Tillie, B., Barbreau, A., Durand, E., Feuga, B., and Peaudecerf, P., 1990a, Modeling fracture flow with a stochastic discrete fracture network: calibration and validation. 1. The flow model. *Water Resources Research*, v. 26, no. 3, p. 479-489.
- Cacas, M.C., Ledoux, E., de Marsily, G., Tillie, B., Barbreau, A., Durand, E., Feuga, B., and Peaudecerf, P., 1990b, Modeling fracture flow with a stochastic discrete fracture network: calibration and validation. 2. The transport model. *Water Resources Research*, v. 26, no. 3, p. 491-500.
- Chaivre, K.R., 1972. The feasibility of determining joint orientations by sampling all sizes of joints. M.S. thesis, Wayne State University, 97 p.
- Cooley, R.L. and Naff, R.L., 1990. Regression modeling of ground-water flow: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. B4, 232 p.
- Day, M.J., 1977. Analysis of movement and hydrochemistry of groundwater in the fractured clay and till deposits of the Winnipeg area, Manitoba. M.S. thesis, University of Windsor.
- Dorr, John A., Jr., and Eschman, Donald F., 1970. *Geology of Michigan*: Ann Arbor, Mich., University of Michigan Press, 476 p.

- Footo, G.S. 1989. Application of environmental isotopes as a test for fracture flow in argillaceous glacial sediments. M.S. thesis, Michigan State University, 67 p
- Fredericia, J., 1990. Saturated hydraulic conductivity of clayey tills and the role of fractures. *Nordic Hydrology*, v. 21, p. 119-132.
- Freeze, R.A. and Cherry, J.A., 1979. *Groundwater*: Englewood Cliffs, New Jersey: Prentice Hall, Inc., 604 p.
- Gale, J.E., 1982. Assessing the permeability characteristics of fractured rock. *GSA Special Paper* 189, p. 163-181.
- Gerber, R.E. and Howard, Ken W.F., 1992. Migration of contaminants through till: Implications for the selection of landfill sites. *Geological Society of America Abstracts with Programs*, v. 24, no. 7, p. 300.
- Grisak, G.E. and Cherry, J.A. 1975. Hydrologic characteristics and response of fractures till and clay confining a shallow aquifer. *Canadian Geotechnical Journal*, v. 12, no. 1, p. 23-43.
- Grisak, G.E., Cherry, J.A., Vonhof, J.A., and Blumele, J.P., 1976. Hydrogeologic and hydrochemical properties of fractured till in the Interior Plains Region. *Glacial Till*, Special Publication No. 12 of the Royal Society of Canada, ed by R.F. Legget, p. 304-335.
- Grisak, G.E. and Pickens, J.F., 1980. Solute transport through fractured media, 1. The effect of matrix diffusion. *Water Resources Research*, v. 16, no. 4, p. 719-730.
- Grisak, G.E., Pickens, J.F., and Cherry, J.A., 1980. Solute transport through fractured media. 2. Column study of fractured till. *Water Resources Research*, v. 16, no. 4, p. 731-739.
- Harrison, B., Sudicky, E.A., and Cherry, J.A., 1992. Numerical analysis of solute migration through fractured clayey deposits into underlying aquifers. *Water Resources Research*, v. 28, no. 2, p. 515-526.
- Hendry, M.J. 1982. Hydraulic conductivity of a glacial till in Alberta. *Ground Water*, v. 20, no. 2, p. 162-169.
- Hendry, M.J., 1983. Groundwater recharge through a heavy-textured soil. *Journal of Hydrology*, v. 63, p. 201-209.
- Herzog, B.L., Griffin, R.A., Stohr, C.J., Folmer, L.R., and Morse, W.J., 1989. Investigation of failure mechanisms and migration of chemicals at Wilsonville, Illinois. *Ground Water Monitoring Review*, v. 9, no. 2, p. 82-89.
- Hill, M.C., 1992. A computer program (MODFLOWP) for estimating parameters of a transient, three-dimensional, ground-water flow model using nonlinear regression: U.S. Geological Survey Open-File Report 91-484, 358 p.
- Holtschlag, D.J., 1994. A generalized estimate of ground-water recharge rates in the lower peninsula of Michigan: U.S. Geological Survey Water-Supply Paper 2437, 81 p.

