Groundwater Flow and Advective Modeling of Contaminant Migration near Ripon, Wisconsin

by

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ABSTRACT

Volatile organic contaminants have been detected in monitoring wells at the City of Ripon landfill, Fond du Lac County, Wisconsin. In addition, 1,2-dichloroethylene (DCE) and vinyl chloride (VC) have been detected in an off-site domestic well open to bedrock. The depth and location of the domestic well suggests that contaminants may be moving from the landfill as a dense non-aqueous phase liquid (DNAPL) in addition to the dissolved phase. Within three miles of this site four municipal wells tap Cambrian and Ordovician bedrock. These wells may be threatened by these contaminants, especially if pumping induces dissolved-phase migration towards the well field.

A review of existing geologic data and stratigraphic information obtained during monitoring well installation delineated complex local geology. Sampling of the monitoring wells between the landfill and municipal well #9 shows that the dissolved phase is present to the south of the landfill. Existing data show that groundwater flow is to the west - southwest, suggesting a DNAPL is present. Between the landfill and municipal well #9, no basal boundaries to DNAPL flow were conclusively identified. The geologic information was coupled with hydraulic conductivity data from other studies to formulate a conceptual model of the study area.

From the conceptual model, a three-dimensional groundwater flow model was constructed. Calibration and sensitivity analysis shows that the model is most sensitive to variations in the hydraulic conductivity of the Cambrian sandstones. The model estimates for the horizontal conductivities of these units were verified by the results of pumping and recovery tests utilizing municipal well #9.

Coupling the calibrated model with a particle tracking routine indicates that the municipal well field is not threatened by dissolved-phase migration, given the known distribution of DCE and VC. These results also demonstrate that pumping of the well field at current rates alters travel paths slightly, but slows groundwater movement in the vicinity of the landfill. Reverse particle tracking solutions suggest that a DNAPL has migrated from the landfill to the southeast through drift or bedrock and is responsible for the observed contamination.

The inferred location of DNAPL sources for the existing dissolved plume, combined with the sampling data, imply that a DNAPL is migrating from the landfill to the southeast. The subsequent dissolved-phase migration to the west and southwest does not immediately threaten the well field, but no predictions may be made regarding rates of DNAPL movement. Further investigation is required to locate the DNAPL plume or plumes more precisely and to identify possible migration pathways, especially in the glacial deposits.

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LIST OF APPENDICES AND ACCOMPANYING MATERIAL

APPENDICES are included at the end of the thesis
ACCOMPANYING MATERIALS are on repository in the Geology Library, University of Wisconsin-Madison. The accompanying material contains computer files used as input or output for the model and the particle tracking. Data is recorded on 3.5 inch high density floppy disks.

APPENDICES

A Monitoring well installation and logs

B Monitoring well development and sampling

C Model layer representations

D Head contours

E Pumping test

ACCOMPANYING MATERIAL

1. Input files for the calibrated steady-state model without pumping
2. Input files for the calibrated steady-state model with pumping
3. Output files for the calibrated steady-state model without pumping
4. Output files for the calibrated steady-state model with pumping
5. Input files for the particle tracking simulations
6. Output files for the particle tracking simulations

CHAPTER 1: INTRODUCTION

A. THE PROBLEM

The City of Ripon Landfill, in Fond du Lac County, Wisconsin (Figure 1.1), was in operation from 1968 to 1983, and accepted municipal waste, solvents and paint sludge from local manufacturers, and wastewater treatment sludge (unpublished EPA report, 1984). Located in an abandoned gravel quarry, the landfill overlies sandy and gravelly glacial deposits filling a pre-glacial bedrock valley floored with Cambrian sandstone. Monitoring wells at the landfill indicate the presence of volatile organic contaminants (VOCs) including benzene, toluene, xylenes, 1,2-dichloroethylene (DCE), trichloroethylene (TCE), and vinyl chloride (VC) (Unpublished Wisconsin DNR report, 1985). It is not known if the landfill is lined, and it is possible that three wells are buried within the landfill (Unpublished EPA report, 1984).

In 1984, DCE and VC were detected in an off-site domestic well open to bedrock (unpublished WDNR report, 1985). A newer and deeper well was drilled in 1989, and that too is contaminated by DCE and VC (unpublished WDNR report, 1989). The presence of the dissolved-phase contaminants at depth in the new domestic well (open from 300 to 375 feet in Cambrian sandstone) suggests that VOCs may be migrating from the landfill as a dense non-aqueous phase liquid (DNAPL).

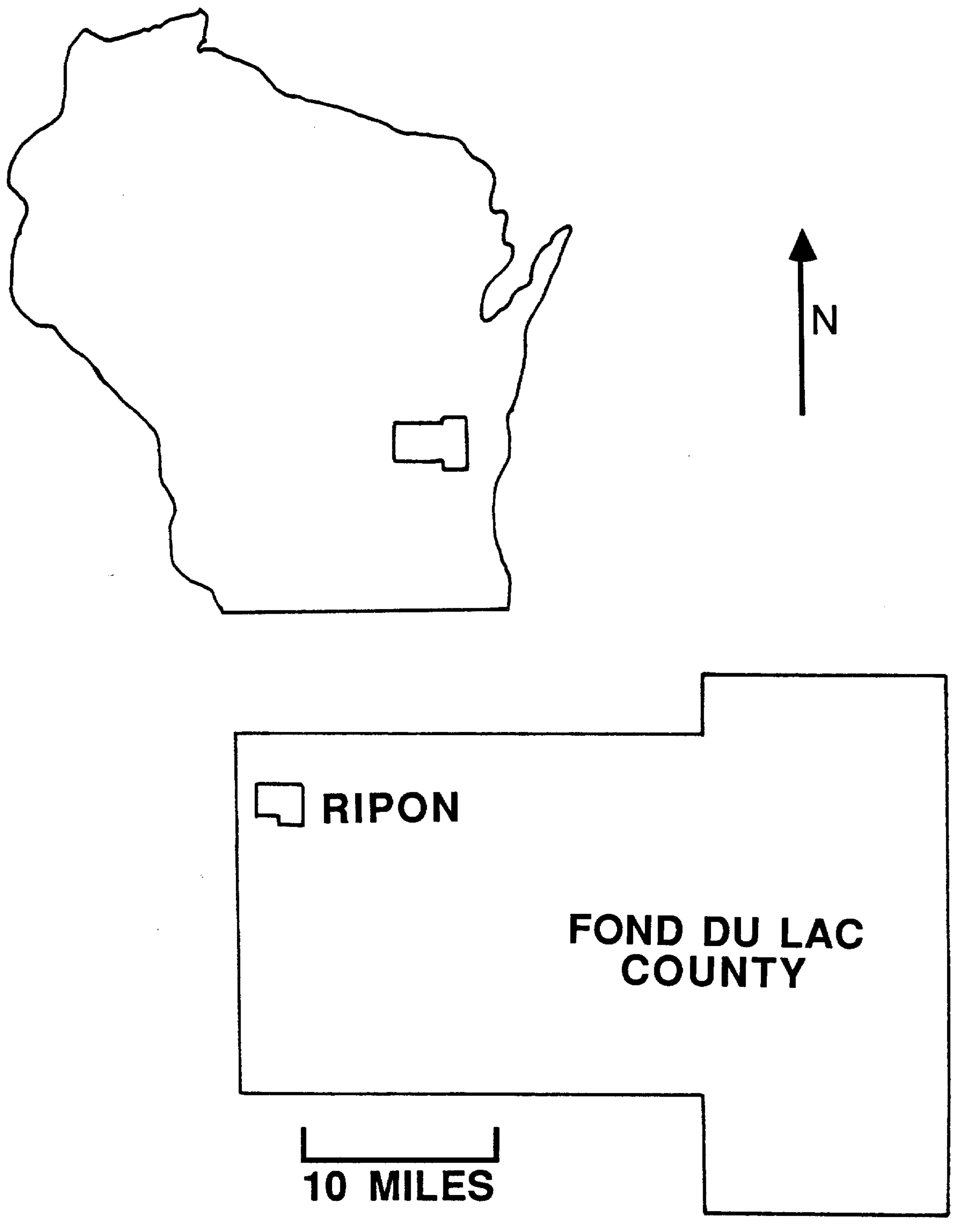


Figure 1.1. Location map showing Fond du Lac County and Ripon.

DNAPL plume migration may deviate from regional groundwater flow, and instead be controlled by the geometry and arrangement of low-permeability surfaces or bodies. DNAPL plumes also produce plumes of dissolved phase contaminants that do move with groundwater flow.

Wisconsin Power and Light Company (WPL) currently owns and operates four municipal wells in the Ripon area (Figure 1.2). Pumping of these wells may alter regional groundwater flow and possibly induce migration of dissolved phase VOCs toward the well field. Although no VOCs have been detected there, municipal well #9 is approximately 0.5 miles (0.8 km) from the landfill, and is thus most likely to be threatened by contaminants from that area. The objectives of this research are to determine 1) what, if any, threat VOCs from the landfill pose to water quality in the municipal wells, and 2) if pumping of the wells affects aqueous phase contaminant migration.

B. OVERVIEW OF DNAPL BEHAVIOR

Although this study did not model DNAPL behavior or locate plumes precisely, the behavior of these contaminants guided the investigation of this problem. The suspected presence of DNAPLs warrants a brief discussion of their properties and behavior before proceeding. Feenstra and Cherry (1988) review DNAPL behavior in the subsurface, and much of their discussion follows from the

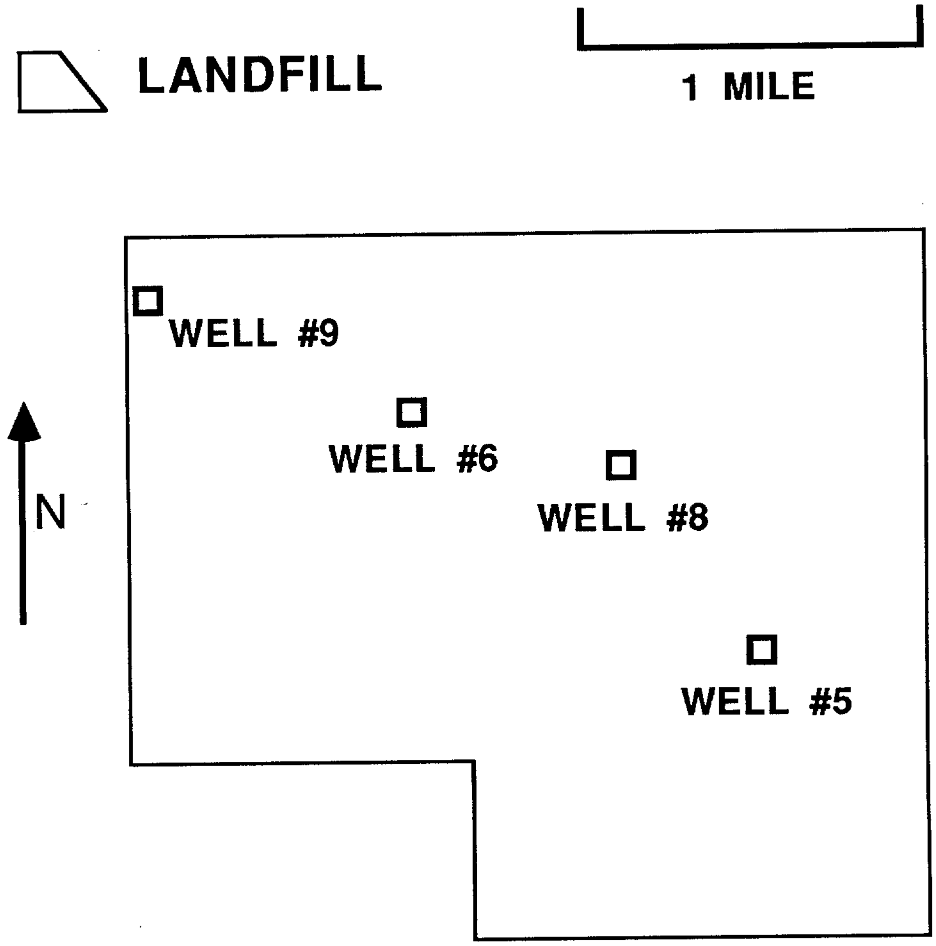


Figure 1.2. Map showing location of municipal wells in the City of Ripon. Note proximity of well #9 to the landfill.

experimental work of Schwille (1981, 1988). In addition, Kueper et al. (1989) and Villiaume (1985) review, respectively, laboratory and field behavior of DNAPLs.

As the name implies, DNAPL chemicals are denser than water ($\rho > 1.0$ g/cm^3), and are relatively insoluble in water. Even though their solubilities in water may be low, concentrations in water can exceed existing drinking water standard levels. DNAPL chemicals are common; approximately one quarter of the chemicals on the U.S. EPA list of priority pollutants are DNAPLs under normal subsurface conditions (Feenstra and Cherry, 1988). Many DNAPL chemicals are suspected or known carcinogens. Thus, they are significant and potentially dangerous sources of groundwater contamination. Some common DNAPLs include DCE, TCE, VC (all three found within the Ripon landfill), carbon tetrachloride, dichlorobenzene, bromoform, chloroform, methylene chloride, composite mixtures of such chemicals, and other substances such as coal tars. Many of these chemicals are used in large quantities as solvents and in other manufacturing processes. As a result, they are commonly found at disposal sites, especially as mixtures of the various chemicals (Feenstra and Cherry, 1989; Villiaume, 1985).

Another significant physical property of DNAPLs is a low viscosity, frequently lower than water (Schwille, 1981). This allows a DNAPL to penetrate rapidly downward in the unsaturated and saturated zones. Once in the saturated zone, this penetration depends upon capillary pressure and retention capacity. If the volume of the DNAPL is large enough, the fluid will displace groundwater and move vertically with little lateral spreading. Vertical migration halts when a lower permeability layer is encountered, whereupon the DNAPL will pool and spread out or pond, depending upon the topography of the less permeable layer (Figure 1.3). The work of Kueper et al. (1989) indicates that subtle changes in permeability, and hence the capillary pressure that must be overcome by the DNAPL, can cause such ponding and pooling. When sufficient DNAPL accumulates to overcome the capillary pressures, migration through these inhomogeneities continues.

Migration is generally independent of groundwater flow patterns. Schwille (1988) describes laboratory experiments in which downward movement of TCE and tetrachloroethylene in sands was unaffected by horizontal flow velocities up to 5.0 x 10-4 ft/sec (14 m/day). In addition, movement of pooled DNAPL may be dictated by topography of basal boundaries, and so the liquid may move down-slope or down-dip, regardless of groundwater flow directions. If depressions in the basal boundary exist, the DNAPL may flow into these, collect, and cease movement.

Another factor that may control movement is the presence of conduits, such as wells and borings. Care must be taken to avoid any sort of cross-contamination during drilling, as a DNAPL will easily flow down an uncased or poorly constructed well (Villiaume, 1985; Feenstra and Cherry, 1988). Abandoned or buried wells may also act as conduits.

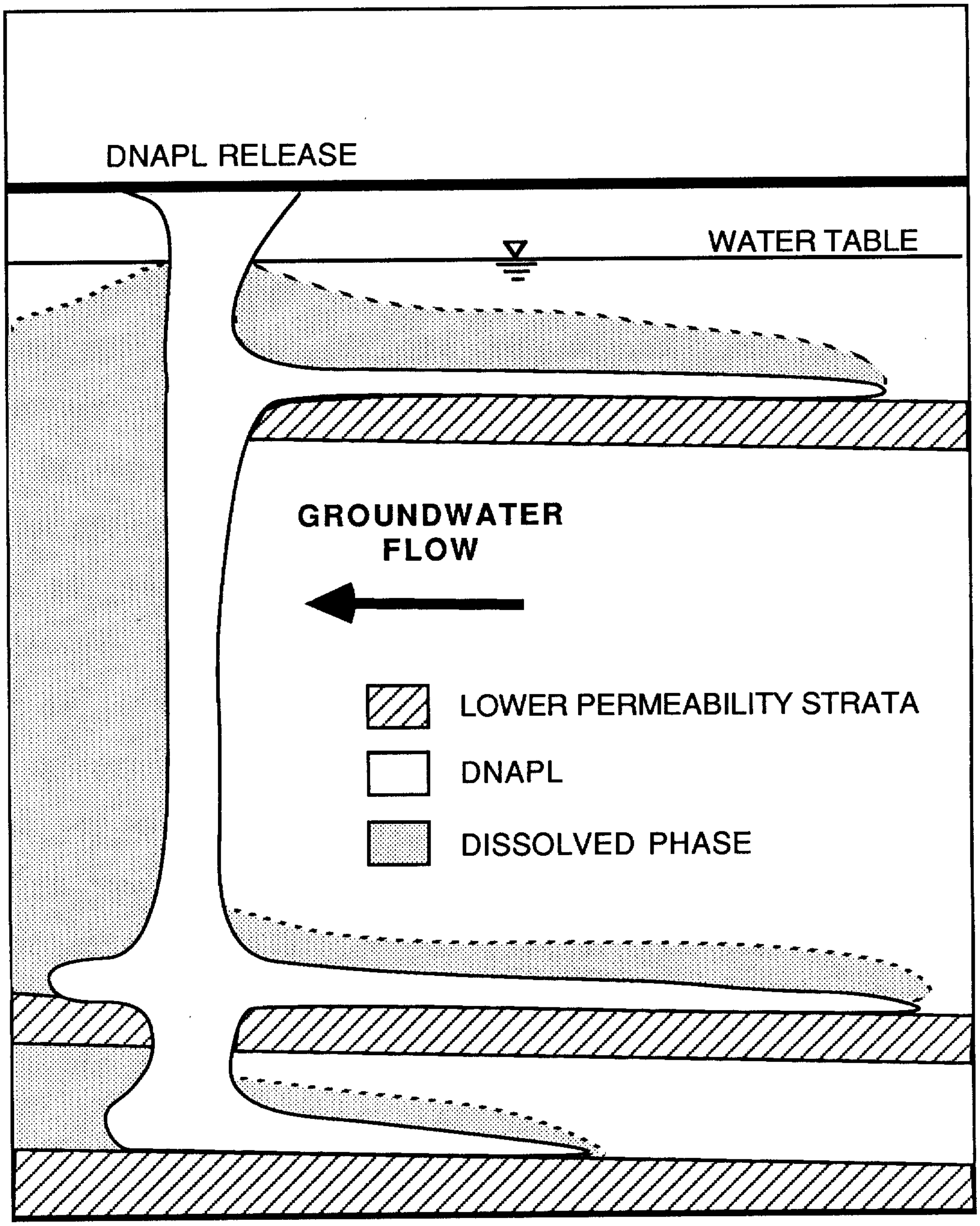


Figure 1.3. Schematic representation of DNAPL migration. (After Feenstra and Cherry, 1988)

As noted above, the DNAPL body is not the sole phase of contaminant present. A dissolved phase plume emanates from the ponds and vertical stringers of DNAPL, as well as from any residual chemical remaining in the porous medium after the main body has passed or dispersed. As long as these pools and residual concentrations remain in the subsurface, some down-gradient contamination by the aqueous phase is likely.

Because DNAPL migration is independent of groundwater flow, the immiscible contaminants can move much more rapidly than a dissolved phase introduced at the same time and location. This is possible in both the horizontal and vertical senses of motion, resulting in contamination patterns that are significantly different than those produced by a near surface source (Feenstra and Cherry, 1988). Manifestations of such patterns include increasing concentration of the aqueous phase with depth, occurrence of contaminants in either phase a relatively long distance from potential sources, and contamination up- or cross-gradient from source areas.

C. APPROACH AND OVERVIEW

Three main objectives were designed to provide an initial assessment of the threat VOCs from the landfill might pose to water quality in the municipal wells. These objectives are:

1. Determining the nature of the contaminant phase or phases

2. Assessing effects of the municipal well field on dissolved-phase movement

3. Predicting the threat contaminants pose to the municipal well field, especially municipal well #9.

To accomplish these objectives, two main methods of investigation were employed. First, installation and sampling of nested multilevel monitoring wells provided information regarding distribution of VOCs, as well as an opportunity to study cuttings and correlate them with existing information in the vicinity of the landfill to locate possible basal boundaries for DNAPL flow. In addition, these wells were observation wells for a pumping test and provided water level information that aided in calibration and verification of a three-dimensional groundwater flow model. A groundwater flow model was the second main method of investigation. When coupled with a particle tracking routine, this model was used to delineate flow paths and travel times of aqueous phase contaminants. This model also was used to examine potential effects of municipal well field pumping upon contaminant migration. The steady-state model was also used to backtrack particle movement and thus identify possible dissolved phase source areas, which may imply the presence of a DNAPL, especially if the source areas are outside of or below the landfill.

Chapter 2 presents results from the first method mentioned above, as well as associated information regarding the hydrogeology and other hydrologic characteristics of the study area that were incorporated in a conceptual model. Creation of the conceptual model from these data leads to Chapter 3, which presents design, calibration, and verification of the three-dimensional groundwater flow model. Results from particle tracking are also included in the third chapter. Chapter 4 summarizes results and lists conclusions and suggests strategies for future work on this problem.

CHAPTER 2:
INVESTIGATION OF THE SITE AREA; FORMULATION OF THE CONCEPTUAL MODEL

A. INTRODUCTION

Construction of a conceptual model is the first step in modeling a groundwater flow system. Information to do this comes from relevant geologic and hydrologic data. For this study, the bulk of such data came from existing studies, but field investigations involving installation and sampling of monitoring wells provided data essential to understanding local hydrogeologic conditions. Dissolved phase migration was modeled in addition to groundwater flow. Accordingly, the conceptual model outlined here will incorporate data pertaining to both the hydrogeologic framework and VOC distribution.

B. HYDROGEOLOGY

1. Introduction

The study area (Figure 2.1A), located in northwestern Fond du Lac county, is in the Eastern Ridges and Lowlands physical province. Topography is moderate, with resistant rock units forming uplands separated by valleys filled with glacial material, which also blankets the higher areas (Paull and Paull, 1977). The study area is in the

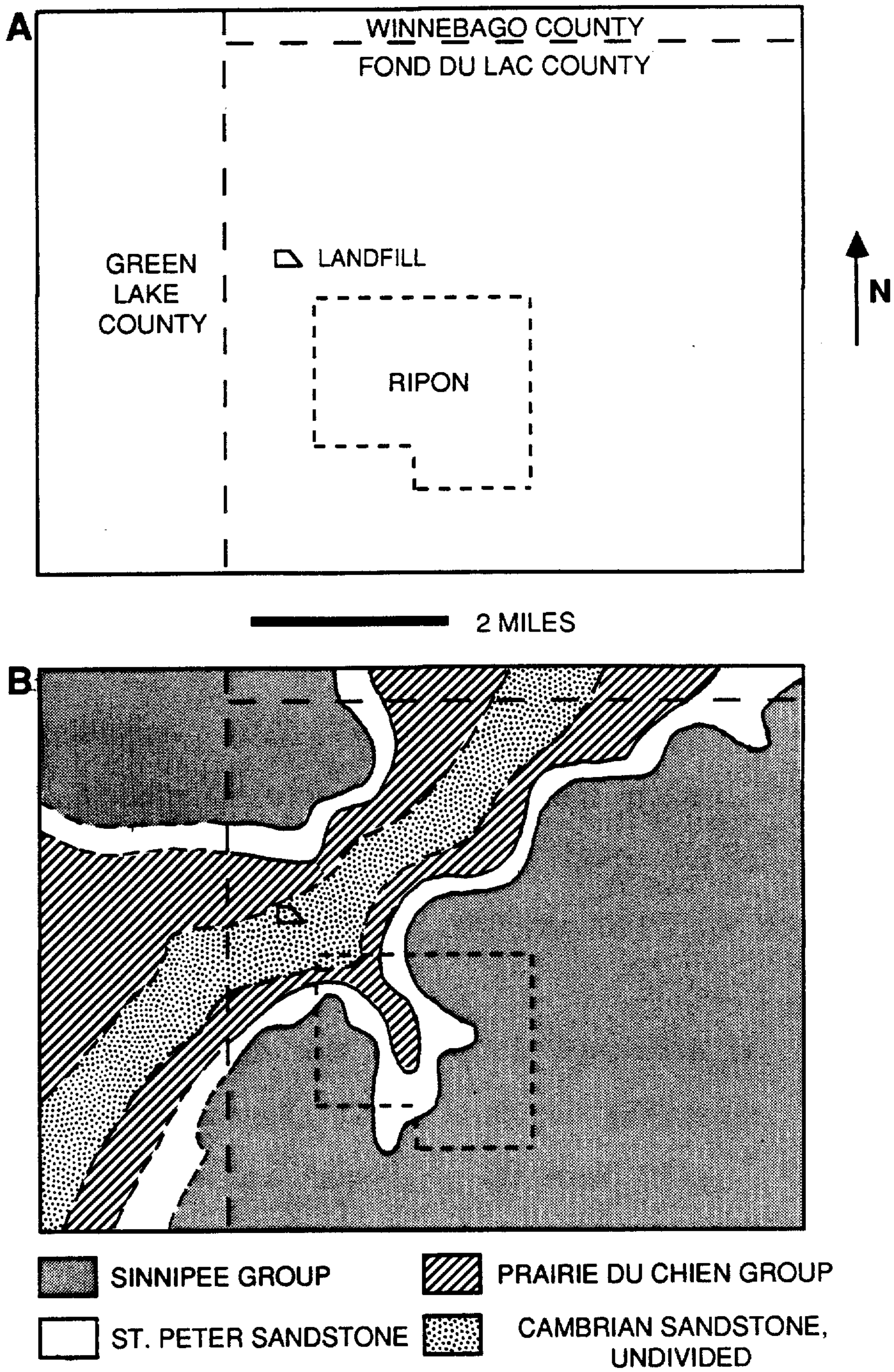


Figure 2.1. A: Map of the study area.
B. Sketch map of bedrock geology. Cambrian sandstone boundaries are not well defined. See Figure 2.2 for more detailed stratigraphic information.
(After Newport, 1962)

Fox-Rock River basin (Olcott, 1968), and is drained by Silver Creek, which feeds into Green Lake and ultimately the Fox River.

Bedrock units in the area include Precambrian crystalline rocks, Late Cambrian sandstones, and Early to Middle Ordovician sandstones and carbonates. Structurally, the Paleozoic units dip gently to the southeast and are overlain to the southeast by younger units of Late Ordovician to Silurian age. The Precambrian surface also dips to the southeast, with poorly defined local highs located to the immediate southeast and east of the study area (Thwaites, 1957; Newport, 1962; Olcott, 1966). This results in a slight thinning of older bedrock units, and also serves to control groundwater flow in those units (Newport, 1962; Olcott, 1968). As noted above, units younger than Middle Ordovician age are not present. All existing units crop out or subcrop in the area (Figure 2.1B). Figure 2.2 indicates accepted lithostratigraphic nomenclature for the Paleozoic sedimentary rocks.

Groundwater flow in this region of Wisconsin is considered to move generally east towards Lake Michigan (Zaporozec and Cotter, 1985), but in the study area flow is to the west. This is controlled by ridges of Precambrian rock adjacent to the area. Newport's (1962) potentiometric surface for the Cambro-Ordovician units illustrates this flow pattern.

Domestic, industrial, and municipal wells commonly tap the Cambrian sandstones and the St. Peter Sandstone, although the Prairie du Chien dolomite units are occasionally productive. The

SYSTEM	GROUP	FORMATION
Ordovician	Sinnipee	Galena
		Decorah
		Platteville
		St. Peter
	Prairie du Chien	Shakopee
		Oneota
Cambrian	Trempealeau	Jordan
		St. Lawrence
	Tunnel City	Lone Rock/ Mazomanie
	Elk Mound	Wonewoc
		Eau Claire
		Mt. Simon

Figure 2.2. Paleozoic stratigraphy of the study area. All units comprise the Cambro-Ordovician Sandstone Aquifer. The aquifer is underlain by Precambrian basement and overlain by Quaternary glacial deposits. (After Ostrom, 1967.)

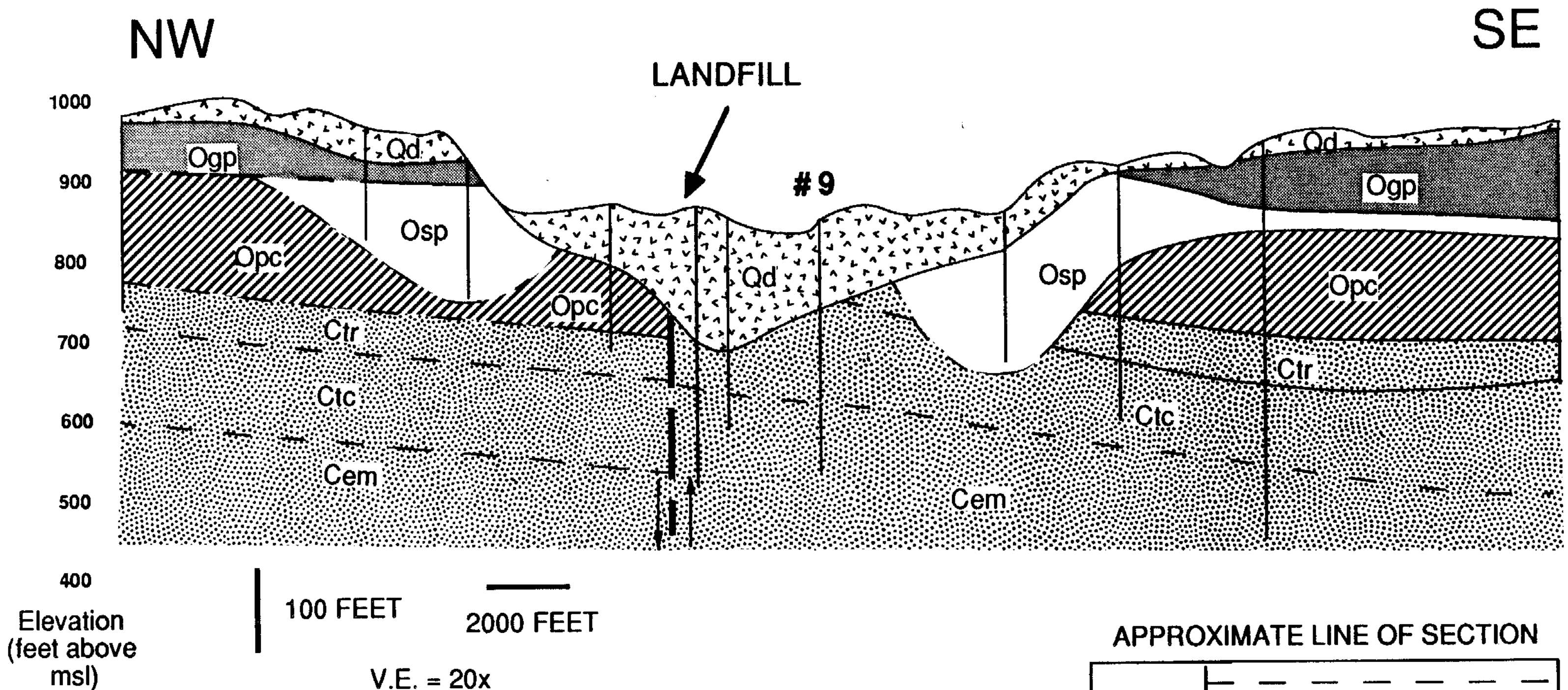
glacial deposits are rarely used as sources of water (Wisconsin Geological and Natural History Survey, unpublished well logs). Because of this, little hydrogeologic information is available for the glacial deposits. Since the municipal wells tap bedrock and all VOC information (outside the landfill) is from wells open to bedrock, this lack of detailed data is not considered detrimental to this study.

Aside from the work of Alden (1918) and Newport (1962), very little work has been done in the specific study area, which includes small portions of Green Lake County and Winnebago County. No geologic or hydrogeologic reports regarding Green Lake County exist, but Olcott (1966) described the hydrogeology of Winnebago County, as well as the Precambrian highs to the south and southeast. Mai And Dott's (1985) study of the St. Peter Sandstone, is the only comprehensive subsurface study for Eastern Wisconsin.

To the north, Krohelski (1986) and Feinstein and Anderson (1986) have modeled groundwater flow, and to the south, Weaver (1988) also modeled the Cambro-Ordovician groundwater system. Emmons (1987) modeled flow for a large region that includes this study area. These reports will be the primary source of data for modeling parameters.

2. Structural Framework

Although the geologic framework appears relatively simple at first, there are some complicating factors. For example, as noted previously, Paleozoic strata dip gently to the southeast at 15 - 30 feet per mile (<1°) and the lowest units thin to the southeast due to the Precambrian highs. Also, an erosion event prior to St. Peter time removed varying amounts of older units, especially the Prairie du Chien Group, creating irregularities in the thickness of that unit. During this time, a northeast to southwest trending valley up to 200 feet deep ran through the present location of the city of Ripon (Figure 2.3). This was filled with St. Peter Sandstone, placing the St. Peter in contact with sandstone of the Cambrian Tunnel City Group. In addition, prior to deposition of glacial materials a river ran through the area on a course subparallel to the pre-St. Peter valley (Alden, 1918; Olcott, 1968). Both Rush Lake and Green Lake lie in this valley, as does the Ripon landfill. Logs of domestic wells in the valley show fill thickness up to 225 feet and Alden (1918) reports that Green Lake is up to 247 feet deep. The valley is flanked on the southeast and northeast by scarps capped by the Sinnipee Group and may have a fault subparallel to its axis. The evidence for this fault is equivocal, but the arrangement of units as seen in the cross section (Figure 2.3) suggests a possible displacement of Paleozoic units across the valley. The pre-glacial valley and other erosional features have a profound effect on the conceptual model, owing to the complexity they introduce. Figure 2.4 shows a schematic northwest-southeast cross section and indicates the general relations of all the lithologic units.



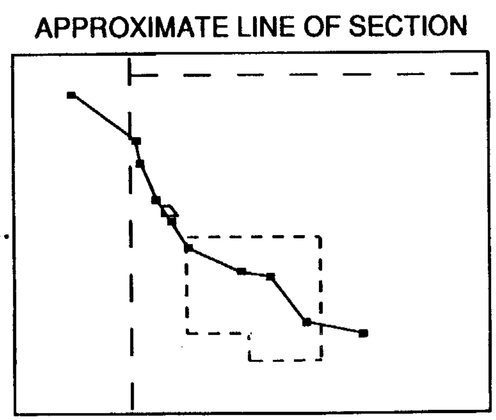
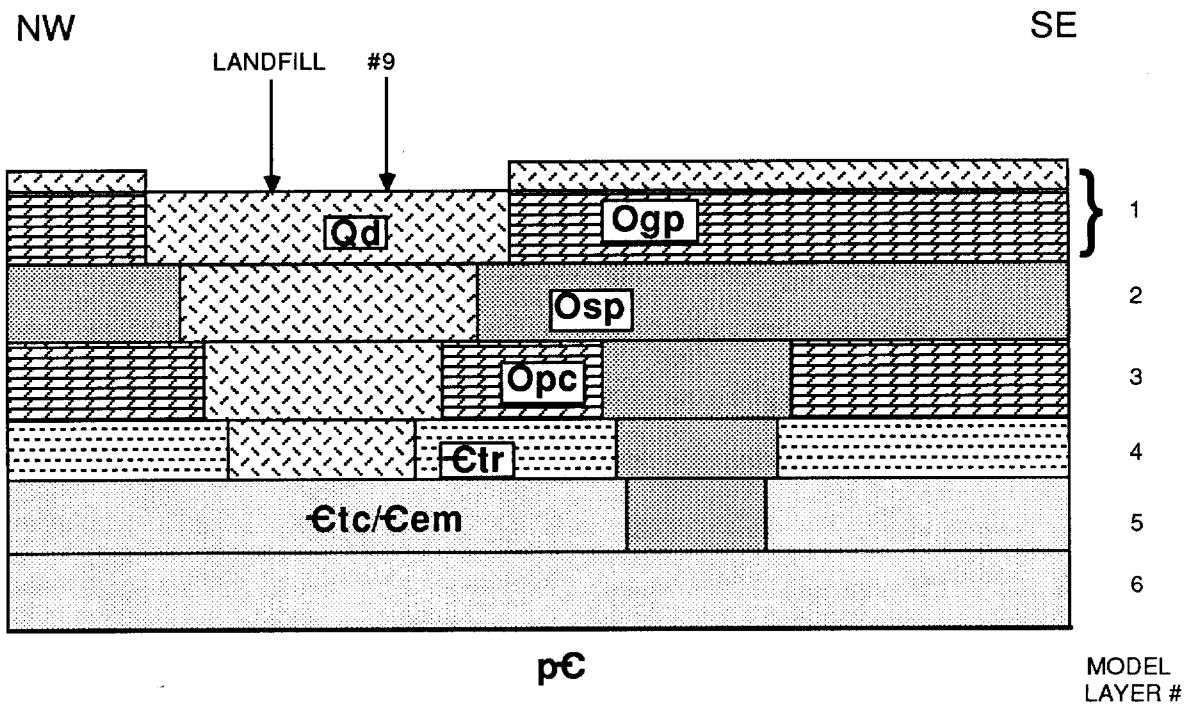


Figure 2.3. Cross section through modeled area. Vertical lines show location and depth of well control (squares on inset map). Contacts and fault dashed where inferred. Qd = drift; Ogp = Sinnipee Group; Osp = St. Peter Sandstone; Opc = Prairie du Chien Group; Ctr = Trempealeau Group; Ctc = Tunnel City Group; Cem = Elk Mound Group. See Figure 2.4 for more information.



EXPLANATION

UNIT	DESCRIPTION
Qd	Glacial deposits ("drift") consisting largely of gravel and sand with silt and clays; fills in paleovalley
Ogp	Galena - Platteville dolomite (Sinnipee Group)
Osp	St. Peter Sandstone; fills in paleovalley
Opc	Prairie du Chien Group; dolomite and sandy dolomite
€tr	Trempealeau Group; sandstones with some siltstones
€tc/€em	Tunnel City and Elk Mound Groups; sandstones (grouped as one hydrogeologic unit)
p€	Crystalline and metamorphic basement; forms bottom no-flow boundary

Figure 2.4. Schematic cross section through the study area. Model layers also designated. Unit symbols are utilized in other figures.

3. Hydrostratigraphic Units

Given the complexity outlined above, it was necessary to treat most of the lithostratigraphic units as separate hydrostratigraphic units. These units were assembled as needed to represent the study area, and then divided into layers based on the relations seen in the map (Figure 2.1B) and the cross section (Figure 2.3). Doing this required construction of a full three-dimensional flow model to represent the flow system, as the geometry of the units makes definition of aquifers and confining units difficult in two dimensions. In this approach, each layer is not a unique rock type with the same properties, but instead is assigned hydrogeologic properties based on which rock type is present in each area of the layer. Lithostratigraphy and hydrogeologic properties provide the basis for assignment of hydrostratigraphic units, as outlined below.

a. Precambrian Basement

Precambrian basement in the area consists of crystalline metamorphic rocks of various protoliths and grades. Rhyolite crops out in Green Lake and Winnebago Counties (Alden, 1918; Olcott, 1966) while quartzite has been encountered at the bottom of a municipal well in the city of Fond du Lac (Newport, 1962). Thwaites (1931) states that the highs to the south and southeast of Ripon are dominated by metasedimentary rocks. Regardless of specific rock type, the Precambrian basement in this area will be considered impermeable, and so provides a basal boundary for the groundwater flow system. There is no basis for considering fracture flow in this area. Although there is no direct evidence for depths to this surface, estimates may be based on the work of Thwaites (1957), Olcott (1966), and Spicer (1950).

b. Cambrian Sandstones - Elk Mound and Tunnel City Groups

These units, as defined by Ostrom (1967) replace the older Dresbach Group and Franconia Sandstone designations. Newport (1962) indicates that the rocks of the Dresbach and Franconia are the most productive sources of groundwater in Fond du Lac County. The Elk Mound Group is in direct, unconformable contact with the Precambrian basement and is overlain conformably by the Tunnel City Group. Both groups are dominantly quartz sandstone, with the Elk Mound consisting of poorly cemented fine to coarse grained sandstone with some siltstone. Examination of geologic logs shows occasional "siliceous white shale" (WGNHS, unpublished well logs). In the cuttings retrieved during well installation, this material was useful for identifying the Elk Mound Group. Without further study, this nomenclature seems useful, if not entirely appropriate. This material is very fine grained, occasionally shows fissility, and fails to react with hydrochloric acid, even when powdered.

The Tunnel City group consists of two laterally equivalent formations, the Lone Rock and Mazomanie. The Mazomanie is commonly present in south-central Wisconsin, while the Lone Rock is more common to the east (Ostrom, 1967). The Tunnel City Group in the vicinity of Ripon consists of the Lone Rock Formation, a glauconitic and sometimes silty sandstone. The glauconite is thus a useful marker of the Tunnel City Group and may be used to distinguish this unit (C.W. Byers, pers. comm.) This study treats these two lithostratigraphic units as one hydrostratigraphic unit, following the examples of Krohelski (1986) and Weaver (1988). Thickness of this hydrostratigraphic unit ranges from 120 to 390 feet.

c. Trempealeau Group

On the regional scale (e.g. Zaporozec and Cotter, 1985) this unit has been considered part of the Cambro-Ordovician sandstone aquifer, but it has also been treated as a confining unit (e.g. Krohelski, 1986; Emmons, 1987). The Group comprises of two subunits, the St. Lawrence and Jordan Formations. The St. Lawrence is a silty dolomite to dolomitic siltstone, and is not always present. The Jordan Formation is mostly clean, dolomitic fine to coarse sandstone with some siltstone, shale, or dolomite interbedded. In the Ripon area, both formations are present, but the St. Lawrence is locally absent. Thicknesses range from 0 to 50 feet, and Newport (1962) states that the Trempealeau Group, when present, is a poor producer of water due to the siltstone and/or dolomite. The presence of the fine clastics and carbonate suggest that this unit acts to inhibit movement of groundwater and has lower hydraulic conductivity than the other Cambrian sandstones. This unit and all younger units were not encountered during monitoring well installation, so no further comments regarding cuttings may be made. These units will together be treated together as one hydrostratigraphic unit, since there is not enough information to discriminate between the formations.

d. Prairie du Chien Group

This group is made up of the Shakopee and Oneota Formations, which are mostly hard, cherty dolomite with occasional sandstone or dolomitic sandstone in the Shakopee. Occasional evidence for these sandy intervals is seen in well logs for this area, but not enough to distinguish between the two formations. Thickness of this group varies considerably because of the erosion event which preceded St. Peter deposition. In some portions of the study area, the Prairie du Chien is absent due to this event, such as in the St. Peter-filled paleovalley. Elsewhere, thicknesses range from 20 feet to 90 feet (WGNHS, unpublished well logs). This is not a major water producing unit, but can yield sufficient water to support domestic use when fractured or sandy (Newport, 1962).

e. St. Peter Formation

The next hydrostratigraphic unit is the St. Peter Formation, the uppermost unit in the Cambro-Ordovician sandstone aquifer. The Tonti Member is a white to gray, fine- to medium-grained poorly cemented sandstone with virtually no finer material such as shale (Mai and Dott, 1985). The Readstown Member is a sandy and locally conglomeratic shale, present locally as scattered lenses at the base of the formation. The Tonti is present everywhere except in the pre-glacial valley area, while the Readstown shows in only a few logs within the pre-St. Peter paleovalley and is of little consequence

(WGNHS, unpublished well logs). Thicknesses vary from 20 to 200 feet, dependent upon the extent of erosion prior to deposition. The St. Peter Sandstone is another significant water producing unit, tapped by municipal well #6 as well as by many domestic wells (WGNHS, unpublished well logs). Although both members of this unit are present, they will be treated as one hydrostratigraphic unit, owing to the predominance of the Tonti Member.

f. Sinnipee Group

Commonly referred to as the Platteville and Galena Formations, rocks in this unit are fossiliferous gray to blue-gray dolomite with some interbedded shale and fossil fragments. In some areas of Wisconsin, the Decorah Formation, a shale, lies between the Platteville and the Galena (Newport, 1962; Ostrom, 1967). Because logs in the area show no evidence of the Decorah (WGNHS, unpublished well logs), the two dolomite formations may be considered to be part of one hydrostratigraphic unit. Thickness of the group ranges from 10 to 160 feet, increasing to the southeast. In the study area, this unit subcrops beneath Pleistocene deposits, except where it forms scarps bounding the pre-glacial bedrock valley. Drift covering the Sinnipee Group is usually less than 50 feet thick, and for simplification, the Sinnipee and the drift were grouped as one hydrostratigraphic unit, as seen in Figure 2.4. The Sinnipee is not a significant water source except where fractured and/or dissolved. Weaver (1988) found that where the Sinnipee subcrops, its hydraulic conductivity is higher than commonly reported estimates.

g. Pleistocene Deposits

Pleistocene (glacial) deposits (also referred to as "drift") in the area are mostly outwash and ground moraine from the Green Bay Lobe of Late Wisconsinan time (Alden, 1918; Mickelson et al, 1984). The lithostratigraphic name for these deposits is the Horicon Formation (Mickelson et al., 1984), which is mostly sandy till with associated sand and gravel. Alden (1918) describes the valley fill as pitted gravel and outwash terraces related to the Rush Lake end moraine, which impinges on the northeastern margin of the study area. The till and outwash represent a wide range of sediment types (gravel, sand, silt, clay) that are interbedded in a complex fashion. As such, the use of one hydrostratigraphic unit to describe the valley fill was preferable, as it keeps the model simpler. Also, there is not enough information to subdivide the glacial deposits into multiple hydrostratigraphic units. Given this and the fact that the problem here is mostly bedrock-related (the municipal wells are cased in bedrock and contaminants have been detected there), the adoption of a single hydrostratigraphic unit seems justified. Thickness of these deposits ranges from 0 to 225 feet, with the thinnest deposits over the Sinnipee Group, and the thickest in the bedrock valley. As noted before, where it overlies the Sinnipee Group, the drift and the bedrock were treated as a single hydrostratigraphic unit.

C. MONITORING WELLS

1. Introduction

Three sets of monitoring wells were placed between the landfill and municipal well #9 (Figure 2.5). At MW-1 and MW-2, there are three nested piezometers within each well, while MW-3A and -3B are individual wells at differing depths. These wells were installed to 1) allow examination of cuttings to check for possible basal boundaries for DNAPL flow between the landfill and the well, 2) monitor groundwater for VOC contamination at different depths to detect any migration towards the municipal well, as well as to look for increasing concentration with depth (thus indicating the presence of DNAPL), and 3) provide water level measurements for model calibration. Locations were chosen to provide stratigraphic information between the landfill and municipal well #9, as well as to detect contaminant movement towards well #9. Details of well installation and construction are provided in Appendix A.