- Hull, L.C., Miller, J.D., and Clemo, T.M., 1987. Laboratory and simulation studies of solute transport in fracture networks. *Water Resources Research*, v. 23, no. 8, p. 1505-1513.
- Hvorslev, M.J., 1951. Time lag and soil permeability in ground water observations: U.S. Army Corps Engrs. Waterways Exp. Sta. Bull. 36, Vicksburg, Mississippi.
- Huntec, Ltd., 1967. Report on a combined geophysical survey. Milan, Michigan, for the Martin-Marietta Corporation, Toronto, Ontario. 25 p., 13 plates.
- Keller, C.K., Van der Kamp, G., and Cherry, J.A. 1986. Fracture permeability and groundwater flow in clayey till near Saskatoon, Saskatchewan. *Canadian Geotechnical Journal*, v. 23, p. 229-240.
- Keller, C.K., Van der Kamp, G., and Cherry, J.A. 1988. Hydrogeology of two Saskatchewan tills, I. fractures, bulk permeability, and spatial variability of downward flow. *Journal of Hydrology*, v. 101, p. 97-121.
- Kunkle, George Robert, 1961. The ground water geology and hydrogeology of Washtenaw County and the Upper Huron River Basin. Ph.D. Dissertation, University of Michigan, 242 p.
- Long, J.C.S., Remer, J.S., Wilson, C.R., and Witherspoon, P.A., 1982. Porous media equivalents for networks of discontinuous fractures. *Water Resources Research*, v. 18, no. 3, p. 645-658.
- Long, J.C.S. and Witherspoon, P.A., 1985. The relationship of the degree of interconnection to permeability in fracture networks. *Journal of Geophysical Research*, v. 90, no. B4, p. 3087-3098.
- Long, J.C.S. and Billaux, D.M., 1987. From field data to fracture network modeling: an example incorporating spatial structure. *Water Resources Research*, v. 23, no. 7, p. 1201-1216.
- McDonald and Harbaugh, 1988. A modular three-dimensional finite difference ground-water flow model. *Techniques of Water-Resources Investigations*, Book G, Chapter A1. U.S. Geological Survey, Washington.
- McKay, L.D., 1991. Groundwater flow and contaminant transport in a fractured clay till. Ph D thesis, University of Waterloo.
- McKay, L.D., Cherry, J.A., and Gillham, R.W. 1993. Field experiments in a fractured clay till 1. hydraulic conductivity and fracture aperture. *Water Resources Research*, v. 29, no. 4, p. 1149-1162.
- McNamee, Porter and Seeley, 1965. Report on groundwater, section 29, 30, 31, and 32. Augusta Township, Washtenaw County, Michigan, for the Cement and Lime Division of Martin-Marietta Corporation. 17 p., 9 plates.
- Moreno, L., Tsang, C., Tsang, Y., and Neretnieks, I., 1990. Some anomalous features of flow and solute transport arising from fracture aperture variability. *Water Resources Research*, v. 26, no. 10, p. 2377-2391.

- Neyer, Tiseo and Hindo, 1987. Report on subsurface investigation. Prepared for Augusta Development Corporation. Project No. 871590W. October 16, 1987.
- Payne, B.R., 1972. Isotope Hydrology: *Adv. Hydrosoci*, v. 8, p. 95-138.
- Pollock, D.W., 1989. Documentation of computer programs to compute and display pathlines using three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 89-381, 188 p.
- Rowe, R.K. and Booker, J.R., 1990. Contaminant migration through fractured till into an underlying aquifer. *Canadian Geotechnical Journal*, v. 27, p. 484-495.
- Rowe, R.K. and Booker, J.R., 1991. Modeling of two-dimensional contaminant migration in a layered and fractured zone beneath landfills. *Canadian Geotechnical Journal*, v. 28, p. 338-352.
- RMT, 1988. Preliminary hydrogeologic investigations of Arkona Road Landfill. May 1988.
- RMT, 1992. Envotech Resource Center, Hydrogeologic report for hazardous waste management facilities. Madison, Wisconsin.
- Rudolph, D.L., Cherry, J.A., and Farvolden, R.N., 1991. Groundwater flow and solute transport in fractured lacustrine clay near Mexico City. *Water Resources Research*, v. 29, no. 9, p. 2187-2202.
- Ruland W.W., Cherry, J.A., and Feenstra, S., 1991. The depth of fractures and active ground-water flow in a clayey till plain in southwestern Ontario, v. 29, no. 3, p. 405-417.
- Snow, David T., 1967. Hydraulic properties of the Dundee Limestone near Milan, Michigan, and an evaluation of quarry seepage for the Martin-Marietta Corp., 42 p.
- Snow, David T., 1969. Anisotropic permeability of fractured media. *Water Resources Research*, v. 5, no. 6, p. 1273-1289.
- Sudicky, E.A. and Frind, E.O., 1982. Contaminant transport in fractured porous media: Analytical solutions for a system of parallel fractures. *Water Resources Research*, v. 18, no. 6, p. 1634-1642.
- Sudicky, E.A. and McLaren, R.G., 1992. The Laplace Transform Galerkin Technique for large-scale simulation of mass transport in discretely fractured porous formations. *Water Resources Research*, v. 28, no. 2, p. 499-514.
- Thoma, S.G., Gallegos, D.P., and Smith, D.M., 1992. Impact of fracture coatings on fracture/matrix flow interactions in unsaturated, porous media. *Water Resources Research*, v. 28, no. 5, p. 1357-1367.
- Thomson, David Gray, 1990. Hydraulic evidence of Wisconsinan-aged fractures in a deep clayey till. M.S. thesis, University of Waterloo, 179 p.

- Twenter, F.R., Knutilla, R.L., and Nowlin, J.O., 1976. Water resources of Washtenaw County, Michigan. U.S.G.S. and Washtenaw County Metropolitan Planning Commission. 74 p.
- Williams, R.E. and Farvolden, R.N., 1967. The influence of joints on the movement of ground water through glacial till. *Journal of Hydrology*, v. 5, p. 163-170.
- Zimmerman, R.W., Chen, D., and Cook, N.G.W., 1992. The effect of contact area on the permeability of fractures. *Journal of Hydrology*, v. 139, p. 79-96.

MICHIGAN STATE UNIV. LIBRARIES



31293017865993