2. Stratigraphy and piezometer placement

At nest MW-1 (Figure 2.5; Appendix A), 123 feet of surficial and glacial deposits overlie bedrock. These deposits consist mostly of sand and gravel, with one significant clay body from about 30 feet to 69 feet depth, and a smaller lens from 88 to 90 feet. In each case, these clay bodies have distinct sand or gravel lenses within, as well as subangular clasts that suggest some ice-marginal deposition. The

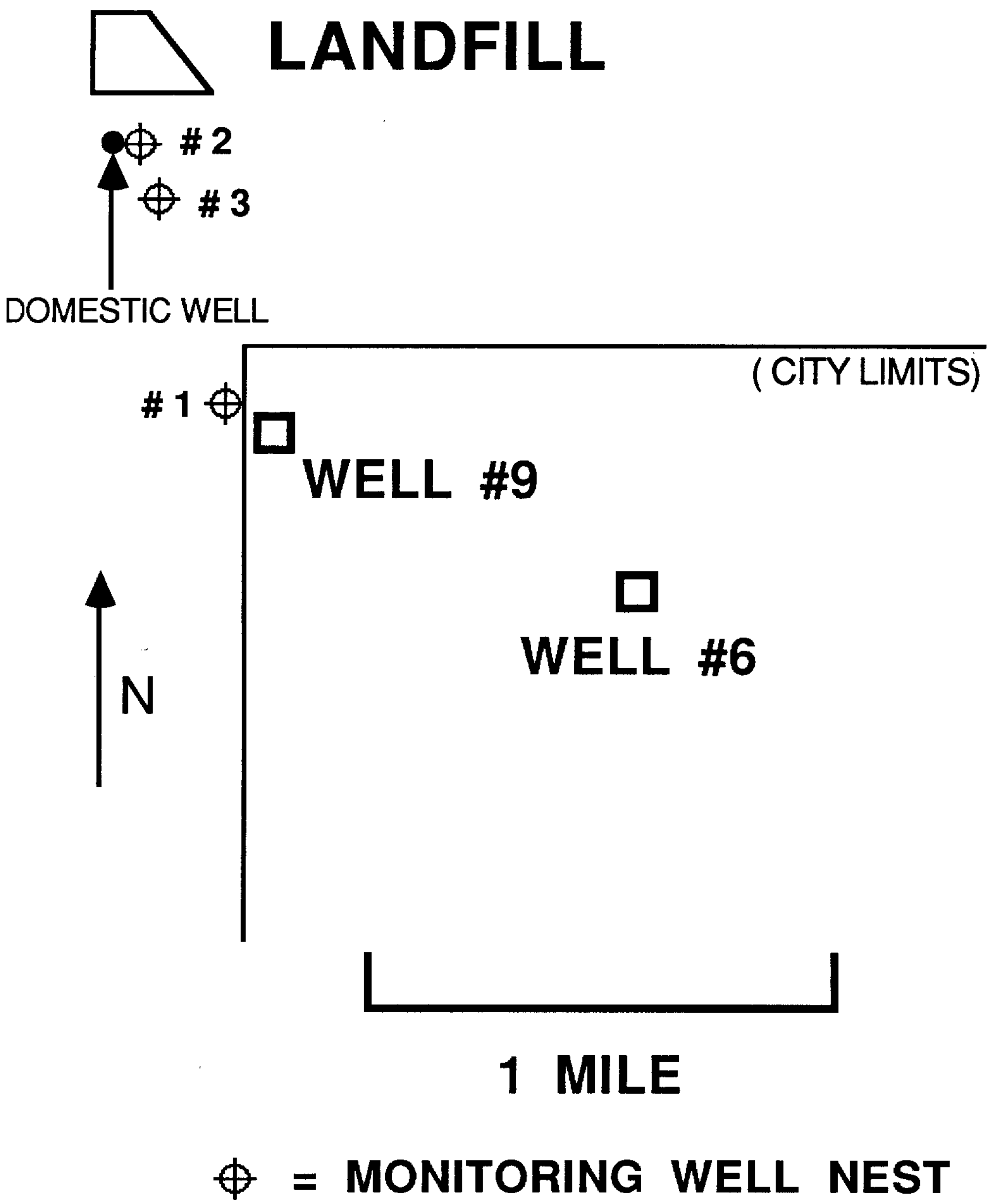


Figure 2.5. Map showing locations of monitoring well nests.

remainder of deposits are probably glaciofluvial, given Alden's (1918) description of this area. Below 123 feet, Cambrian sandstones of the Tunnel City and Elk Mound Groups are present. The contact between the Tunnel City and the Elk Mound is hard to place. A few distinct siltstone layers exist at 180 feet and 190 to 196 feet, as well as some interspersed shale, and from 262 to 264 feet, there is a definite layer of orange chert. In other geologic logs (WGNHS, unpublished well logs), the boundary is placed below a silt or shale layer, or below the last significant occurrence of glauconite. Here, the contact may be placed anywhere from 198 to 225 feet, and for the purposes of the model, it is placed at 200 feet depth. The identification of these units is fairly certain, as the significant amounts of glauconite generally are indicative of the Tunnel City Group (C.W. Byers, pers. comm.). Other geologic logs (WGNHS, unpublished) have called sandstones with the chert, minor "white shale", and pale red to maroon cemented layers Elk Mound.

Bedrock at nest MW-2 (Figure 2.5; Appendix A) is somewhat similar, although there is less of the Tunnel City Group present. The Elk Mound Group here shows less chert, many more hematitic concretions, and much more "white siliceous shale." Another noticeable difference is the lack, in either unit, of distinct layers of siltstone, shale, or chert. This rules out any confident correlation of low permeability layers within the bedrock that might serve as basal boundaries for DNAPL flow. There is also no discernible layer or unit in the glacial material which might be confidently correlated to MW-

1. While MW-1 was dominated by sand and gravel, the deposits at MW-2 show a significant clay and silt lens from 70 feet to 142 feet, with sandy gravel and sand above and below. Some of the silt and clay chips brought up during drilling displayed fine lamination, suggesting that portions of this body are lacustrine in origin, which implies that this lens may be of limited areal extent. This silt and clay unit may also extend under the landfill, since trace amounts of VOCs were detected as drilling proceeded past the top of the layer. The top may then be one basal boundary for DNAPL migration.

Because MW-3 (Figure 2.5; Appendix A) was drilled using direct circulation rotary methods, lower quality cuttings were recovered compared to the other wells. Using mud to drill through the drift causes a loss of fine (silt, clay) particles, meaning that one must rely on the drillers' expertise regarding the "feel" of various sediment types and on any chips that might be brought up. Virtually no chips were recovered, but some loose sediment settled out of the drilling fluid, and this was mostly sand and/or gravel. Also, cuttings may collect material from the sides of the hole as they move upward, which is manifested here by a seemingly continual presence of sand, even where the driller reported tight clay. In the graphic log of MW-3 (Appendix A), sand is almost continually present. A silt and clay lens from about 45 to 120 feet may correlate with the lens at MW-2, but here there are many more sand and gravel lenses. It is likely that these bodies correlate, especially given the elevation difference between the wells (Figure 2.6; Appendix A).

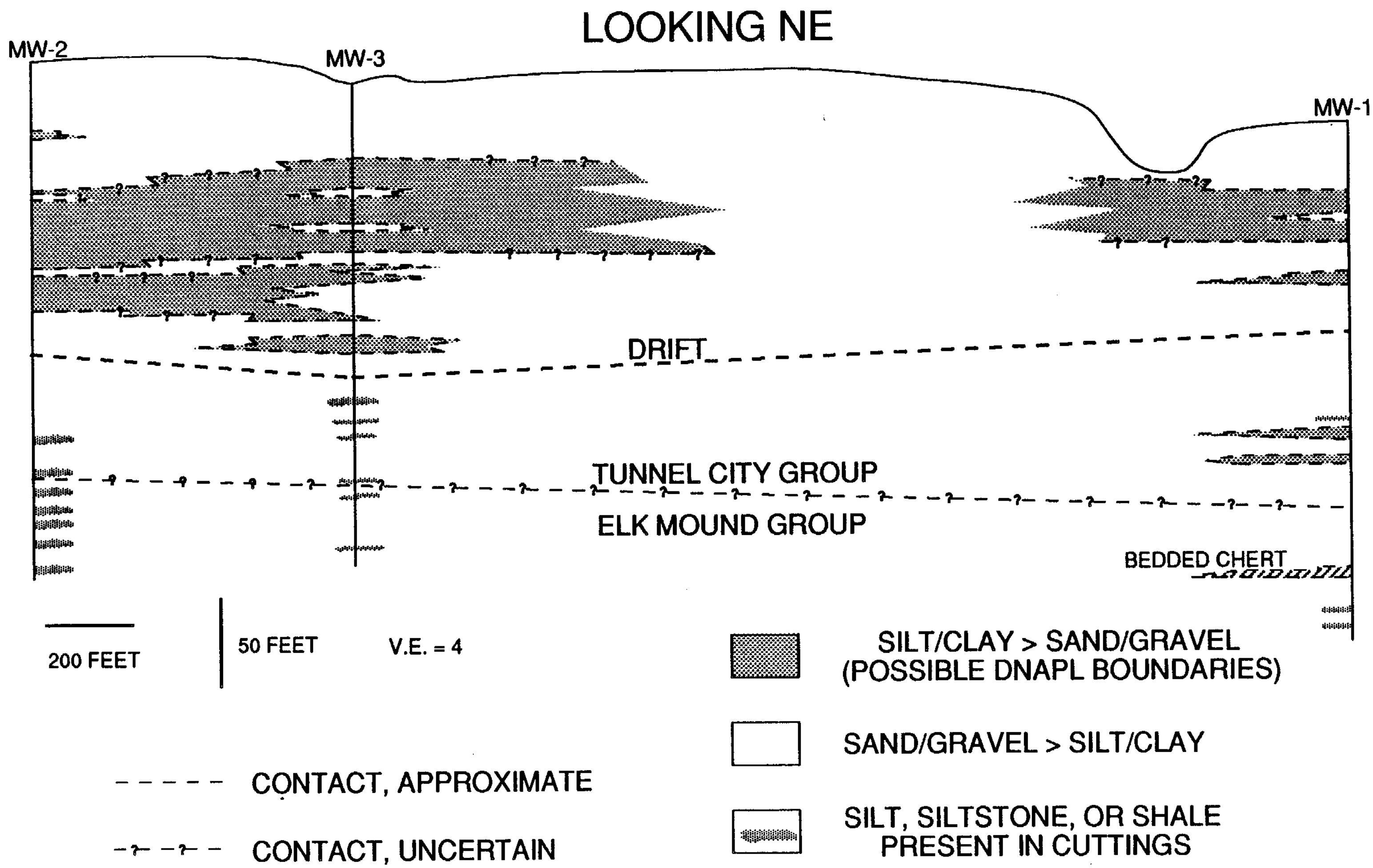


Figure 2.6. Cross section between monitoring wells. Correlation of the silt and clay units is difficult, especially between MW-3 and MW-1.

Assuming these are lacustrine deposits of silt and clay, these wells may be near the margin of the lake, which suggests that MW-1 is away from or marginal to the lake where fluvial deposits dominate. Thus, this silt and clay lens may be a discontinuous basal boundary which does not extend all the way to municipal well #9 (Figure 2.6).

Bedrock at MW-3 is also Cambrian sandstone, and here there may be even less Tunnel City Group present. Because pale red and maroon layers exist within 10 feet of the bedrock surface, and "white siliceous shale within another 15 feet, it is possible that at most, 20 to 30 feet of Tunnel City exists here. The lower quality of the cuttings at MW-3 obscures the relationships. Within the sandstone, there is some minor silt and shale, but not in distinct layers. Again, this bars identification of DNAPL boundaries in the bedrock.

Placement of the piezometers was originally intended to be based on the arrangement of correlatable low permeability layers, but once MW-2 was drilled, it became apparent that this strategy was not applicable. As a result, the remaining piezometers were placed at roughly equal elevations, and above or near less permeable layers.

3. Sampling

Development and sampling procedures are outlined in Appendix B, and Table 2.1 summarizes the results of sampling from all the monitoring wells. VOCs were present in MW-2S, -2D, and in

TABLE 2.1
SUMMARY OF SAMPLING RESULTS

WELL	DATE	VC (μg/l)	DCE (μg/l)	T (μg/l)
MW-1S	11/15/90	0	0	0
	5/5/91	0	0	0
MW-1I	11/15/90	0	0	0
	5/5/91	0	0	0
MW-1D	11/15/90	0	0	0
	5/5/91	0	0	0
MW-2S	11/15/90	4.2	4.2	0
	5/5/91	2.8	5.2	0
MW-2I	11/15/90	0	0	0
	5/5/91	0	0	0
MW-2D	11/15/90	3.4	3.3	0
	5/5/91	0	0	0
MW-3A	2/18/91	0	0	28
	5/7/91	0	0	35
MW-3B	2/18/91	0	0	25
	5/7/91	0	0	15

VC = vinyl chloride
DCE = 1,2-dichlorethylene
T = toluene

both MW-3 wells. The toluene in the MW-3 wells is probably not related to the landfill, but is likely a result of contaminated drilling fluid. It is not unusual to see benzene, toluene, or xylene in wells that have been drilled with mud-rotary methods, due to contamination of the fluid by fuel or other petroleum products from the drilling rig. Given that toluene concentrations are lower at the landfill (1.0 - 10 μg/l) (WDNR, unpublished report) than in the wells, the occurrence here is very likely due to contaminated drilling fluid. During drilling, there was a loose seal on top of the drill string which may have allowed fuel or grease to contaminate the drilling fluid. Further, toluene is lighter than water and is thus unlikely to have migrated cross-gradient from the landfill to the MW-3 wells

Trans-1,2-dichloroethylene and vinyl chloride were detected in MW-2S and -2D. These are the same VOCs seen in the domestic well, but in lower concentrations. The failure to detect these contaminants in MW-2D in the second sampling round suggests that cross-contamination may have occurred during drilling. Because casing was driven during drilling through the drift, it is possible that the detection in MW-2S is valid, while the MW-2D detection represents contamination downhole from there. It is likely that development of MW-2I was more thorough, while MW-2D was not developed well enough or purged long enough to initially provide a representative sample. A DNAPL may be present at the top of the thick clay and silt layer. This was suggested by a low-level detection of VOCs in the drilling fluid and cuttings with an HNU meter (a hand-held instrument that detects volatile organics) as the bit passed the top of that layer.

As the levels in MW-2 are about an order of magnitude lower than in the domestic well (Figure 2.5), it is possible that a DNAPL plume lies between the two wells. According to Feenstra and Cherry (1988), even wells close to a suspected source may show low concentrations due to heterogeneous DNAPL distribution, non-uniform groundwater flow through and around DNAPL zones and pools and the possible blending of waters during sample collection. Also, since the groundwater flow is generally to the west, the existence of VOCs south of the landfill is another indication of a DNAPL plume that has migrated in the subsurface to the south or southeast from the landfill.

Contamination at the domestic well may be a result of cross-contamination during drilling, given that the most recent well shows high concentrations at depth even though it is cased to 350 feet. Since this well was drilled by mud rotary methods, the casing was not driven until drilling was completed. While the hole was open, some contaminated water may have moved downhole and may not have been removed during development. The old well, if uncased or poorly constructed, may have acted as a conduit for a DNAPL source in the drift, but no log was found and so details of its construction are unavailable.

D. WATER TABLE AND POTENTIOMETRIC SURFACE

As noted previously, groundwater flow in the study area is generally to the west and southwest, as Newport's (1962) composite Cambro-Ordovician potentiometric surface shows (Figure 2.7). Data from well constructor's reports and well logs (WGNHS, unpublished) in the area support this, at least for groundwater in the Paleozoic units. The two data sets are complementary, indicating similar elevations and gradients, but few of the wells are screened in the same intervals. In addition, water levels from the monitoring wells provided more precise water levels that aided in calibration of the groundwater flow model. They also indicate vertical gradients in the sandstone of about 1 foot per 100 feet downward. Water levels derived from well logs and well constructor's reports are of widely varying accuracy, as many wells could not be located accurately enough on topographic maps to estimate surface elevations.

In addition, the levels are from various times in the last 50 years and so do not provide a consistent set of data. This spread of data, however, was useful in calibration of the steady-state models, which represent the system prior to pumping of the municipal well field and under current conditions. One data set represents conditions prior to pumping of the municipal well field, while the other represents conditions in which all municipal wells are pumped, as they are now. This allows steady-state calibration to the two sets of data, although both do not represent specific time periods.

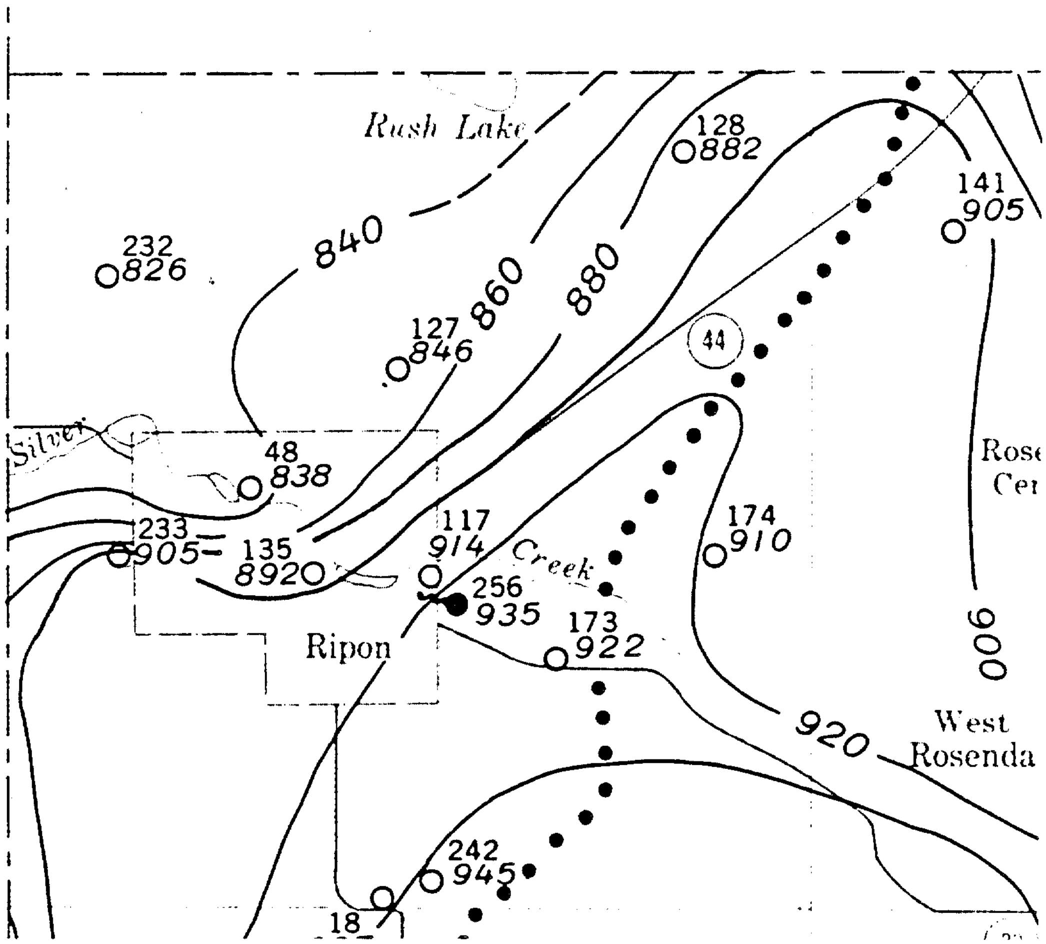


Figure 2.7 The portion of Newport's (1962) potentiometric surface map which includes part of the study area.

Unfortunately, information regarding the water table is virtually non-existent, especially if it occurs in Pleistocene deposits. No wells open to the drift are recorded (WGNHS, unpublished). All information available is for the drift filling the bedrock valley between Rush Lake and Green Lake. Depth to water table was recorded during drilling of the monitoring wells MW-1 and MW-2, but not MW-3, since the mud-rotary method does not allow such measurements. Marshes are indicated on the relevant U.S.G.S. 7.5 minute quadrangles, but verification of these levels was not possible. Silver Creek also provides a general check, but a stream may not necessarily represent the water table for the general area through which it passes. Further complicating this is the fact that the drift in the valley is not always connected hydraulically to the drift overlying the Sinnipee Group because of the steep scarps bounding the valley. A few springs are reported to exist on the scarps southwest of the city, but they could not be located during field work. In the northwest corner of the area, the water table is probably not even in the Sinnipee Group, given the water levels in domestic wells there (WGNHS, unpublished). Thus, the water table occurs in various geologic units, ranging from the drift to the Sinnipee Group to the St. Peter Formation.

Overall, water levels are higher to the east and north, and decline to the west and southwest. Discharge from the system is to Green Lake, Rush Lake, and the surrounding wetlands, although there is probably some underflow. Some groundwater discharges locally into Silver Creek, but no specific data are available. Also, Olcott (1968) shows a potentiometric surface with a local high in the northwestern corner of the study area which could generate flow to both Rush Lake and Green Lake. Lastly, Newport's (1962) potentiometric surface places a groundwater divide east of Ripon, with flow westward from there. Flow lines drawn from this divide to Rush Lake and Green Lake, as well as from the high to the northwest, provide no-flow (streamline) boundaries for the model. Location of boundaries and evaluation of the boundary conditions will be discussed further in the next chapter.

E. RECHARGE

Recharge may be defined as water that enters the saturated zone at the water table surface (Freeze and Cherry, 1979). Fetter (1980) further states that the amount of recharge is controlled by three factors: evapotranspiration and runoff, which prevents some amount of water from recharging a system; hydraulic properties of surficial deposits and other strata in the area of recharge, which control how much water way move to the water table; and the hydraulic properties of the aquifer, which control how much water can move away from the recharge area. If a system is at steady-state, recharge to the aquifer or flow system equals the amount of water exiting the system.

Estimating recharge amounts is difficult owing to the wide variability of the controlling factors mentioned above. Often, it is expressed as a percentage of average annual precipitation. Young and Batten (1980) estimate that 3 to 30% of the precipitation in Wisconsin will recharge aquifers (1 to 10 in/yr). With detailed observation, one may be able to measure recharge, but in this study, recharge had to be taken as a calibration parameter in the flow model. Even so, given an average annual precipitation rate (from 1947 to 1956) of 28.40 inches (Newport, 1962), a range of 0.85 inches to 8.5 inches/yr was used to help constrain estimates for the flow model.

Although the actual areal distribution of recharge is not uniform, it is assumed to be in this case. A lack of specific and detailed data for the whole study area prevents any estimation of areal variation. Feinstein and Anderson (1987) or Stoertz and Bradbury (1989) demonstrate that fixing the water table as a constant head boundary allows estimation of recharge, but the absence of water table data prevents the use of this technique.

F. SURFACE WATER

In the Ripon area, the only significant stream is Silver Creek. Green Lake and Rush Lake are the only surface water bodies of significant size. The lakes provide convenient constant head boundaries, with elevations found on USGS topographic maps. Silver

Creek, however, acts as either a source or sink for the groundwater system. Approximate stream levels were taken from topographic maps, but transient fluctuations in stream level and variations in stream parameters were not investigated. Thus, river conductance (McDonald and Harbaugh, 1988) of Silver Creek was assumed constant and was varied during calibration of the flow model.

G. HYDRAULIC CONDUCTIVITIES OF HYDROSTRATIGRAPHIC UNITS

Prior to the pumping test, no direct measurements of hydraulic conductivity were available for the study area. The results of the pumping test were used for parameter verification, as the test was conducted after completion of model calibration. Other sources were therefore necessary to provide initial estimates for hydraulic conductivities. Calibrated models for nearby regions provide one such source. Weaver (1988) constructed a profile model of an area to the south, incorporating all the Paleozoic units and Pleistocene deposits. Krohelski (1986) modeled flow for Brown County, to the north of the study area. Feinstein and Anderson (1987) also modeled an area north of the site, and Emmons (1987) modeled a large region of Eastern Wisconsin which includes this study area. From these sources a range of conductivity estimates was extracted (Table 2.2) and utilized in construction and calibration of the flow model.

TABLE 2.2
CONDUCTIVITY ESTIMATES FOR MODEL UNITS

UNIT	K_H (feet/sec)	K_V (feet/sec)	REFERENCE
Qd	1.74×10^{-7}	7.28×10^{-10}	W
	6.4×10^{-5}	-------	K (average)
	1.2×10^{-4}	5.4×10^{-7}	F (sand; average)
Ogp	8.33×10^{-5}	1.62×10^{-6}	W (weathered)
	5.94×10^{-7}	7.87×10^{-10}	W
	-------	5.8×10^{-8}	K (average)
	-------	1.2×10^{-9}	E
	2.0×10^{-4}	1.0×10^{-6}	F (top of unit)
	8.0×10^{-7}	1.0×10^{-8}	F
Osp	2.11×10^{-5}	1.76×10^{-6}	W
	2.4×10^{-5}	-------	K (includes Opc)
	9.6×10^{-5}		E (units below Ogp)
	3.0×10^{-5}		F
Opc	1.20×10^{-6}	7.97×10^{-10}	W
	8.0×10^{-7}	1.0×10^{-8}	F
Ctr	1.20×10^{-6}	7.97×10^{-10}	W
	--------	3.5×10^{-8}	K
Ctc/em	1.01×10^{-4}	2.03×10^{-6}	W
	6.3×10^{-5}	-------	K

Key for references:
- W = Weaver, 1988
- K = Krohelski, 1986
- E = Emmons, 1987
- F = Feinstein and Anderson, 1987

Unit abbreviations as in Figure 2.4.

Additionally, specific capacity data from well logs may be used to estimate conductivity using the computer code of Bradbury and Rothschild (1985). The code solves the equation given by Theis et al. (1963) for transmissivity:

$$T = (Q/4\pi s)\ln(2.25Tt/r^2S)$$

where T is transmissivity (ft^2/sec), Q is discharge (ft^3/sec), s is drawdown (ft), r is the well radius (ft), t is pumping time (sec), and S is the storage coefficient. Except for S, all data are available from well constructor's reports and geologic logs. Fortunately, the solution is relatively insensitive to S, so a reasonable estimate, in this case 0.0002 (Newport, 1962), will serve.

Logs of wells open to only one hydrostratigraphic unit or with 90% of their uncased length in a single unit were chosen for analysis with this code. Results are presented in Table 2.3. It is important to note that these values are most useful in constraining a range of values to use along with the values from other models. Further, the values calculated are high compared to the previously modeled conductivities in Table 2.2. At least for the Sinnipee and Prairie du Chien Groups, the data set is probably biased, since wells in those units are probably in areas of fracturing or dissolution, as noted before.

TABLE 2.3
HYDRAULIC CONDUCTIVITY ESTIMATES USING THE METHOD OF BRADBURY AND ROTHSCHILD (1985)

UNIT	Range (ft/sec)	Average K_H (ft/sec)	n	σ (ft/sec)
Ogp	2.3×10^{-5} to 8.5×10^{-5}	5.0×10^{-5}	3	3.2×10^{-5}
Osp	7.9×10^{-5} to 5.4×10^{-4}	2.1×10^{-4}	5	1.9×10^{-4}
Opc	2.0×10^{-5} to 5.3×10^{-4}	2.8×10^{-4}	4	2.8×10^{-4}
Ctc/em	8.7×10^{-6} to 1.1×10^{-3}	3.1×10^{-4}	10	4.3×10^{-4}

Unit abbreviations as in Fig. 2.4
n = number of wells used in analysis
σ = standard deviation

H. SUMMARY

In the study area, seven hydrostratigraphic units delineate the groundwater flow system: 1) Precambrian basement, the basal confining unit, 2) Elk Mound and Tunnel City Groups (Cambrian), both significant water-bearing sandstones with similar properties, 3) Trempealeau Group (Cambrian), sandstone, siltstone, and dolomite of lower conductivity than the other Cambrian sandstones, 4) Prairie du Chien Group (Ordovician), dolomite with some sandstone, but of low overall conductivity, 5) St. Peter Sandstone (Ordovician), another high conductivity sandstone unit, 6) Sinnipee Group (Ordovician) and overlying Pleistocene units, but a low conductivity unit due to the carbonates, and 7) Pleistocene deposits (drift) in the bedrock valley, mostly sand and gravel of high conductivity, with some irregular bodies of clay and silt. Complex relations introduced by the two paleovalleys necessitate these divisions so that the flow system may be represented accurately.

Groundwater flow in the system is generally to the west and southwest, with some flow to Rush Lake in the northern portion of the study area. Although the water table is not defined in the area, there is suitable information about head distribution in the bedrock units to show the aforementioned flow directions and to allow for model calibration. Data regarding recharge, surface water, and associated fluxes through the system are also lacking, and so these may be varied during the calibration process. Lastly, boundary conditions are loosely indicated by Newport's (1962) potentiometric surface map, and will be described further in Chapter 3.

Results of groundwater sampling suggest that a DNAPL plume may be migrating south to southeast from the landfill, given the nature of the flow system and the distribution of VOCs. Although there may be cross-contamination in the MW-2 nest, the fact that DCE and VC were detected and may have migrated downhole further implies the presence of a DNAPL. Although these results are far from conclusive, they will be used with the flow model to evaluate further the threat they pose to the municipal wells, as well as to define possible DNAPL plume locations and migration patterns.

CHAPTER 3:
THREE-DIMENSIONAL GROUNDWATER FLOW MODEL WITH PARTICLE TRACKING

A. INTRODUCTION

Further assessment of the danger posed by the City of Ripon landfill required the use of a groundwater flow model in order to investigate advective transport of the dissolved-phase contaminants. Because of the complexity of the local geology, a three-dimensional model was used. By utilizing historical and recent water level data, steady-state models for both the pre- and post-pumping flow systems were calibrated. Taken together, these two simulations demonstrate the effects of the municipal well field upon groundwater flow and contaminant migration in the area. Results of a pumping test in the Cambrian sandstones, conducted after model calibration, provided a partial verification of the parameters used in the calibrated model. Transient pumping simulations aided in evaluation of the applicability of the steady-state pumping model by indicating the scale of water level variations introduced by the daily cycling of the municipal wells.

When coupled with a particle tracking routine, the model estimated dissolved-phase contaminant migration pathways, as well as the effects of pumping on those pathways and their associated travel times. Additionally, the particle tracking routine may be used with the steady-state solutions to "backtrack" particle motion through time and thus indicate potential dissolved-phase source locations. This provided further evidence for the presence of a DNAPL plume (or plumes) and potential migration paths. In turn, these results can be used to guide further investigations in and around the site.

MODFLOW, the U.S. Geological Survey finite-difference code (McDonald and Harbaugh, 1988) was used for the steady-state and transient simulations. Input files for the program were created with ModelCad, a pre-processor created by Rumbaugh and Duffield (1989). Use of this pre-processor allowed for rapid adjustment of parameters, especially conductivities, and so reduced calibration time considerably. Once a satisfactory calibrated model was produced, the head distribution and MODFLOW modules were input to the particle tracking code PATH3D (Zheng, 1990) for evaluation of dissolved-phase movement.

B. INPUT DATA

Data for the construction of the models were derived from the sources and investigations outlined in the previous chapter. Because of the inability to conduct extensive field investigations to derive model parameters and other input or calibration data, this study relies heavily upon the data collected in adjacent areas by other workers. Fortunately, these data are in rough agreement with each other, simplifying the choices for starting values of parameters. On the other hand, the lack of field data complicates the calibration process. Because almost all of the parameters may be varied to arrive at a solution, the calibrated solution may be non-unique. Deciding which parameters to vary, and how much to vary them is a subjective part of a trial-and-error calibration which cannot be avoided (Anderson and Woessner, 1992). Normally, the range of variation of these parameters would be based on field data and determined prior to calibration.

For initial parameter input, Weaver's (1988) hydraulic conductivity values were used, and other parameters were estimated based on the work of others (e.g., Newport, 1962; Emmons, 1987; Krohelski, 1986; and Feinstein and Anderson, 1987). The parameters indicated by these other authors also provide ranges through which the parameters might be varied, thus constraining values to be used in the calibration process. Complete MODFLOW input files are included in the accompanying material.

C. MODEL CONSTRUCTION

The hydrogeologic framework for the local groundwater flow system was outlined in the previous chapter. The design of the actual three-dimensional model framework required additional work and is discussed here. Specifically, the conceptual model must be discretized in a grid, boundary conditions must be assigned, hydrostratigraphic units assigned to their appropriate model domains, and the initial parameters entered.

1. Discretization

Hydrostratigraphic units were assigned as indicated in Chapter 2 (Figure 3.1). This results in a six-layer model with six hydrostratigraphic units, the seventh (Precambrian basement) being the basal no-flow boundary. These divisions were chosen to provide maximum flexibility in representing the geologic framework while keeping model size to a minimum. Except for the Sinnipee Group and the drift overlying it, all hydrostratigraphic units represent a single rock type. Because the thickness of the drift overlying the Sinnipee is usually less than half that of the carbonates, this approach seems reasonable. The Tunnel City and Elk Mound Groups are divided into two layers to aid in representation of the two paleovalleys. All units are assumed to be homogeneous and isotropic in the horizontal directions.

The model grid is shown in Figure 3.2. It is 23 rows by 28 columns, with cell widths ranging from 1000 to 2000 feet. Variable spacing was incorporated to give more information in the well field and landfill area and because more well log data are available in these areas, which allows more detailed representation of those portions of the system. Additionally, this moved the area of interest away from the boundaries, which are not well established. The area is roughly 44,000 feet (13,500 m) east to west and 34,000 feet (10,400 m) north to south. Individual layer arrangements are shown in Appendix C. Because no information exists regarding primary horizontal hydraulic conductivity directions, a north - south aligned

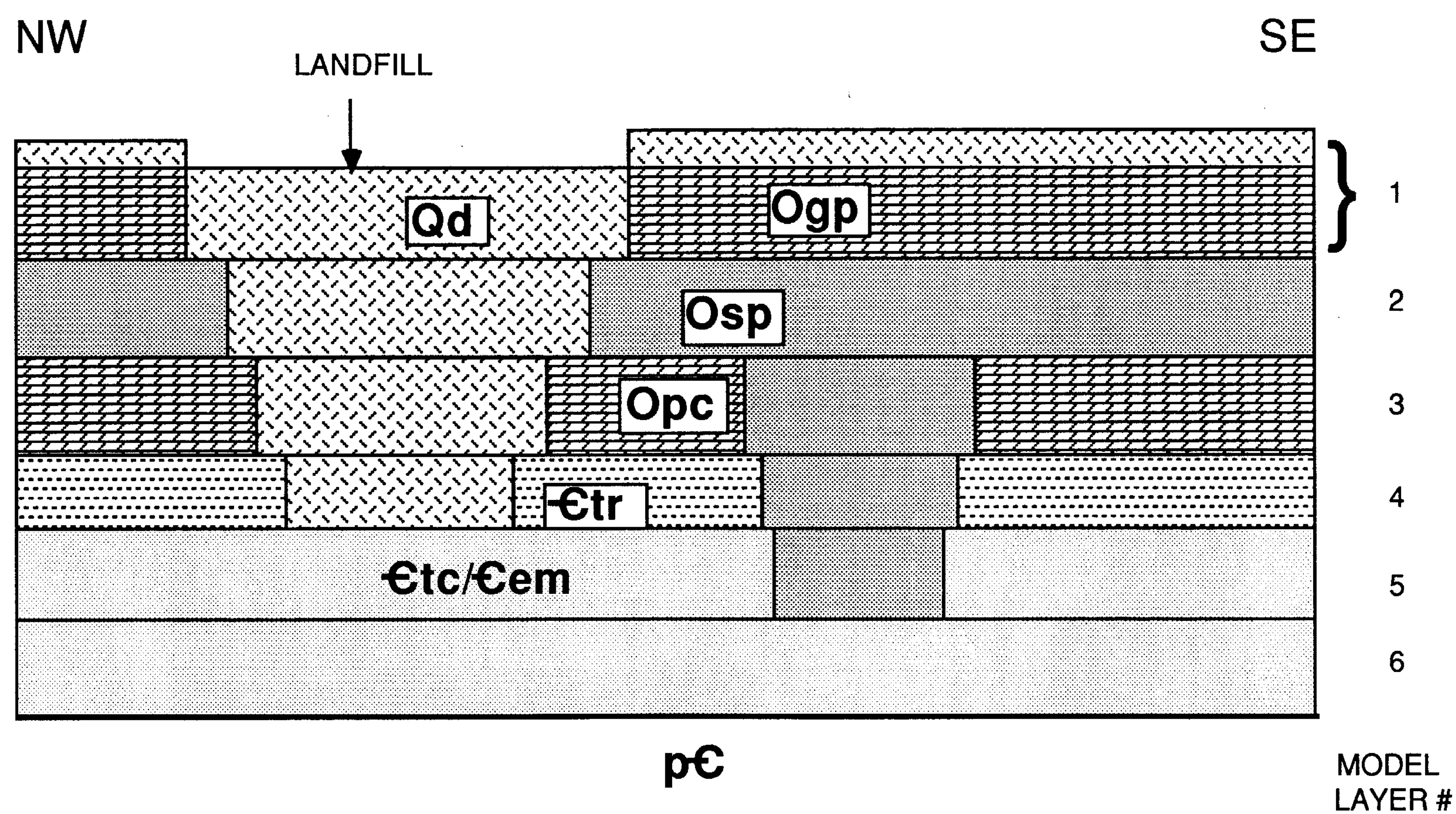


Figure 3.1. Schematic cross section through study area. Hydrostratigraphic units are designated by unit symbols. Note that the drift and underlying carbonates in the first layer comprise a single hydrostratigraphic unit, and that the remainder of the drift is another unit.

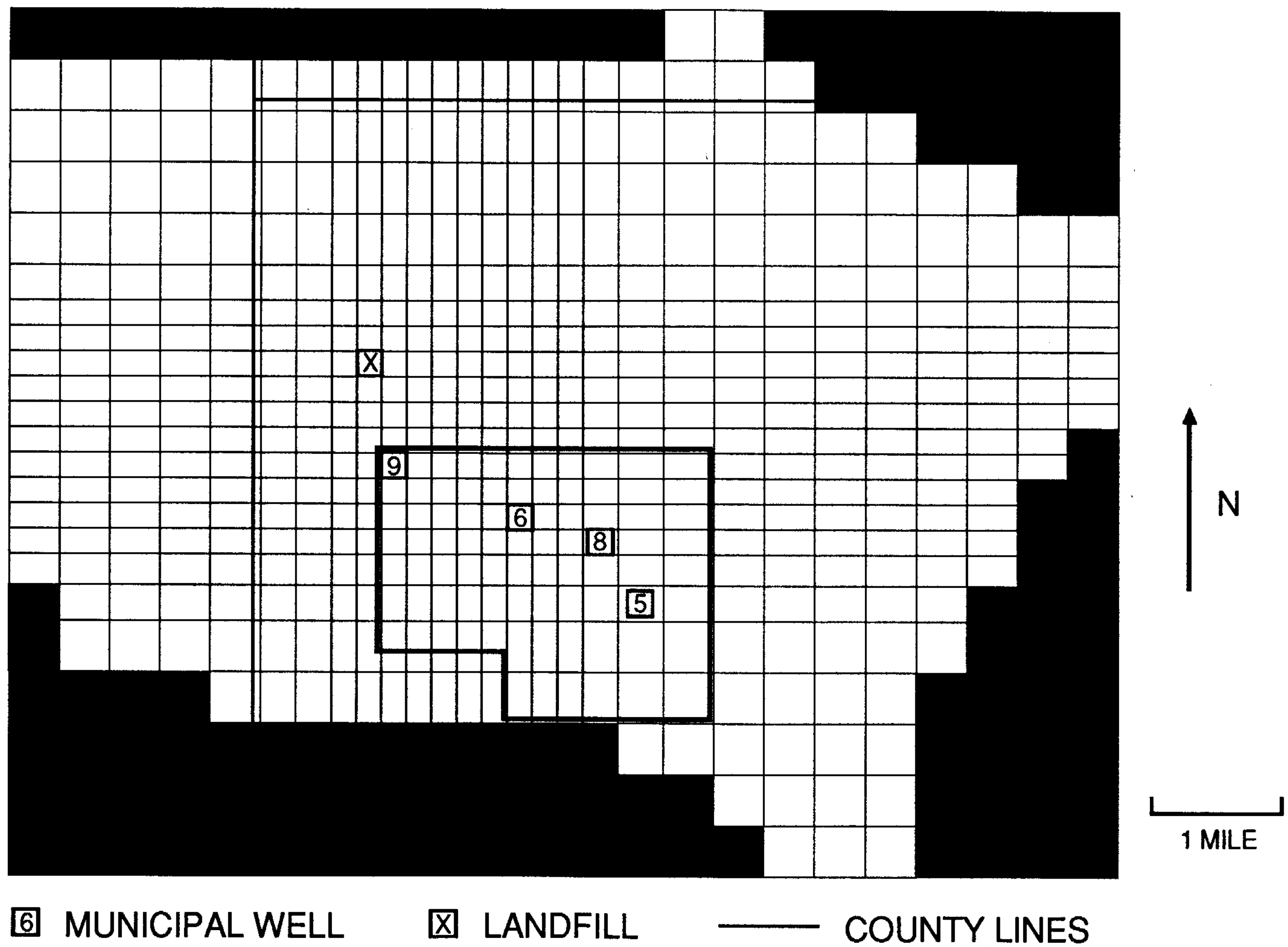


Figure 3.2. Model grid with municipal wells, landfill, city limits, and county lines located for reference. Largest cells are 2000 feet square.

grid is as rational a choice as any other. Such a grid also conforms well to the boundary conditions which are laid out below.

2. Boundary Conditions

The basal no-flow boundary of the model is taken as the surface of the Precambrian crystalline rocks. The eastern boundary is coincident with Newport's (1962) groundwater divide in the Cambro-Ordovician units (Figure 2.7). This boundary was initially designated as no-flow, but was changed to a general head boundary (McDonald and Harbaugh, 1988; a type of head-dependent boundary) during the calibration procedure to allow some underflow into or out of the system at this boundary, thus allowing for slight shifts in the location of the divide. The southern boundary was also derived from Newport's map, based on a flow line drawn according to the potentiometric surface contours. A similar procedure was followed for the northern boundary east of Rush Lake. The lake itself is a constant head boundary, as are Green Lake and an associated contour from Olcott's (1968) potentiometric surface. In the northwest corner, flow lines drawn according to Olcott's map delineate no-flow boundaries. The upper water table boundary need not be specified explicitly because MODFLOW, using the Dupuit assumptions, assumes horizontal flow at the upper boundary of the model. Lastly, Silver Creek is represented as a head-dependent boundary by the river package of MODFLOW. Figure 3.3 shows the boundary conditions graphically.

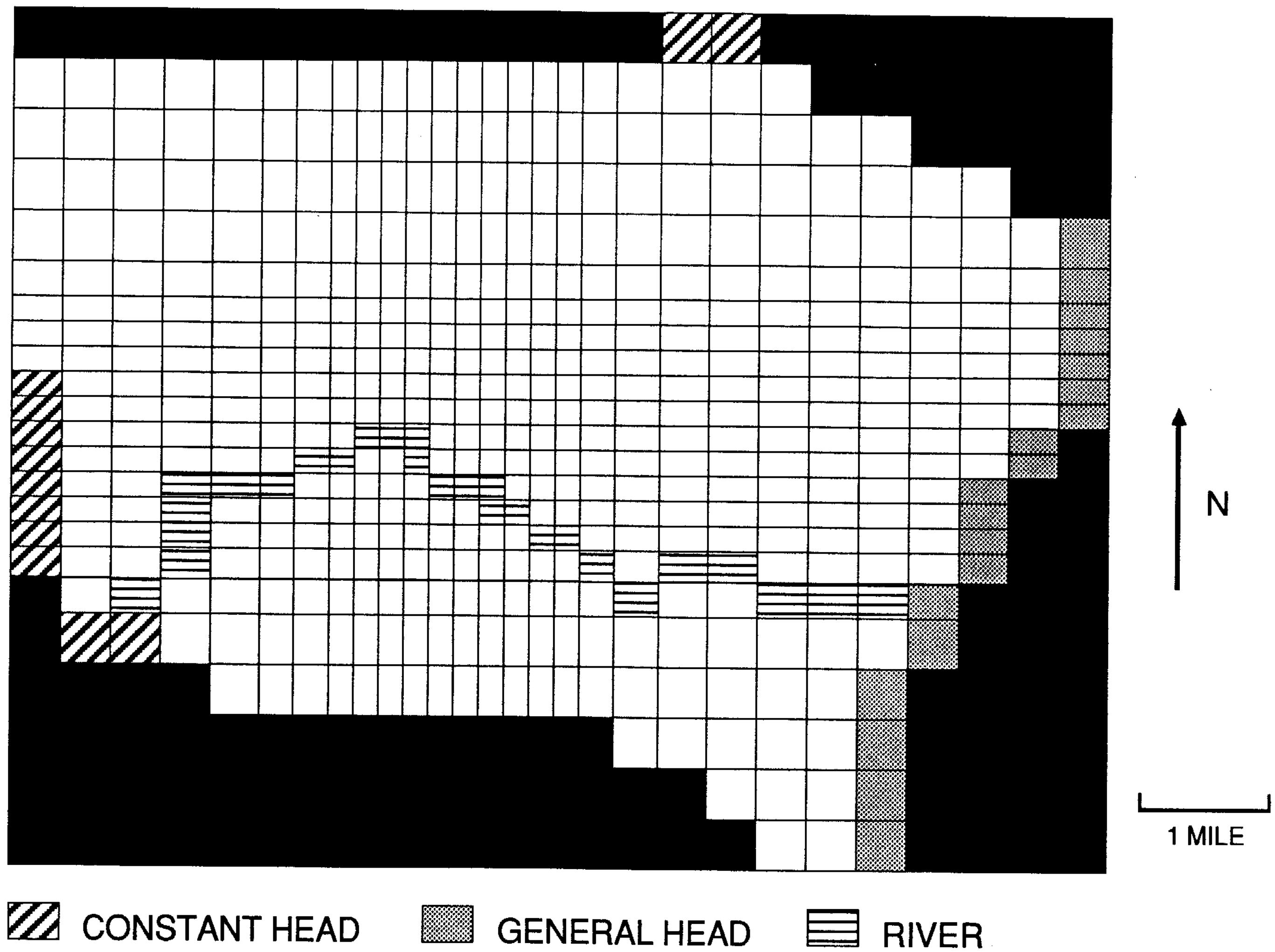


Figure 3.3. Model boundary conditions for all layers, except that river nodes are only located in the top layer. Remaining boundaries are no-flow.

3. Parameter Input

Hydrogeologic parameters required for this flow model include horizontal and vertical hydraulic conductivities for all units, recharge, river conductance, and in the transient model, storage coefficients. Sources for this information, except river conductance, are discussed in Chapter 2. It is worth repeating that these sources did not provide any fixed parameter values, but rather a range in which to vary the parameter values. As a result, all (except storage coefficients) were varied during the calibration of the steady-state models. However, starting values for all these parameters had to be chosen, so what follows is a brief explanation of the rationale behind the choices.

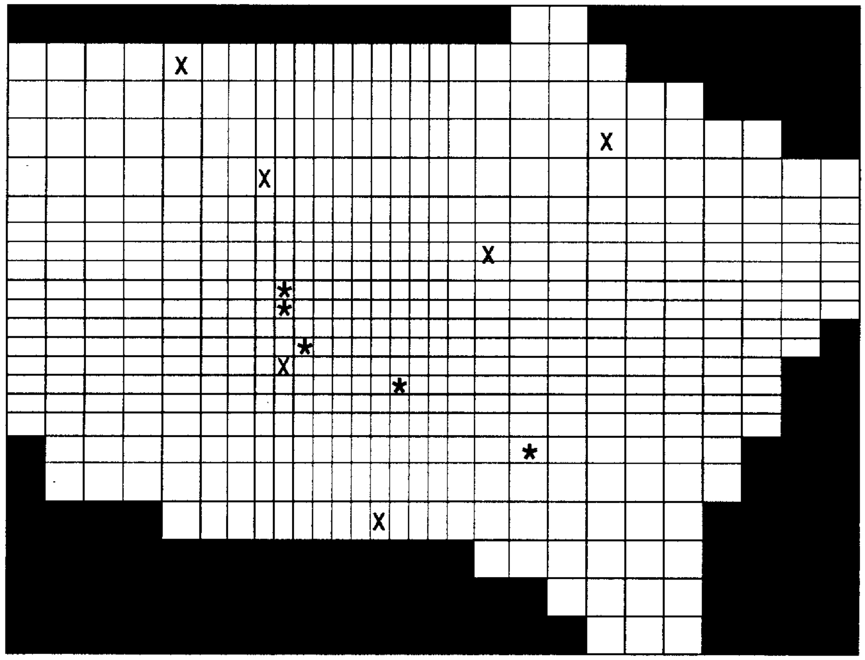
Initial estimates of hydraulic conductivities in the bedrock were based on Weaver (1988), as this was the only study including all the rock units and both horizontal and vertical conductivities. For the drift, an initial estimate one to two orders of magnitude higher than Weaver's was chosen because of the larger proportions of sand and gravel in this area. Recharge was estimated to be between 3% and 30% of average local annual precipitation, or between 0.85 to 8.5 inches per year (2.3×10^{-9} to 2.3×10^{-8} ft/sec). River conductance is a property based on hydraulic conductivity of river bed sediments, river reach length, river width, and river depth (McDonald and Harbaugh, 1988). The final value of this parameter was calculated by ModelCad, using a vertical hydraulic conductivity estimate of 1.0

x 10^{-5} ft/sec, which is based on the range for silty sand as indicated by Freeze and Cherry (1979).

Storage coefficients for the transient model were set at 0.0002 for confined units, and at 0.02 for unconfined units. The first value is based on Newport's (1962) calculation of storage coefficients from several pump tests conducted in the Cambro-Ordovician units. The unconfined coefficient (specific yield) was estimated as 100 times greater than the confined number. Heath (1983) suggests that specific yields are 100 to 10,000 times greater than storage coefficients of confined aquifers. Using the lower limit of specific yield produces the most rapid response to pumping and would allow faster transport of a dissolved phase, producing a conservative set of results.

D. CALIBRATION

Initially, output from the steady-state, no pumping simulation was compared with observed water levels in eight wells open to the sandstone units, as well as to two water table elevations determined during drilling (Figure 3.4). This continued until heads were close to those values, then the steady-state model with pumping was also run for calibration. At this point, the data were split into two sets representing estimated pre-pumping heads and estimated post-pumping heads, based on the date of completion of the well. Calibration water levels for wells completed before pumping of the



* = PRIMARY CALIBRATION TARGET (LISTED BELOW)
X = SECONDARY "REALITY CHECKS"

LAYER	COLUMN	ROW	TARGETED HEAD (FEET ABOVE MSL)	PRE/POST PUMPING
2	15	15	841 ± 1	PRE
5	10	13	823.5 ± 1	PRE
5	20	18	840 ± 2	PRE
6	10	13	823.5 ± 2	PRE
1	9	10	820 ± 2	POST
1	10	13	820 ± 2	POST
5	9	10	819 ± 0.5	POST
5	9	11	817 ± 0.5	POST
6	9	10	817 ± 0.5	POST
6	9	11	815 ± 0.5	POST

Figure 3.4. Location of primary calibration targets and additional "reality check" points. All listed information is for the primary targets.

municipal well field were calculated from the geologic logs of those wells (WGNHS, unpublished). For post-pumping data, water levels from the monitoring wells were used. Ultimately, for steady-state pre-pumping calibration, four wells were used, and for the post-pumping model, four head values plus the water table elevations observed during drilling could be used.

Because the calibration targets corresponding to reasonably well-known water levels are not widely distributed, it is useful to have additional checks on the model fit to the field system. Approximate water levels (within 10 feet) derived from well constructor's reports were used as a rough "reality check" to assure that portions of the model were producing reasonable head values (Figure 3.4). These levels are not very accurate because of difficulty in locating the wells on topographic maps. Nevertheless, these data ensured that there were no unreasonable variations in heads throughout the model domain. The other main calibration targets consisted of vertical gradients measured at the monitoring well nests. Reproduction of observed gradients (approximately 0.01 ft/ft, downward) combined with a reasonable fit to observed heads provides stronger evidence for calibration than head values alone.

A range in modeled head value deviation from observed heads must be designated as the calibration criterion. Realizing that water levels fluctuate temporally (up to three feet in Eastern Wisconsin (Webb, 1989)), and bearing in mind the conditions mentioned above, a root mean squared (RMS) error of less than five feet was chosen for both the pumping and non-pumping models. RMS error may be defined as:

$$RMS = [(\Sigma(h_o - h_s)^2)/n]^{1/2}$$

where n = number of nodes where comparison is made, h_o is observed head, and h_s is simulated head.

At the outset, a five foot RMS error for head calibration targets was chosen based on the estimated accuracy of the existing data. Matching the vertical gradients, however, resulted in a maximum RMS error for heads of less than two feet. A two foot RMS value seems more reasonable than five feet given that there is often less than two feet of variation between adjacent nodes in the sandstone units (a low horizontal gradient). This RMS error therefore minimizes error created by comparison of values calculated at nodal points with observed values elsewhere in the cell.

E. INITIAL MODEL RESULTS

Output for this phase of the modeling process is a set of estimates for hydraulic head in all six layers of the model. These estimates were used during the particle tracking phase of modeling. Table 3.1 shows the final RMS error distribution, Table 3.2 lists parameters representing the calibrated model, and Appendix D contains contours of the calibrated head distribution for each model

TABLE 3.1
COMPARISON OF CALIBRATED MODEL HEAD VALUES WITH TARGET HEAD VALUES

PRE-PUMPING

LAYER	COLUMN	ROW	TARGET	MODEL	DIFFERENCE
2	15	15	841	842.44	1.44
5	10	13	823.5	823.97	0.47
5	20	18	840	840.23	0.23
6	10	13	823.5	823.85	0.35
				RMS =	**0.79**

POST-PUMPING

LAYER	COLUMN	ROW	TARGET	MODEL	DIFFERENCE
1	9	10	820	817.52	2.48
1	10	13	820	817.98	2.02
5	9	10	819	816.84	2.16
5	9	11	817	816.24	0.76
6	9	10	817	815.47	1.53
6	9	11	815	815.01	0.01
				RMS =	**1.72**

(Heads, differences, and RMS in feet)

TABLE 3.2
CALIBRATED MODEL PARAMETERS COMPARED WITH ORIGINAL ESTIMATES

UNIT	K_H (ft/sec)	K_V (ft/sec)	K_H/K_V	
Qd	3.0×10^{-4}	3.0×10^{-6}	100	
	4.0×10^{-4}	9.0×10^{-8}	4444	original estimate
Ogp/Qd	4.0×10^{-7}	2.0×10^{-8}	20	
	4.0×10^{-7}	8.0×10^{-10}	500	original estimate
Osp	4.0×10^{-5}	3.0×10^{-7}	133	
	2.1×10^{-5}	2.0×10^{-6}	11	original estimate
Opc	1.0×10^{-6}	3.0×10^{-10}	3333	
	1.2×10^{-6}	8.0×10^{-10}	1500	original estimate
Ctr	3.0×10^{-5}	7.0×10^{-9}	4285	
	1.0×10^{-5}	5.0×10^{-7}	20	original estimate
Ctc/em (5)	2.0×10^{-4}	1.0×10^{-6}	200	
	1.0×10^{-4}	2.0×10^{-6}	50	original estimate
Ctc/em (6)	9.0×10^{-5}	1.0×10^{-6}	90	
	1.0×10^{-4}	2.0×10^{-6}	50	original estimate

RECHARGE (ft/sec) 3.25×10^{-9}

layer. Contours for the model with and without pumping are included. Complete MODFLOW input and output files are included in the accompanying material.

The contours are roughly similar to the Cambro-Ordovician surface of Newport (1962), but vary because they represent individual layers, while Newport's map (Figure 2.7) was based on values from all units, and wells screened across more than one unit. Overall, the simulated head contours show a general flow to the southwestern portion of the modeled area, with some outflow to Rush Lake in the north. In the upper layers, the flow is from the north and east, but in the lower layers, the flow is more from east to west. Also, in the lower layers, horizontal gradients are much lower than in the upper layers. Interestingly, the overall head distribution only varies slightly between the two simulations, with noticeable changes only adjacent to the municipal wells.

Further, the groundwater divide near the eastern model boundary is defined more specifically. It appears that at least in the upper three layers, the divide is located to the west of the original boundary (see contours for layers 1-3, Appendix D). In lower layers, the divide may also exist within the model area, but is difficult to locate precisely because of the decreased gradients. Simulations with and without pumping indicate essentially identical positions for the divide, indicating that the municipal well field has not altered the position of the divide.

F. SENSITIVITY ANALYSIS, INCLUDING THE TRANSIENT MODEL

A sensitivity analysis tests the effect of the uncertainty of model input on model results. Typically a single parameter, such as unit conductivity, recharge, or river conductance is varied while the others are left constant. For this study changes were made to the steady-state model without pumping in order to speed up the process, but if the resulting variation seemed small or unusual, the pumping was also incorporated.

In addition, various conditions for the eastern boundary were checked to evaluate the possible assumptions regarding this indefinite boundary. Lastly, results of a month-long transient simulation demonstrate water level variations due to the cycling of the municipal wells for comparison to the steady-state model.

1. Sensitivity to hydraulic conductivity

While estimates of conductivity for the various units constrain the values somewhat, there is no defined range within which these parameters should be varied for a sensitivity analysis. As a result, each calibrated value is multiplied and divided by five for the tests. This is done for each hydrostratigraphic unit, and both the horizontal and vertical conductivities were changed at the same time, thus keeping the ratio of horizontal to vertical conductivity constant. Doing this gives a range of one-half an order of magnitude on either side of the calibrated estimate. Figure 3.5 displays the results of

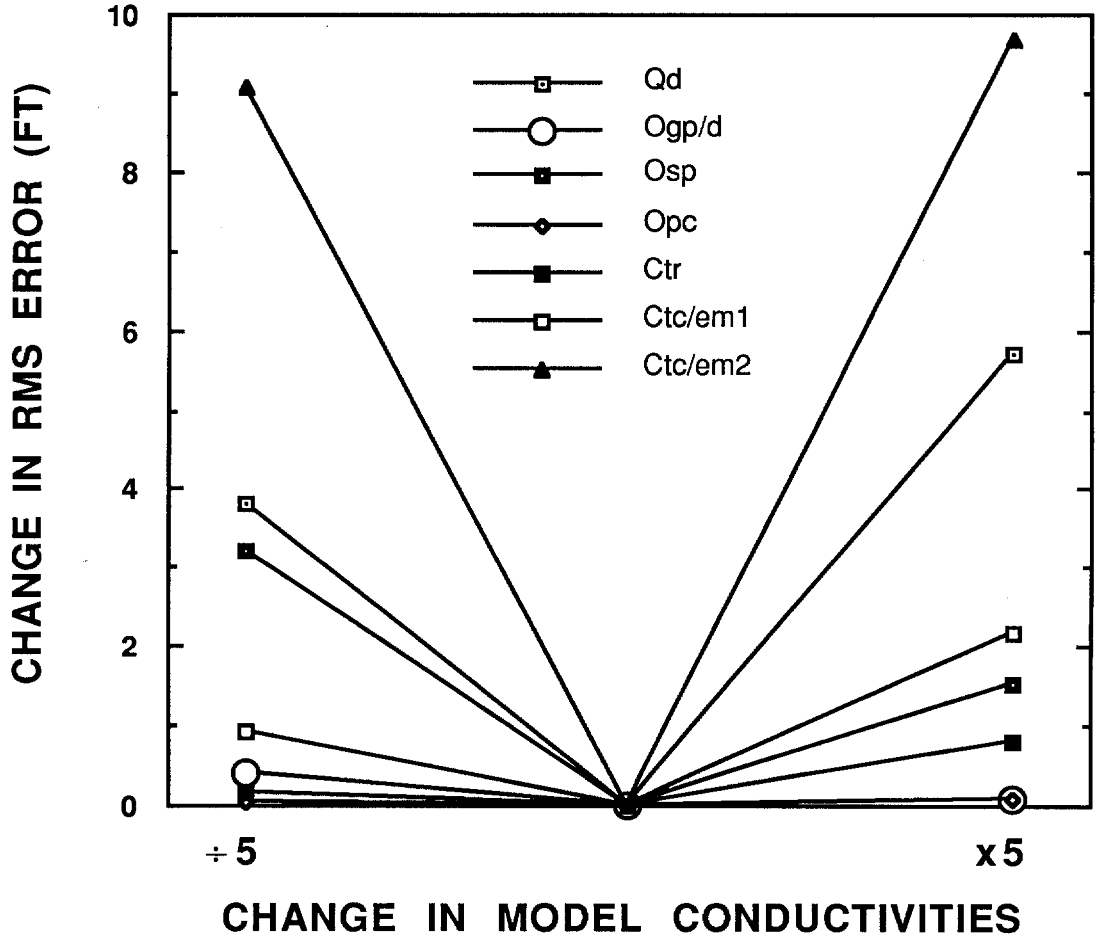


Figure 3.5. Sensitivity of model to variations in hydraulic conductivity of stratigraphic units. Vertical to horizontal conductivity ratios kept constant. Unit symbols as in Figure 2.4.

these operations by showing the difference between the RMS error for the calibrated run and the varying sensitivity runs. Note that except for the drift, the units which most affect results are the significant water-bearing units, and are those for which the most accurate water level data are available (the St. Peter Sandstone and the Elk Mound/Tunnel City Group layers). Because these units, especially the Cambrian sandstones, comprise the bulk (volumetrically) of the flow system, it is understandable that they are the most sensitive portions of the input data.

2. Other variables

Other parameters tested for sensitivity include recharge, river leakage, and the eastern boundary conditions. Recharge was checked by adding and subtracting 30% of the final calibrated amount (3.25×10^{-9} ft/sec). Figure 3.6 shows that adding recharge has more of an effect than subtracting it, but both produce noticeable deviations, especially in the heads of the upper layers. In addition, decreasing recharge during pumping causes an error in steady-state calibration (as seen in the final water balance error of -3.2%) that is twice as large as that of the calibrated model.

River conductances were varied by an order of magnitude in order to examine the system's sensitivity to river leakage. Figure 3.6 indicates that the model is very sensitive to the increase, but this sensitivity is the result of the fact that one of the calibration targets is in a node near Silver Creek. Otherwise, the change would be

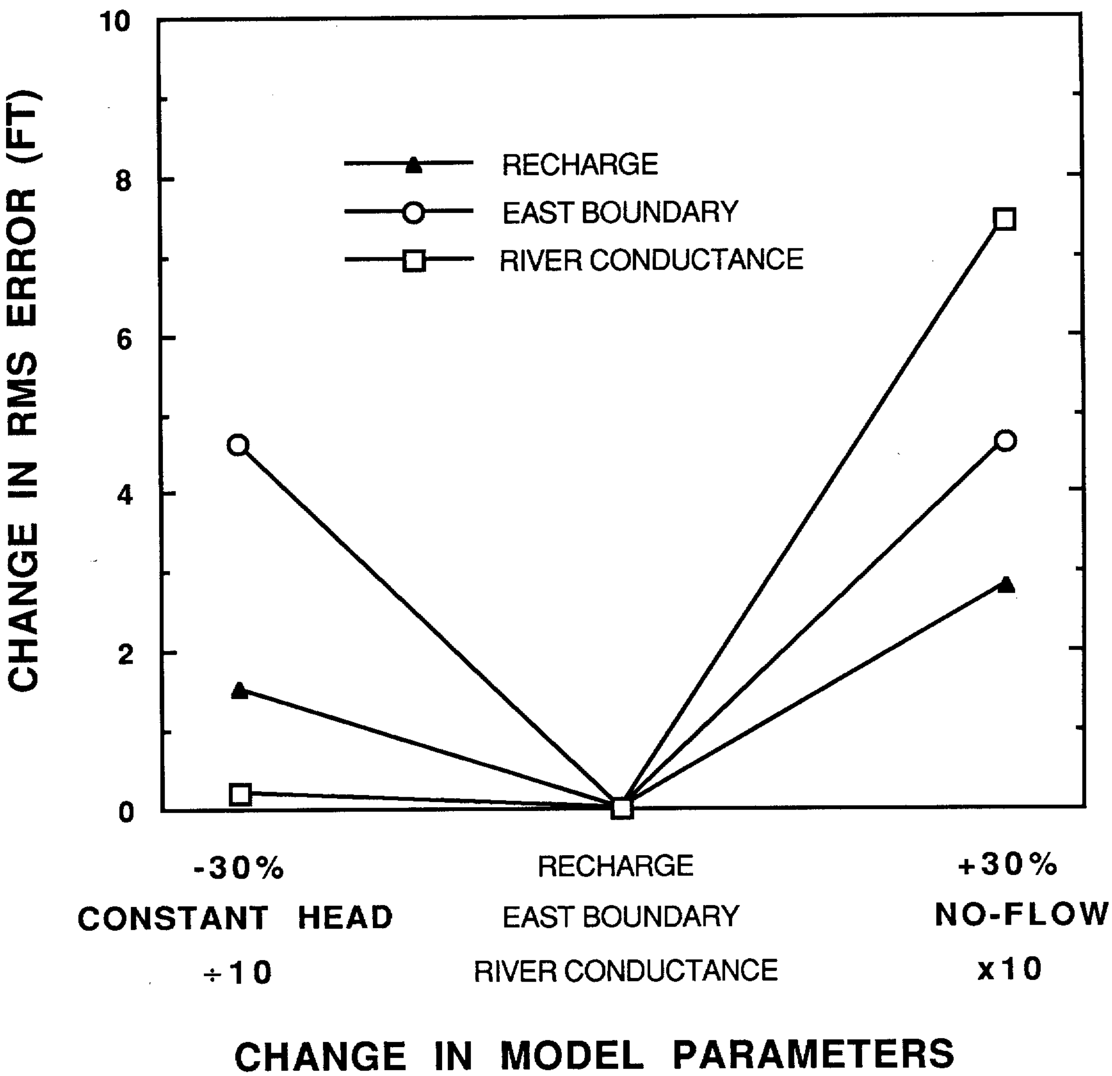


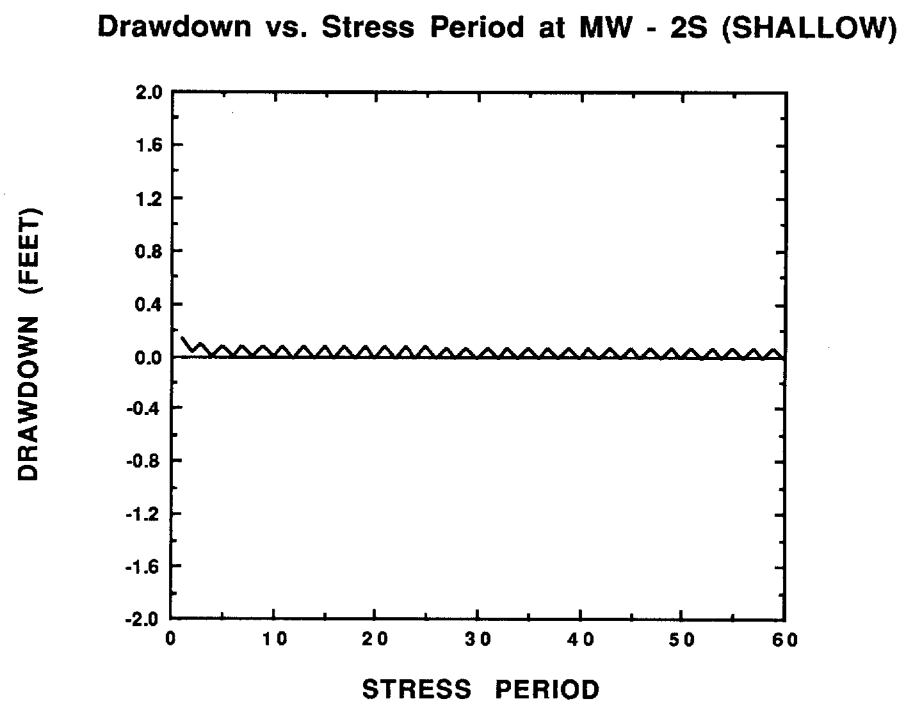
Figure 3.6. Sensitivity of model to changes in certain parameters.

similar to that produced by decreasing conductance. In fact, during calibration changes in this variable did not improve simulated head values except immediately adjacent to the river.

Of all the variables tested during sensitivity analysis, the type of boundary at the eastern margin of the model is the most significant. Replacing the (calibrated) general head boundary with both no-flow and constant head boundaries caused RMS error increases of approximately four and one-half feet. Furthermore, the presence of the general head boundary allows reproduction of observed vertical gradients. From these exercises, it is apparent that the groundwater divide delineated by Newport (1962) is slightly mislocated. It is possible that pumping in the city of Fond du Lac (to the east) has caused the divide to move to the west.

3. Transient simulation

The final stage of the sensitivity analysis involved a transient simulation to assess the effect of daily cycling of the municipal wells on head variations from from steady-state conditions. To do this, a 30-day period was divided into 60 stress periods, two representing each day. A six-hour stress period represents the part of the day in which all four wells are pumping, while no pumping occurs during the remaining 18 hours. When initial heads are derived from the steady-state model, MODFLOW calculates the changes in each time step as drawdown. Figures 3.7 and 3.8 show the variations at two depths in monitoring well nests MW-2 and MW-3. Since MW-3 is



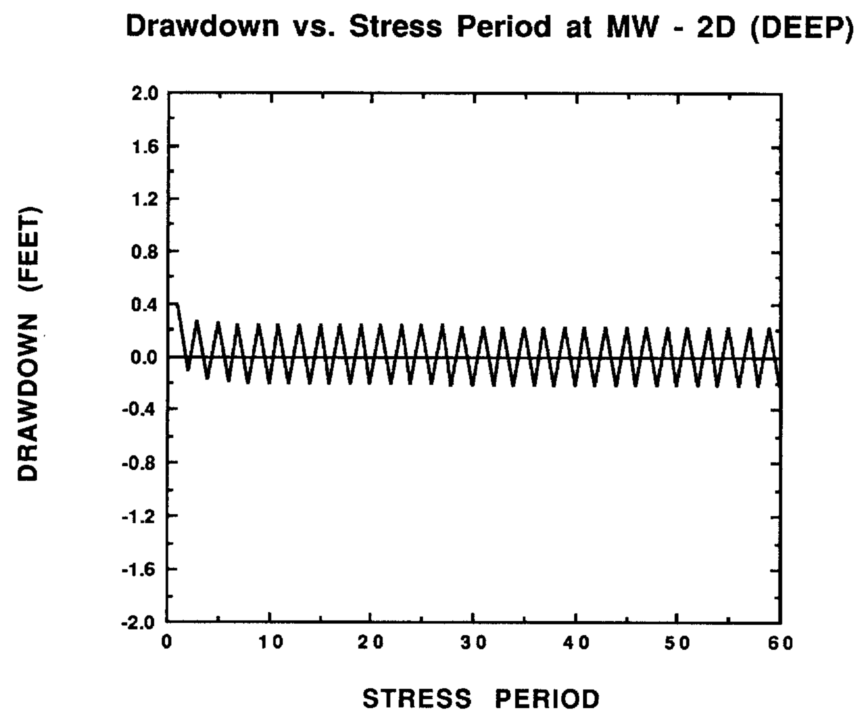
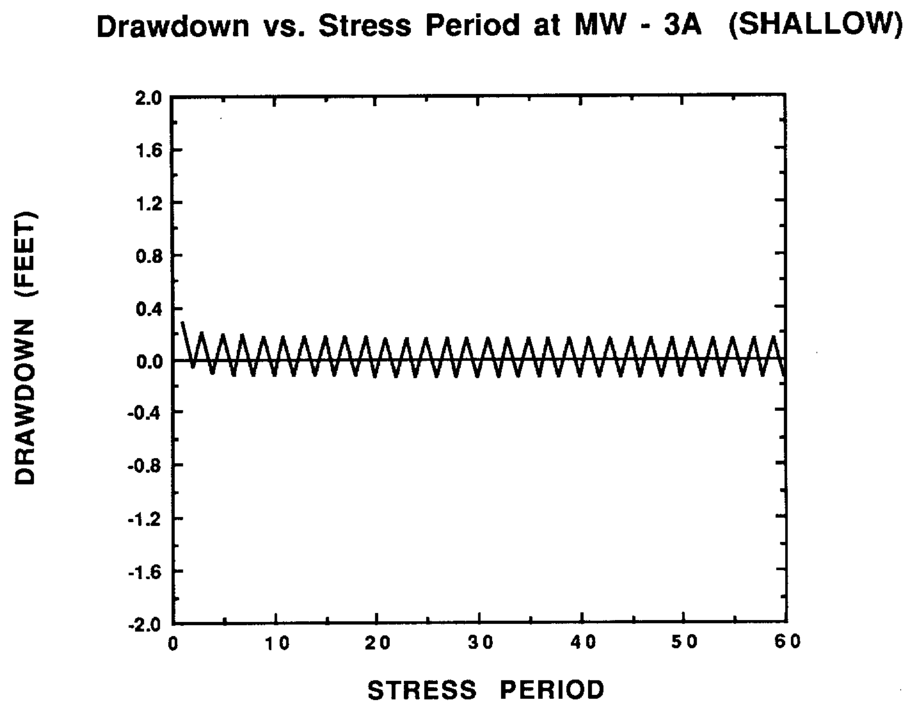


Figure 3.7. Transient head variations at the MW-2 nest.



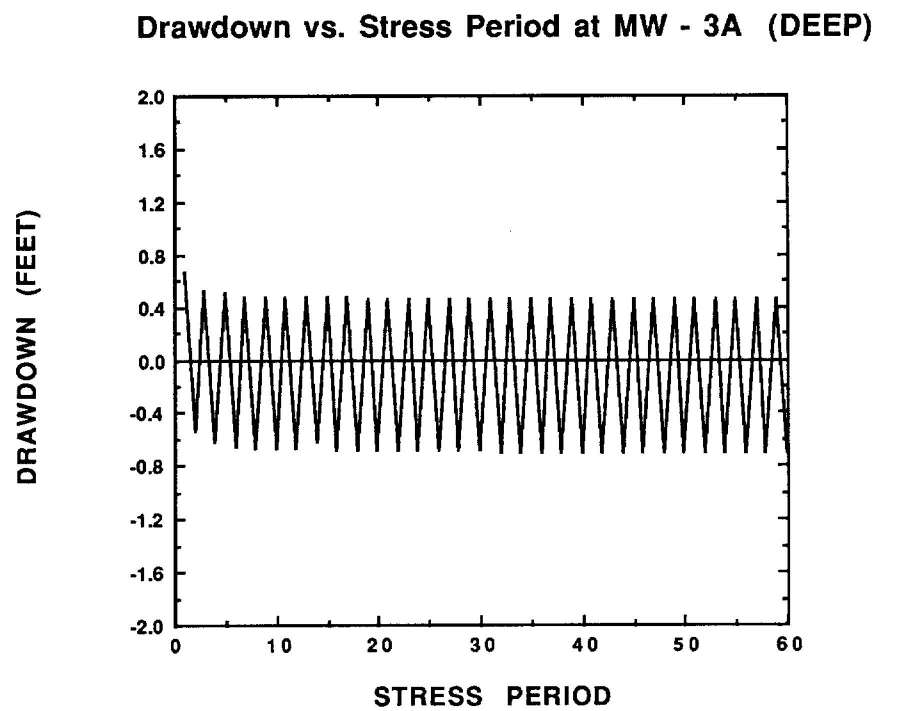


Figure 3.8. Transient head variations at the MW-3 nest.

closer to municipal well #9, a greater head variation is observed. Cells nearest the wells show the greatest variations, as would be expected. The simulation shows the greatest changes in the lowest layer (layer 6). Although municipal well #9 is open to subequal portions of layers 5 and 6, the lower conductivity derived for layer 6 likely causes the increased drawdown. Another important result is that water levels in the upper layers show almost no variation (<0.05 feet), except near municipal well #6, which is the only well open to the second through fourth model layers. The values also stabilize very quickly (within about five days), and then vary constantly around the steady-state values for the rest of the simulation. These results support the assumption that a steady-state model is a suitable representation of the flow system.

For these transient simulations, the confined storage coefficient was set at 0.0002, and the specific yield at 0.02. Doubling and halving these values produced drawdown changes averaging about 0.2 feet, with the variation increasing for the lower storage values and increasing for the higher values. Again, the effects are most significant near the pumping wells.

G. VERIFICATION OF CALIBRATED HYDRAULIC CONDUCTIVITIES

Because only one set of field data is available, a verification in the sense that Anderson and Woessner (1992) describe is not possible. The predictive capabilities of this model cannot be tested, either in the transient or steady-state mode. However, the calibrated values of hydraulic conductivity can be verified through the results of a pumping test. In this case, the pumping test was conducted after model calibration and sensitivity analysis had been completed. The conductivity values determined from the test can be compared to model values and help in turn to support the validity of other parameter estimates. This pumping test was conducted using municipal well #9 as the pumping well and the piezometers in monitoring well nests MW-1 and MW-3 as observation wells. Parameters derived from this test can be compared with the modeled estimates for the Tunnel City/Elk Mound Group layers.

A description of the test, the associated measurements, and the matched type curves are in Appendix E. Curves were matched to the data using the computer program AQTESOLV (Duffield and Rumbaugh, 1989). For the pumping data, the Theis curve matching option was utilized, using the partial penetration option. In the case of MW-1S, the Hantush leaky confining unit solution option was utilized. The AQTESOLV code can perform the curve matching and parameter estimation automatically, but also allows visual fitting by the user, which was done in all cases. Table 3.3 lists the resulting conductivity values and compares them to estimates obtained during model calibration.

Results confirm that model layers five and six have different horizontal hydraulic conductivities. This difference was not apparent until calibration, when the conductivity of the two layers had to be

TABLE 3.3

MODEL CONDUCTIVITIES FOR THE ELK MOUND/TUNNEL CITY HYDROSTRATIGRAPHIC UNIT COMPARED WITH PUMPING AND RECOVERY TEST RESULTS

PUMPING

WELL	LAYER	T (ft^2/sec)	b (ft)	K (ft/sec)
MW-1S	5	7.1×10^{-3}	50	1.4×10^{-4}
MW-3B	5	2.9×10^{-2}	50	5.7×10^{-4}
MW-1I	6	2.3×10^{-2}	340	6.6×10^{-5}
MW-1D	6	2.4×10^{-2}	340	6.9×10^{-5}
MW-3A	6	3.6×10^{-2}	340	1.1×10^{-4}

RECOVERY

WELL	LAYER	T (ft^2/sec)	b (ft)	K (ft/sec)
MW-1S	5	9.5×10^{-3}	50	1.9×10^{-4}
MW-3B	5	3.6×10^{-2}	50	7.2×10^{-4}
MW-1I	6	1.9×10^{-2}	340	5.6 x 10-5
MW-1D	6	1.7×10^{-2}	340	5.1×10^{-5}
MW-3A	6	1.7×10^{-2}	340	5.1×10^{-5}

MODEL VALUES

LAYER	T (ft^2/sec)	b (ft)	K (ft/sec)
5	1.0×10^{-2}	50	2.0×10^{-4}
6	3.1×10^{-2}	340	9.0×10^{-5}

T = transmissivity determined from curve matching (Appendix E)
b = layer thickness
K = hydraulic conductivity = T/b

varied to reproduce the observed head distribution and the vertical gradient between the layers. This validates an assumption that was significant in the calibration process and helps support the hypothesis that existing conditions are represented by the calibrated model.

For the pumping test, the values calculated for the two deeper piezometers at MW-1 (corresponding to the lower model layer of the Tunnel City/Elk Mound Group) are in fairly close agreement with the model values, especially when averaged with the MW-3A value (K_{ave} = 8.2 x 10^{-5} ft/sec; model value = 9.0 x 10^{-5} ft/sec). For the upper model layer of the Tunnel City and Elk Mound unit, the average conductivity calculated from MW-1S and MW-3B is higher than the model value. It is likely that the MW-3B well is affected by the flow in the overlying sand and gravel. During drilling through the lower sand and gravel layers, a large amount of water entered the borehole (estimated by the driller as approximately 200 gallons per minute). If conductivity is calculated with a greater thickness that represents the contribution of the sand and gravel, that calculated value will decrease towards the calibrated estimates for both model layers. Also, the siltstone layer seen at MW-1, which may separate the upper piezometer from the lower two, is not seen at the MW-3 location. Heterogeneities such as this are likely to create variability in response to pumping, especially over a large distance (Driscoll, 1986). This might explain the higher values seen here, compared to other observation wells.

The same pattern is seen in the recovery results, including a much higher K calculated from the MW-3B data. All recovery data were analyzed with AQTESOLV, using the Theis recovery method option and visually fitting the straight line. Lower K values were obtained for the lower sandstone in this case, and this may be due to the fact that storage changes more during recovery than during pumping (Jacob, 1963). This produces irregular recovery curves and makes fitting a straight line to the data problematic (Appendix E). Since the slope is what determines transmissivity and conductivity, any slope variation in the data can cause varied results. Still, these data confirm the pumping data, which in turn reinforce the conductivity values arrived at during model calibration.

In summary, although the values derived from the aforementioned tests are not in exact agreement, they demonstrate that the estimates of conductivity obtained during the calibration process are reasonable. Varying the model conductivities to match pumping test results will not affect the head distribution (and thus particle paths) enough to warrant further model runs. More importantly, the results show that the differences between layers five and six introduced during calibration were justified and accurately represent existing conditions. For the purposes of this study, then, the model parameters are considered partially verified.

H. PARTICLE TRACKING

The head distributions from the calibrated steady-state models (with and without pumping) were coupled with the particle tracking routine PATH3D (Zheng, 1990) to predict dissolved-phase migration. By comparing pre- and post-pumping results, the effect of the pumping can be evaluated. Travel times and paths for particles placed at the landfill can be compared to locations of dissolved phase detections to give an initial indication of the possibility of the presence of a DNAPL plume. Also, the backtracking feature of PATH3D can be used for qualitative determination of DNAPL presence and to suggest possible plume locations.

Initial particle tracking runs involved the placement of 6 particles: one at monitoring well MW-2S, one at the top of the large silt and clay body in the drift at MW-2, two just below the water table at the landfill, one at 100 feet below the landfill, and one 200 feet below the landfill. Figure 3.9 shows paths and travel times of three selected particles for the pumping solution. The other particle paths are parallel to or merge with those shown in Figure 3.9. Particle paths with pumping are similar to those without pumping, except that the particles only move about one-half to two-thirds as far with pumping. From these results, it is clear that 1) pumping affects contaminant paths only slightly, 2) the most significant effect of pumping is on travel times, 3) a DNAPL that has migrated from the landfill must be present to account for detects, given both the

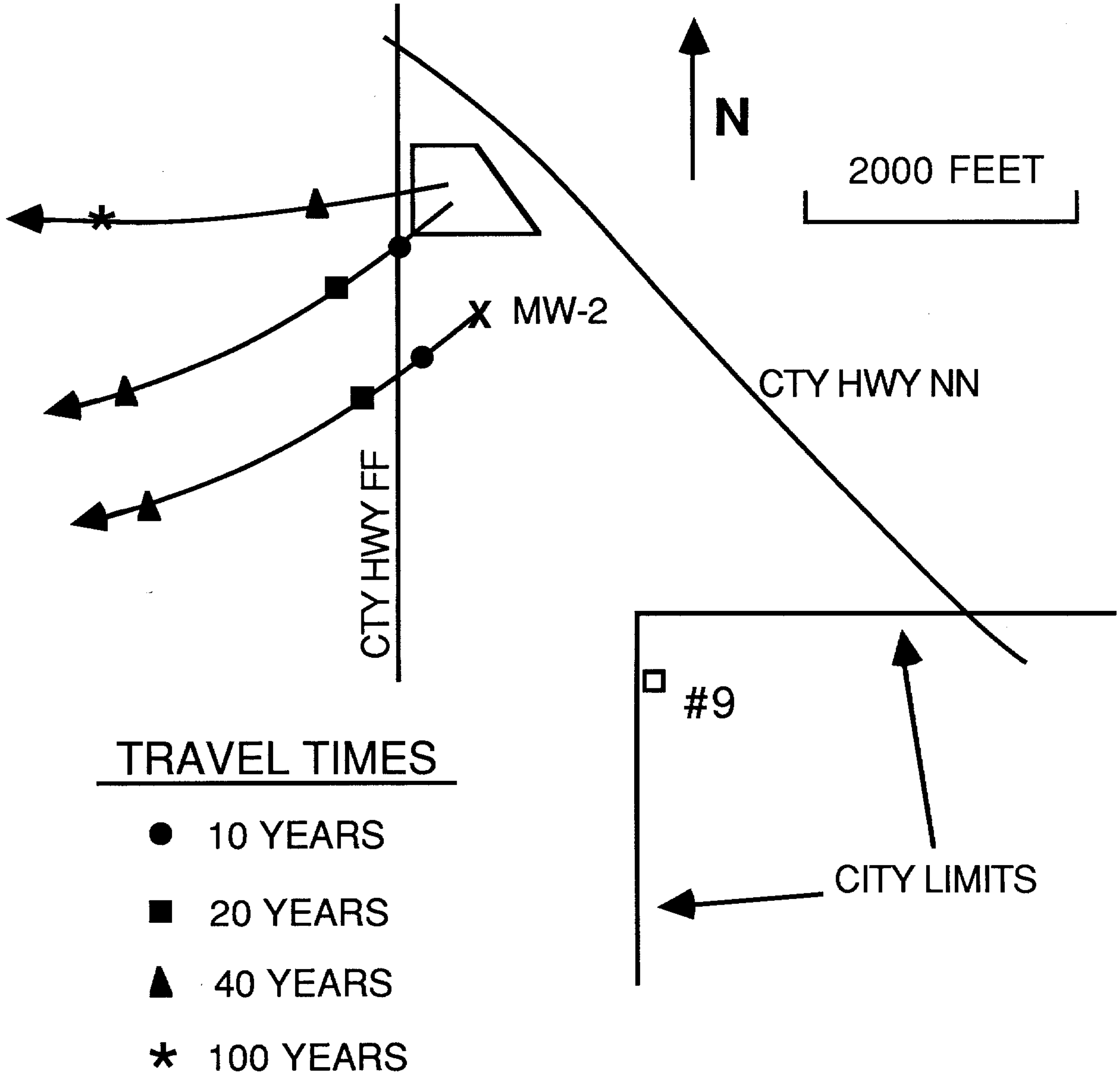


Figure 3.9. Paths of particles inserted at various locations. The northernmost path is for a particle inserted 250 feet below land surface (in bedrock). The other two paths are for particles inserted in the drift 30 to 80 feet below land surface. A particle inserted at bedrock depths at MW-2 will follow a path parallel to the particle originating below the landfill.

travel times and paths, 4) given the indicated flow directions, the DNAPL plume is south to southeast of the landfill, and 5) currently, dissolved-phase migration from the vicinity of the Ripon landfill poses no direct threat to the municipal well field. It should be mentioned that under the current flow regime as delineated by the model, the ultimate fate of the aqueous phase contaminants is to end up in Green Lake, as most flow paths move toward the boundary that is created by that body.

These initial runs provide the first, albeit indirect, evidence that a DNAPL is present, especially when the vertical component of motion is considered. For a particle inserted at or near the water table, the time required to reach the depths where the closest detects occurred (domestic well, MW-2S, MW-2D) is in the 60 to 100 year range. Even if the detects at the domestic well and MW-2D are not valid, the time required to reach MW-2S or the top of the thick clay layer at MW-2 is still in the range of 40 to 70 years. Since the landfill opened in 1968, the presence of 1,2-DCE and vinyl chloride at these depths must then require a DNAPL source at some depth below the surface and outside of the landfill boundaries. Such a source could be provided by a DNAPL plume migrating down and away to the south-southeast from the landfill.

To further investigate this possibility, the backtracking feature of PATH3D may be invoked. This feature allows the user to place particles and have them moved "backward" through time along a path dictated by the steady-state velocity field. For this case, particles are entered at the top of the clay layer and at the MW-2S location. Figure 3.10 indicates results for this run. Ten to twenty year travel times, especially for the MW-2 particle, suggest that a DNAPL source or sources may exist in the sandstone or drift within 500 - 1000 feet northeast of the MW-2 location. The distances involved are the result of the relatively rapid velocity in the drift, into which the MW-2S particle moved after 5 to 10 years of backwards simulation time. Another possible DNAPL plume location is between MW-2 and the domestic well, as paths and times backtracked from the domestic well suggest a DNAPL source near MW-2. Given that concentrations of 1,2 DCE and vinyl chloride were about 10 to 20 times greater in the domestic well compared to the MW-2 wells, this scenario is quite possible. Further sampling of the domestic well could help to verify this possibility. Additionally, PATH3D does not account for dispersion, which may also play a large role in the observed contaminant distribution.

Finally, since PATH3D may be used in the backward tracking mode with a steady-state solution, it was possible to delineate zones of contribution (ZOCs) for all four municipal wells. In this case, six particles were placed around each municipal well and tracked backwards for 200 years. From the resulting data, 100-year ZOCs were drawn and are presented in Figure 3.11.

The particles that travelled the farthest horizontally were used to describe these ZOCs. Since particles were inserted in all the model

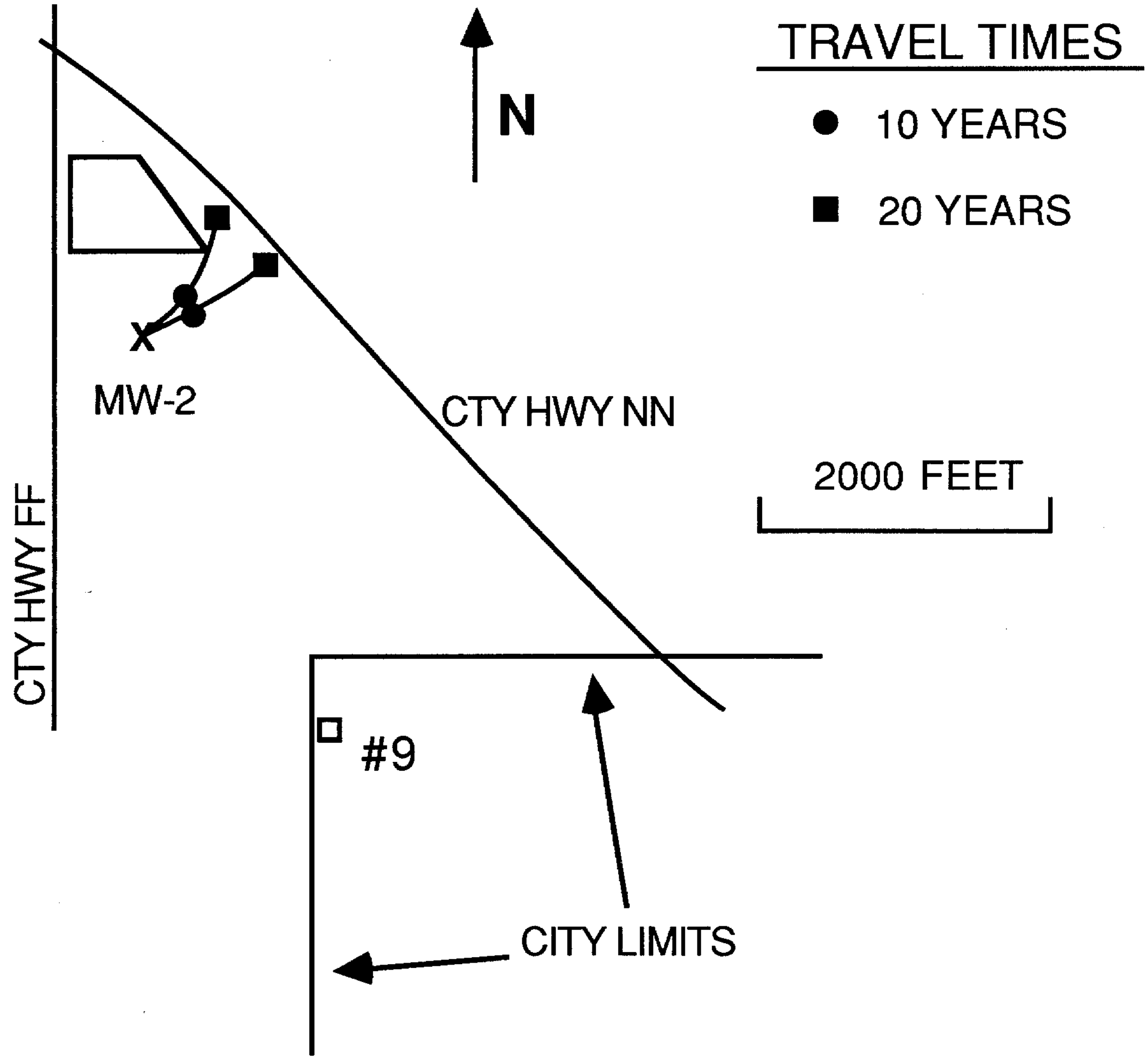


Figure 3.10. Paths for particles backtracked from MW-2. Northern path is for a particle inserted 65 feet below ground surface, while the lower path is for a particle inserted at the depth of the shallow piezometer (185 feet).

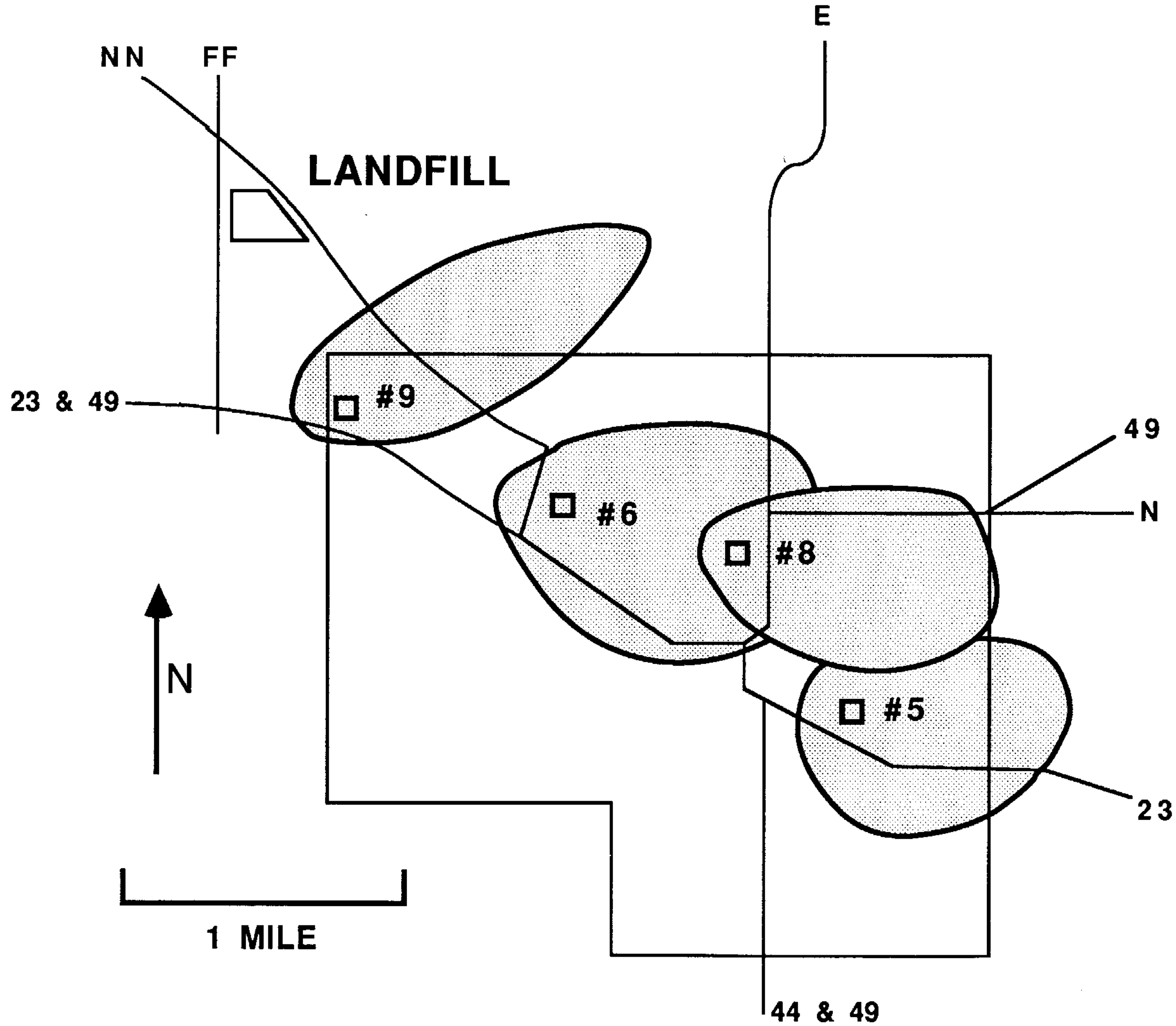


Figure 3.11 100-year zones of contribution for the municipal wells

layers that the wells tap, these are then composite ZOCs which represent a maximum area. For municipal well 6, the maximum distances were all for particles in the upper layer (layer 2) and all exited the system at the water table after the 50-year point. In lower layers, however, the 100-year ZOC lies within the ZOC described by the upper layer particles.

The ZOC for municipal well #9 lies well away from the landfill and the DNAPL plume emanating from it. This further supports earlier particle tracking results which suggest no threat is posed to municipal well #9. If the DNAPL were to move further to the south or southeast, however, a threat would be posed.

To further investigate this situation, scenarios involving doubled and quadrupled pumping rates at municipal well #9 were modeled. Figure 3.12 shows the enlarged ZOCs for municipal well #9. When the pumping rate is doubled, the ZOC moves nearer to the landfill and the inferred DNAPL plume. Quadrupling the pumping rate expands the ZOC to include the landfill and the areas where contamination is known to exist. Results of a forward particle tracking simulation under these conditions indicate the dissolved-phase contaminants would require 60 - 100 years to move from the landfill and the DNAPL plume location to municipal well #9.

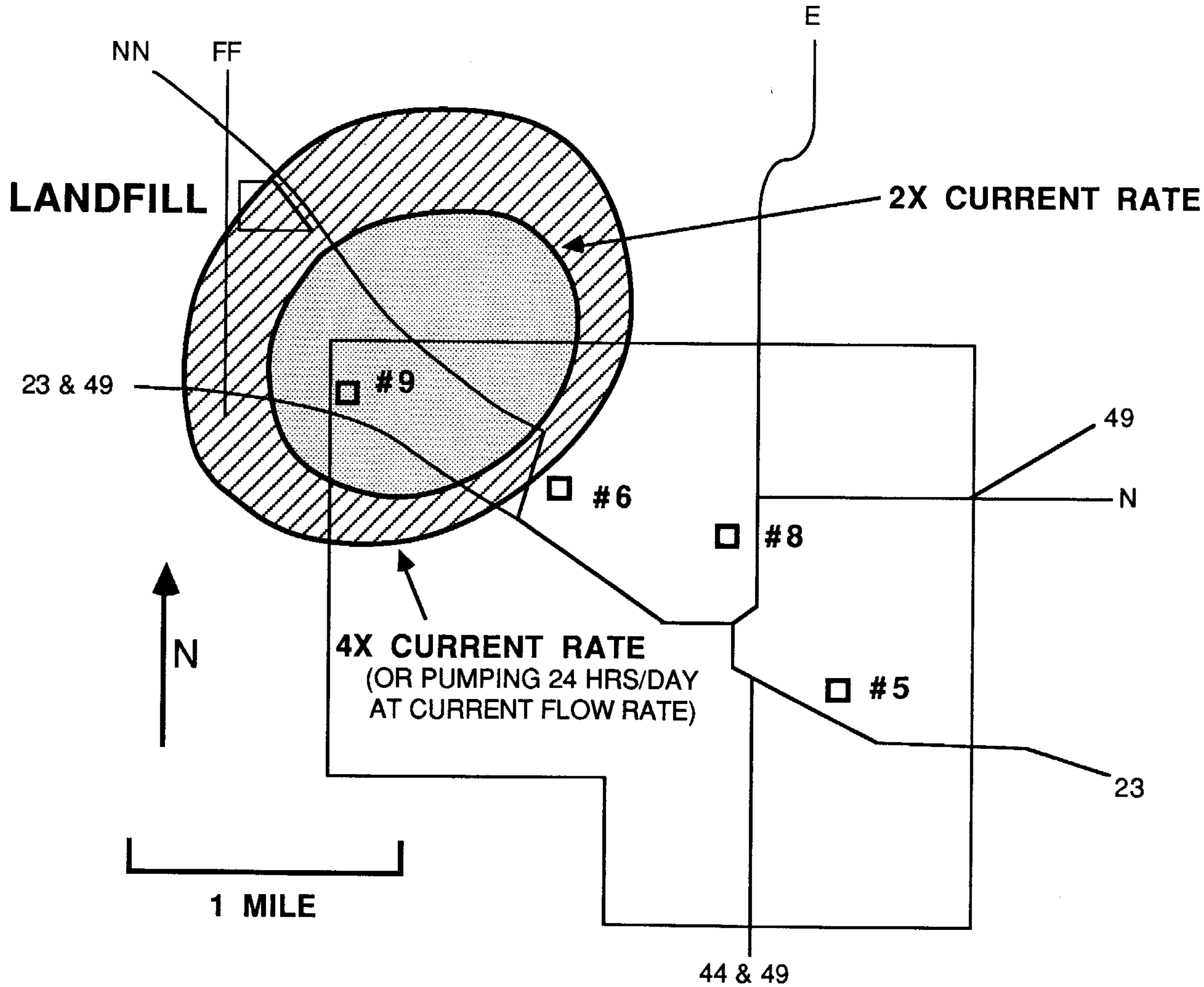


Figure 3.12 Zones of contribution for municipal well #9 with altered pumping rates.

I. SUMMARY AND CONCLUSIONS

Construction and calibration of the three-dimensional flow model yields results which suggest that contamination from the landfill poses no direct threat to the municipal well field. Additionally, this process has yielded insight into this flow system, as well as the methods used in reproducing it.

The sensitivity analysis shows that the hydraulic conductivity values for the Elk Mound and Tunnel City Groups, have the most profound effect upon the system. Pumping test results support the conductivity estimates determined from the calibrated model for these units. This indirectly bears out the conductivity estimates for the other units because the system is so sensitive to the Elk Mound/Tunnel City layers.

The conductivity of the drift is also a parameter to which the model is quite sensitive, and there is no information on the hydrogeologic properties of this material in this area. However, since the bulk of the system modeled here is bedrock, this is not a serious limitation to the results.

Another notable result of the sensitivity analysis is the illustration of effects of the eastern boundary conditions on the system. Because they were poorly defined, these conditions were simulated as general head boundaries rather than as a groundwater divide. When the head contours are examined (Appendix D), it is clear that the divide lies farther to the west than estimated by

Newport (1962). The divide also is not as well defined in the lower model layers as it is in the upper layers. Because this divide lies within the model area, the system containing the landfill and the municipal wells remains well-represented.

Similarity of the parameters of the calibrated model to those in other models of similar systems also supports the validity of the results obtained in this study. Specifically, hydraulic conductivity estimates obtained by this model can be compared to the other models from which the starting values were derived. Comparison of Tables 2.2 and 3.1 shows that the conductivities from this model are very similar to those in the other models. Considering all the possible variations that weathering, varying drift compositions, and differing stratigraphic relations might introduce, this model and its parameters are a reasonable representation of the local flow system. Because this model serves as a tool for interpreting contaminant migration and distribution in a general sense, further refinement is unnecessary. To evaluate the system or the contamination to any finer degree, however, would require further investigation.

As this case indicates, it is possible to model a flow system without detailed study of the hydrogeologic properties of the materials in the area. A review of existing data and models can often provide sufficient information to model a local groundwater system, provided there are enough basic data contained in well logs and from regional studies. This method might prove useful for other problems on similar scales, as it minimizes costs for drilling and sampling to evaluate the situation. Preliminary models of this type can also aid significantly in designing site-specific investigations.

CHAPTER 4: SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

A. SUMMARY

To investigate the migration of VOC contaminants from the City of Ripon Landfill, it was first necessary to examine geologic logs, well logs, and other studies to understand the hydrogeologic framework of the area. Field investigation involving installation of monitoring wells, together with groundwater sampling and water level measurements from those wells added further information for a conceptual model, and provided insight into potential dissolved-phase and DNAPL migration pathways and aqueous phase distribution.

In turn, this information was used to model groundwater flow within the system and to evaluate dissolved-phase migration under the effects of pumping of the municipal well field. Two steady-state models were calibrated to two sets of head values: one representing heads prior to pumping, and one representing heads after pumping of the municipal well field had commenced. The calibrated model parameters are partially verified by the results of a pumping test conducted after completion of the model. These efforts provided an early indication that the observed distribution of dissolved phase VOC contaminants cannot be accounted for solely by movement of an aqueous phase from within the confines of the landfill.

The model incorporating pumping was then paired with a particle tracking routine to evaluate dissolved-phase contaminant migration. This phase of the modeling was used to identify possible locations of DNAPL plumes that may have migrated from the landfill.

B. CONCLUSIONS

Based on the modeling results and the known distribution of VOCs near the Ripon Landfill, the aqueous phase contaminants currently pose no direct threat to the municipal well field, particularly well #9. For the current arrangement of municipal wells and their current pumping rates, pumping alters flow paths only slightly; the biggest effect is on travel times. It should be noted, however, that the existing chemical data provide only minimal information about VOC distribution and may not accurately reflect the full extent of contamination.

Modeling results and chemical data imply that a DNAPL plume outside of the landfill area must be present in order to explain the location and depth of dissolved phase VOC detects. Reverse particle tracking suggests that such a plume has migrated from the landfill to the south or southeast, and exists at some depth below the surface and the bottom of the landfill. This plume might exist on top of the silt and clay body seen at MW-2, or may be deeper in the drift or bedrock. Because the particle tracking routine does not consider dispersion, and the VOC distribution is poorly defined, the exact location of the plume(s) cannot be determined, especially in the vertical sense.

Although existing information (from well logs) does not clearly and conclusively delineate any continuous low permeability basal boundaries for DNAPL flow, several such entities may exist, such as the thick silt and clay lens in the drift as seen in the MW-2 and MW-3 logs, or any of the siltstone or chert layers seen in bedrock in the monitoring well logs. The continuity of such layers, however, is not known, and cannot be constrained with available data. The possibility that more than one unit or body is acting as a basal boundary should also be considered. This is suggested by the presence of dissolved phase VOCs in the shallow well at MW-2, the possible presence atop the silt and clay lens, and at depth in the domestic well, although the last two occurrences are of uncertain reliability.

The preceding conclusions are based on results of the flow model, which is based on limited information regarding the hydrogeologic properties (especially conductivity and recharge) of the system. As a result, the trial and error calibration procedure may have produced a non-unique set of parameters and head distributions. However, because the calibrated hydraulic conductivities were partially validated by the pump test results, the initial insights into groundwater flow and contaminant migration provided by the model can serve as an important guide to further investigations of the Ripon landfill and the municipal well field. It should be noted, however, that the predictive capabilities of the model have not been verified directly. Water level fluctuations due to seasonal conditions or additional pumping by other wells may need to be considered, which would necessitate a more intensive data-gathering process.

The methods used to reach the above conclusions provide a different approach to investigation of sites with suspected DNAPL contamination. Coupling geologic data and a particle tracking model with a limited set of chemical data allows for a relatively low-cost evaluation of contaminant phase distribution and migration. In addition, zones of contribution for wells can be delineated easily once the model is completed, thus providing further information with which to evaluate potential threats to a well or well field.

Lastly, some observations may be made regarding the groundwater flow system. These include the realization that the groundwater divide of Newport (1962) is not necessarily a well-located no-flow boundary. Also, flow in the pre-glacial valley drift and the flow to Green Lake and Rush Lake provides the eventual outlet for much of the groundwater in the system. Given these observations, the Green Lake system is likely the ultimate end point of dissolved-phase migration, especially in the drift; however, particle tracking suggest travel times greater than 1000 years. Finally, although obvious drawdown effects of municipal well pumping are confined to the areas within 1/2 to 3/4 mile of the municipal wells, groundwater velocities are reduced over a much larger area.

C. RECOMMENDATIONS

The major uncertainty affecting this study is the stratigraphic arrangement and hydrogeologic properties of the drift, particularly adjacent to and below the landfill. Especially valuable would be wells screened in the drift surrounding and below the landfill, particularly to the east and southeast, in the area of the suspected DNAPL source identified by particle tracking in this study. Additional wells up-gradient, down-gradient, and possibly to the north of the landfill could also be useful. These wells could serve to define locations and geometries of basal boundaries in the drift. Stratigraphic data could define the distribution of clay and silt lenses, especially the one seen in MW-2.

Besides addressing the uncertainties about the drift, more wells would be useful in locating and monitoring plumes of both contaminant phases. A few additional monitoring wells south and southeast of the landfill (between MW-2 and MW-3) could serve as an "early warning system" in case of further DNAPL and/or dissolved-phase migration towards municipal well #9. It would also be prudent to install monitoring wells in the drift and in the bedrock down-gradient from the landfill and thus warn homeowners that might be threatened by the contamination. During installation of any such wells, care should be taken to avoid cross-contamination if a DNAPL body is intercepted.

Installation of additional wells would also provide more detailed data regarding the hydrogeologic parameters of the flow system, such as hydraulic conductivities (especially in the drift) and anisotropy. Water levels from these wells would also aid in improving the uniqueness and capabilities of the groundwater flow model. A water table map would be extremely valuable, since all recorded wells in the area are cased in bedrock and virtually no information about the water table is available.

At the very least, continued annual sampling of MW-3A and MW-3B would be advisable to monitor such a threat. This might be coupled with a program of intermittent sampling of nearby domestic wells, especially down-gradient (to the west and southwest) on an annual or biannual basis. Also, if the MW-2 nest could be sampled again, the question of cross-contamination there might be resolved.

Additional useful information would be derived from an investigation of the two domestic wells near the landfill. The older well might be acting as a permanent breach that allows DNAPL to migrate deep into the bedrock, especially if it is uncased. Further, the newer well could have induced additional vertical migration during installation, although casing should prevent further action as a conduit. In that case, a new sample from the well may indicate that the old results were due to contamination during drilling.

Another small-scale inquiry that could provide valuable data is a search for any historical information regarding introduction of waste into the landfill. This could aid in constraining the timing of contaminant movement and thus improve interpretation of existing particle tracking results and aid in constructing further particle tracking exercises.

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APPENDIX A
MONITORING WELL INSTALLATION AND LOGS

Drilling and installation of monitoring well nests MW-1 and MW-2 occurred from August 29 to September 20, 1990. Layne-Northwest Company of Pewaukee, Wisconsin was contracted for this work. In each case, a six-inch diameter hole was drilled to 300 feet using the reverse-circulation air rotary method. Steel casing was driven along with the bit until it reached the bedrock surface. After reaching bedrock, no more casing was driven, but the casing through the drift was left in place after completion of the hole. Description of cuttings collected during drilling provided a means for locating and correlating potential basal boundaries for DNAPL flow, as well as guiding piezometer placement. Originally, individual piezometers were to be placed above potential boundaries, but once MW-2 was drilled, it was apparent that few, if any such layers exist in the bedrock. As such, the three nested piezometers in each well were placed to be screened at roughly equal elevations.

Individual piezometers were constructed with threaded, one-inch diameter schedule 80 PVC piping, with a five-foot, number 10 slot (0.01 inch) screen at the bottom. A coarse sand filter pack was poured to two feet above and below the screen, and the intervals between the screens were filled with bentonite chips. Above the uppermost piezometer, bentonite grout was pumped in up to ground level.

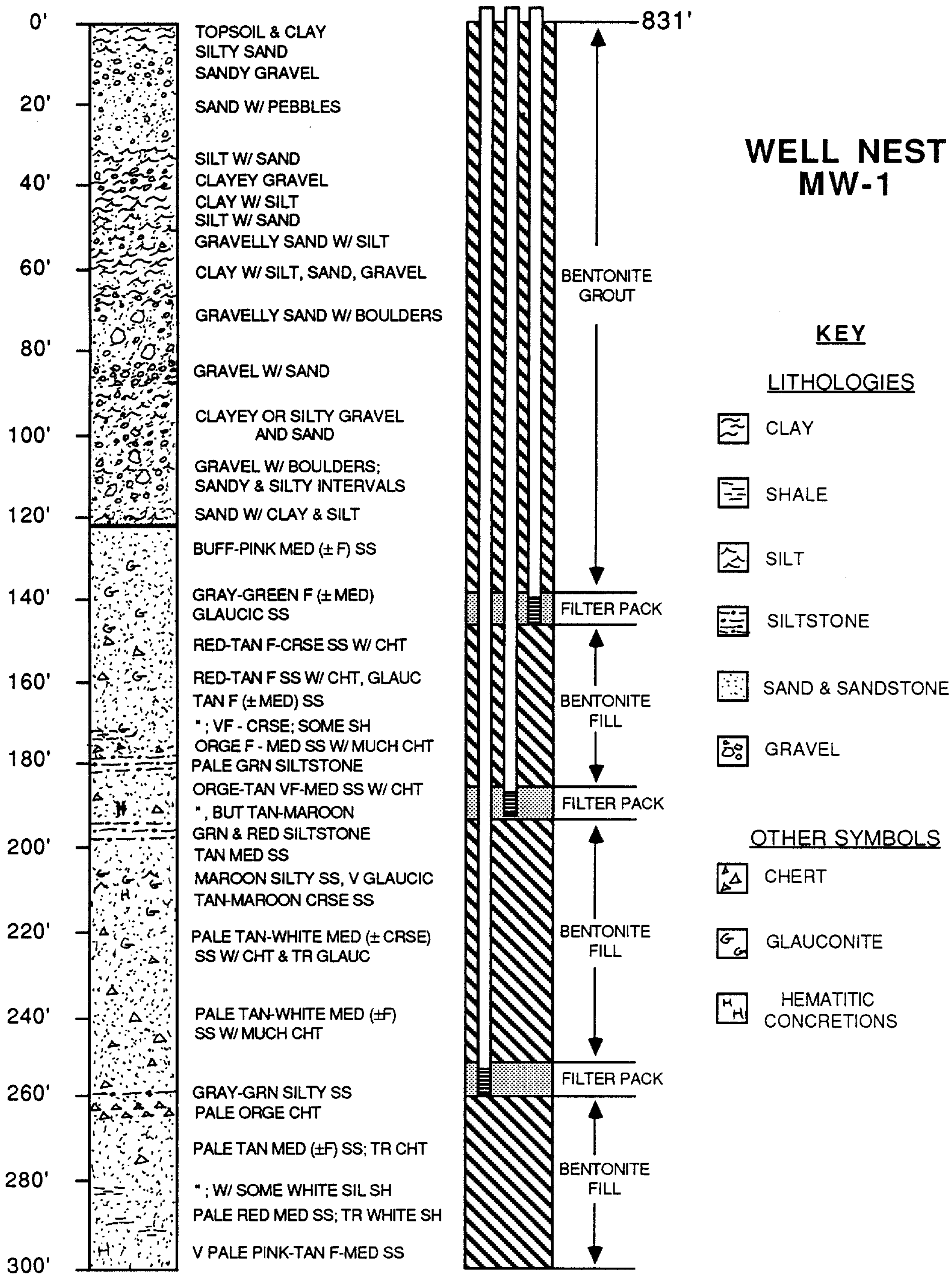
The third set of monitoring wells, MW-3A and MW-3B, are separate wells located within seven feet of each other. These were drilled and installed by CTW Corporation from January 7 - 25, 1991. In this case, the method employed was direct circulation rotary. While drilling through the drift, bentonite mud was the fluid, and air was used in bedrock. Casing through the drift was driven after the bit reached bedrock.

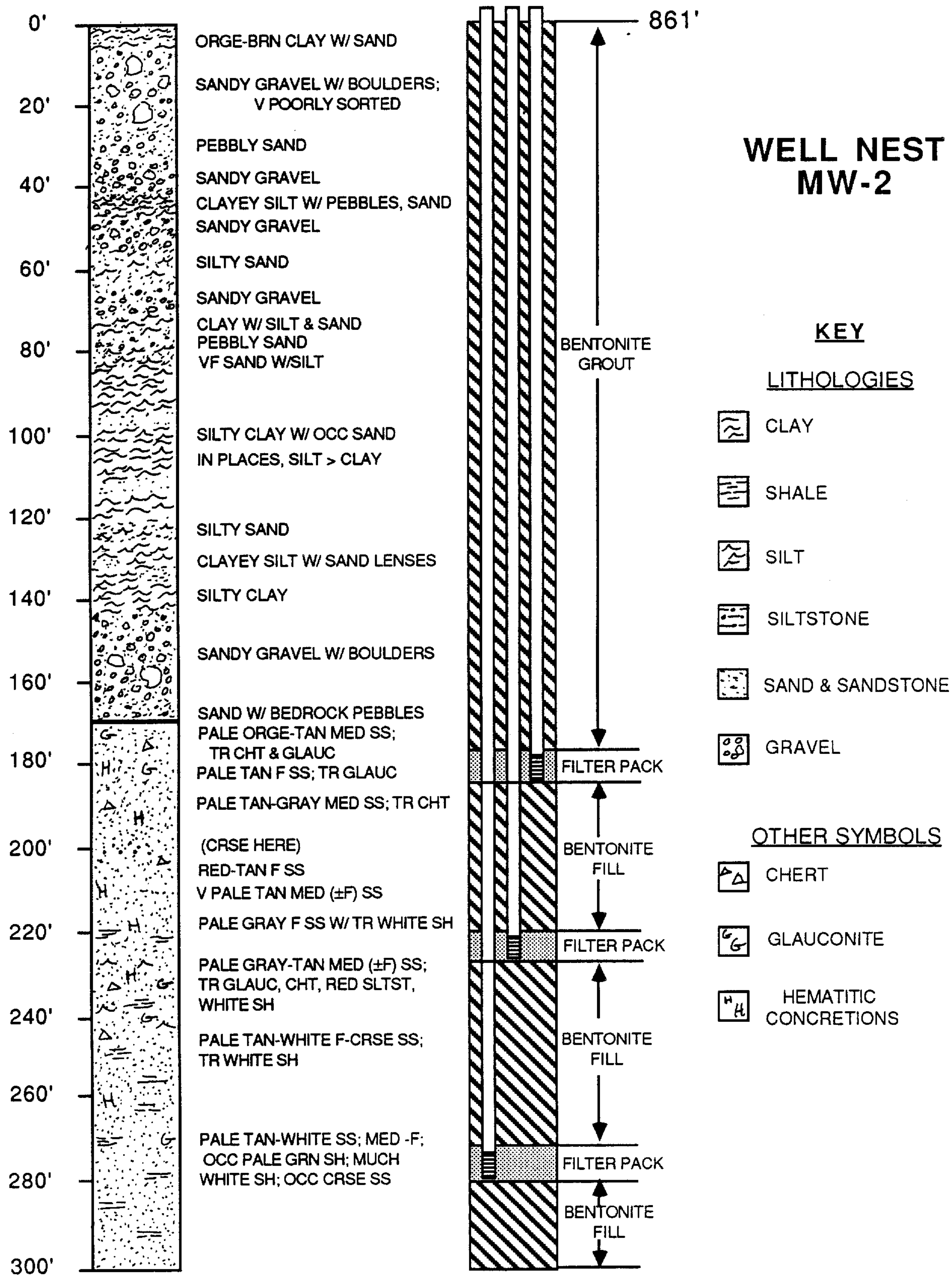
MW-3A is the deeper of the two holes, extending to 278 feet, while MW-3B extends to 182 feet deep. Each well was constructed with threaded, two-inch diameter schedule 40 PVC with five-foot number ten slot screens and two-foot blanks at the bottom. As before, a coarse sand filter pack was poured to two feet above the screen, but was topped with two feet of pure quartz sand and then two feet of bentonite pellets. The remaining portion of each hole was filled with bentonite grout.

The following figures are graphic logs and cartoons showing the stratigraphy and construction of each well. Abbreviations used in descriptions are as follows:

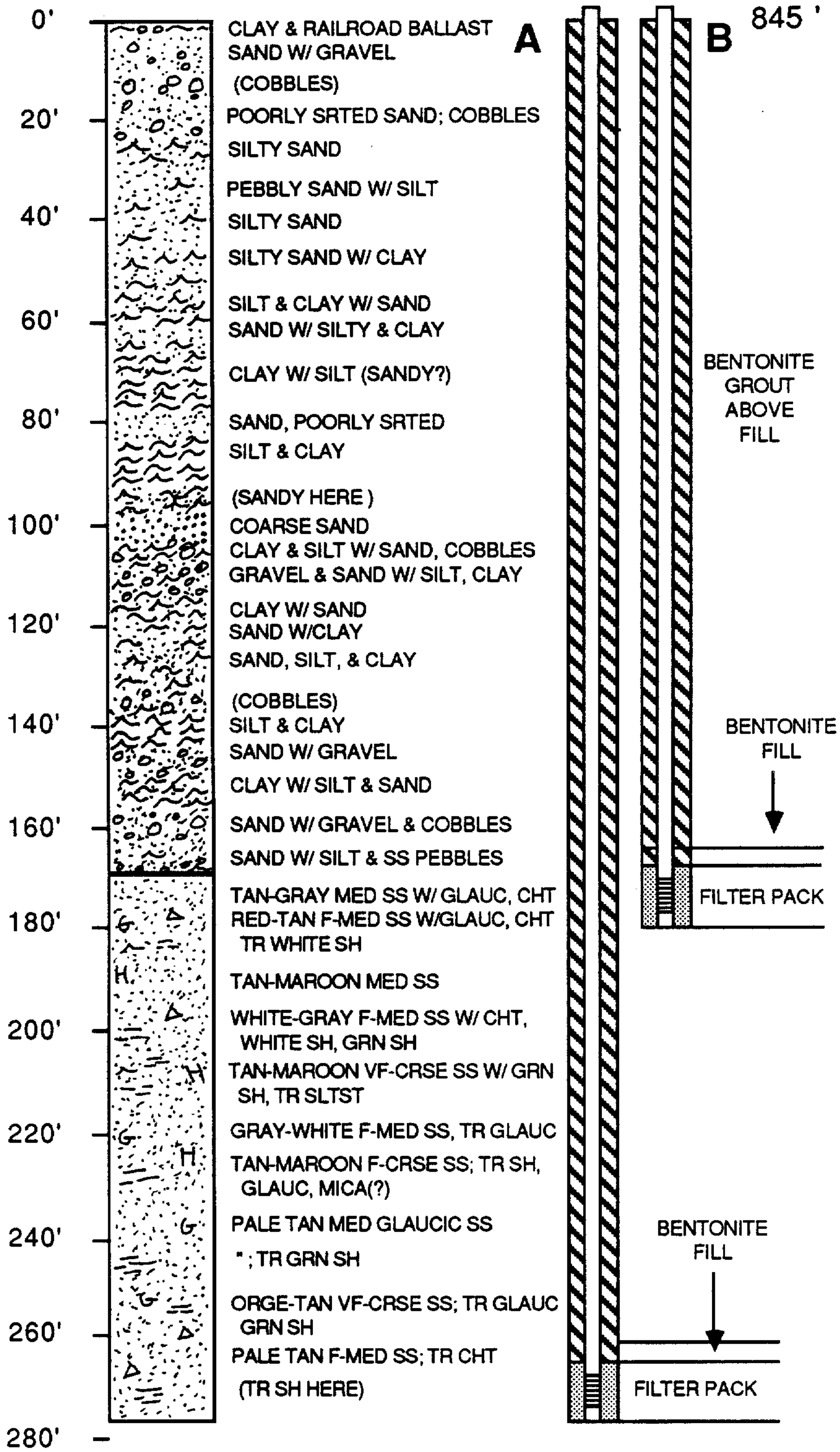
BRN = brown; CHT = chert; CRSE = coarse; F = fine; GLAUC = glauconite; GLAUCIC = glauconitic; GRN = green; MED = medium; OCC = occasional; ORGE = orange; SH = shale; SRTED = sorted; SS = sandstone; TR = trace; V = very; VF = very fine; W/ = with.

WELL NEST MW-1




0'
20'
40'
60'
80'
100'
120'
140'
160'
180'
200'
220'
240'
260'
280'
300'
ORGE-BRN CLAY W/ SAND
SANDY GRAVEL W/ BOULDERS; V POORLY SORTED
PEBBLY SAND
SANDY GRAVEL
CLAYEY SILT W/ PEBBLES, SAND
SANDY GRAVEL
SILTY SAND
SANDY GRAVEL
CLAY W/ SILT & SAND
PEBBLY SAND
VF SAND W/SILT
SILTY CLAY W/ OCC SAND
IN PLACES, SILT > CLAY
SILTY SAND
CLAYEY SILT W/ SAND LENSES
SILTY CLAY
SANDY GRAVEL W/ BOULDERS
SAND W/ BEDROCK PEBBLES
PALE ORGE-TAN MED SS; TR CHT & GLAUC
PALE TAN F SS; TR GLAUC
PALE TAN-GRAY MED SS; TR CHT
(CRSE HERE)
RED-TAN F SS
V PALE TAN MED (±F) SS
PALE GRAY F SS W/ TR WHITE SH
PALE GRAY-TAN MED (±F) SS; TR GLAUC, CHT, RED SLTST, WHITE SH
PALE TAN-WHITE F-CRSE SS; TR WHITE SH
PALE TAN-WHITE SS; MED -F; OCC PALE GRN SH; MUCH WHITE SH; OCC CRSE SS
861'
BENTONITE GROUT
FILTER PACK
BENTONITE FILL
FILTER PACK
BENTONITE FILL
FILTER PACK
BENTONITE FILL
WELL NEST MW-2
KEY
LITHOLOGIES
CLAY
SHALE
SILT
SILTSTONE
SAND & SANDSTONE
GRAVEL
OTHER SYMBOLS
CHERT
GLAUCONITE
HEMATITIC CONCRETIONS

WELLS MW-3A, MW-3B



KEY

LITHOLOGIES

- CLAY
- SHALE
- SILT
- SILTSTONE
- SAND & SANDSTONE
- GRAVEL

OTHER SYMBOLS

- CHERT
- GLAUCONITE
- HEMATITIC CONCRETIONS

APPENDIX B
MONITORING WELL DEVELOPMENT AND SAMPLING

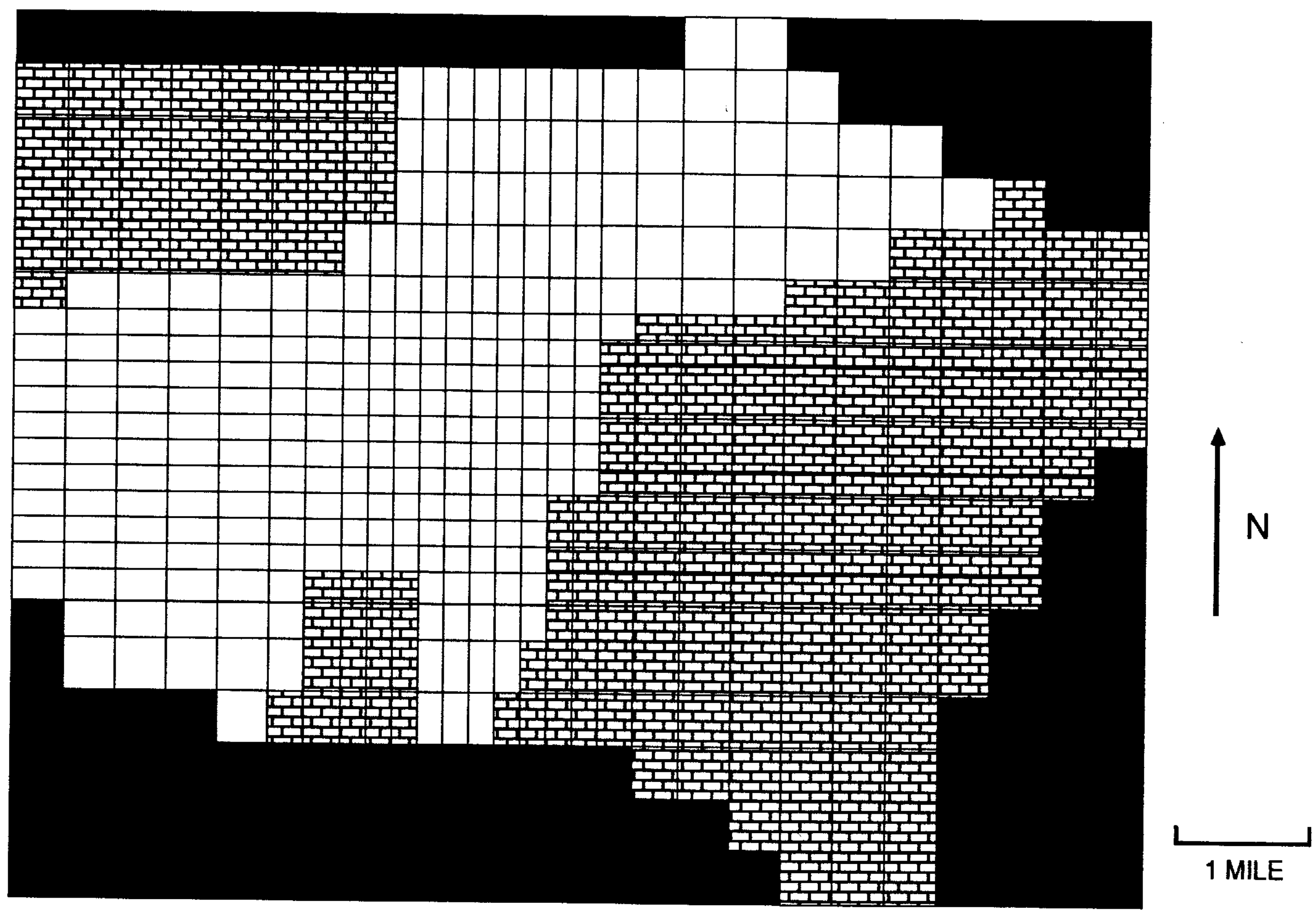
Nests MW-1 and MW-2 were developed on November 15, 1990. In each case, high purity nitrogen gas was pumped down the well to blow out standing water. This was repeated until approximately three well volumes were expelled. The well was then pumped by hand to remove an additional three volumes. After this, the first set of samples was collected with the hand pump.

The MW-3 wells were developed on February 8, 1991. Because of the larger diameter of these wells, it was possible to use a Fultz backpack pump, which promptly failed. A hand pump was then used to remove at least four well volumes and then sample the wells.

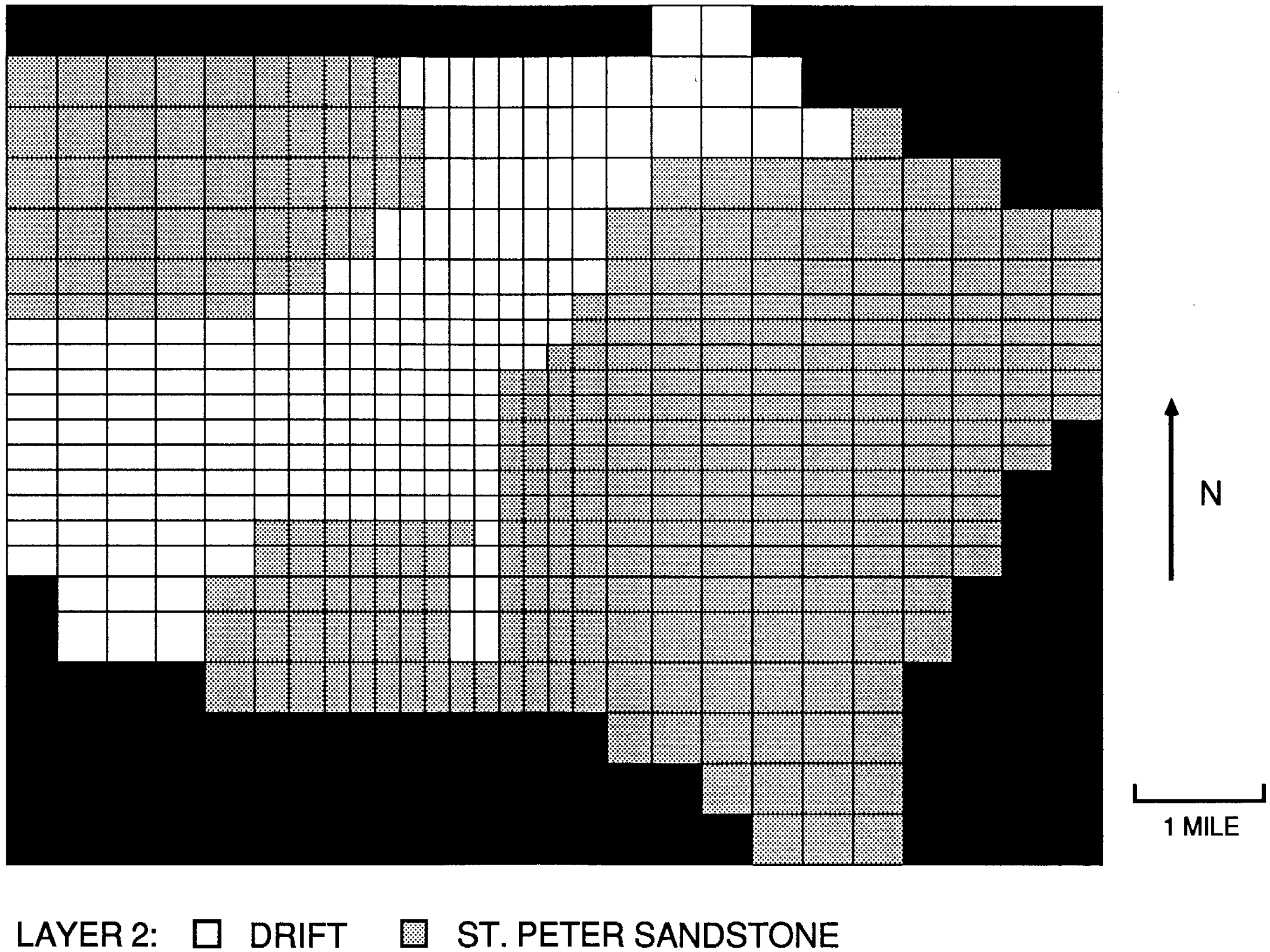
All wells were sampled once more, on May 5 or May 7, 1991. For this round, the hand pump was used to remove three well volumes prior to sample collection. Sampling results are in Table 2.1.

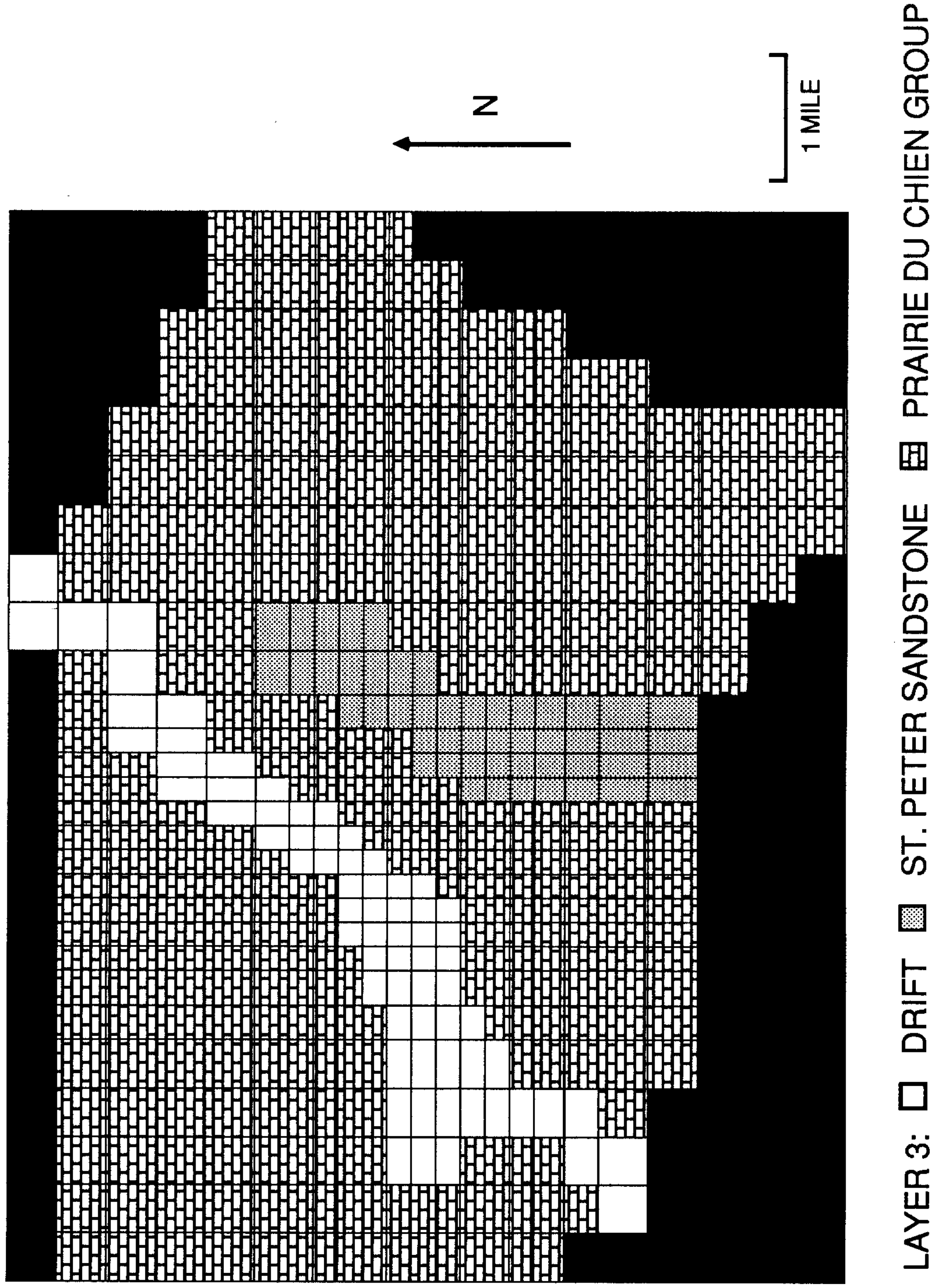
APPENDIX C
MODEL LAYER REPRESENTATIONS

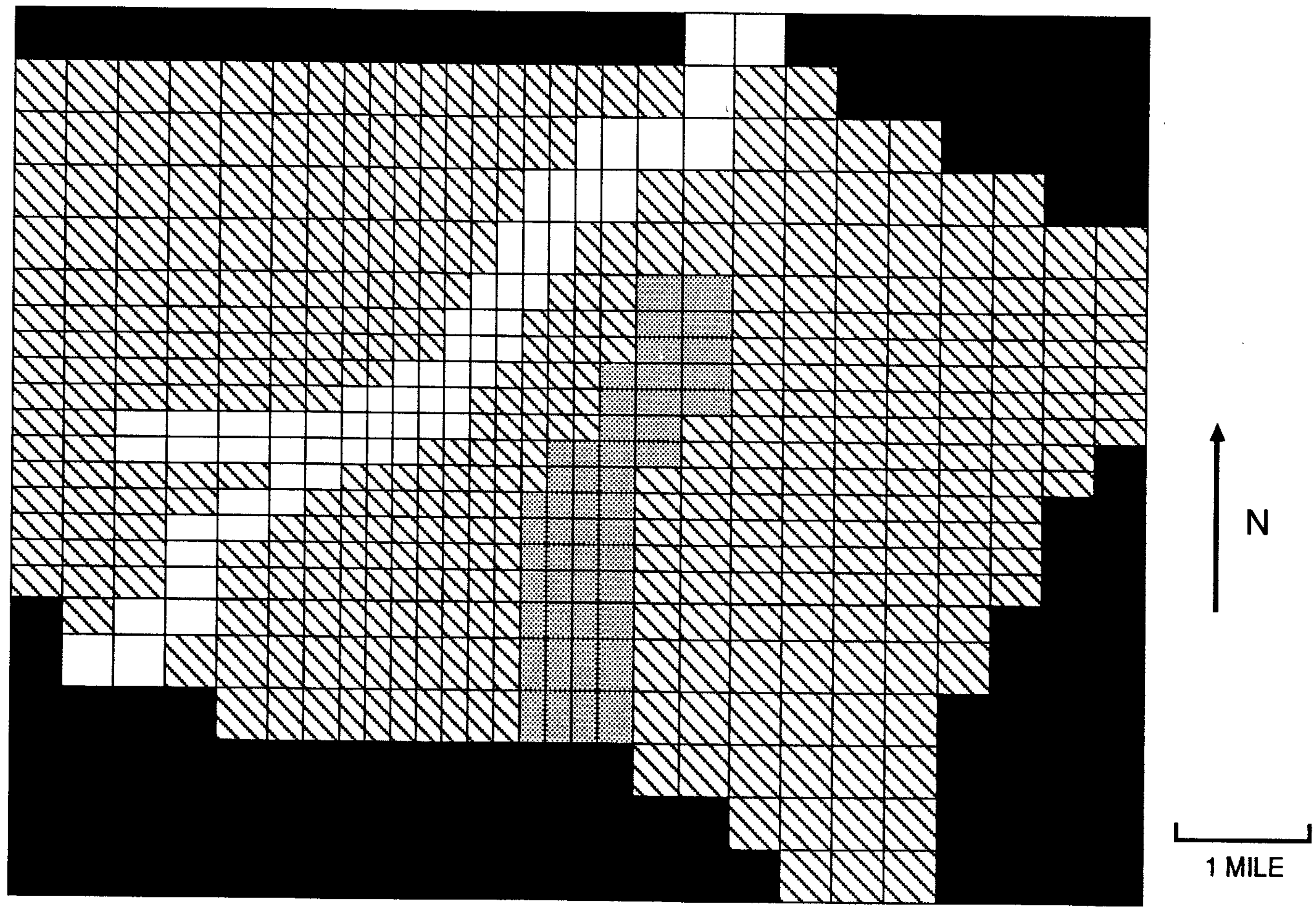
The following six figures show the distribution of hydrostratigraphic units among the model layers. Information on thickness may be found in the MODFLOW input files in the accompanying material.



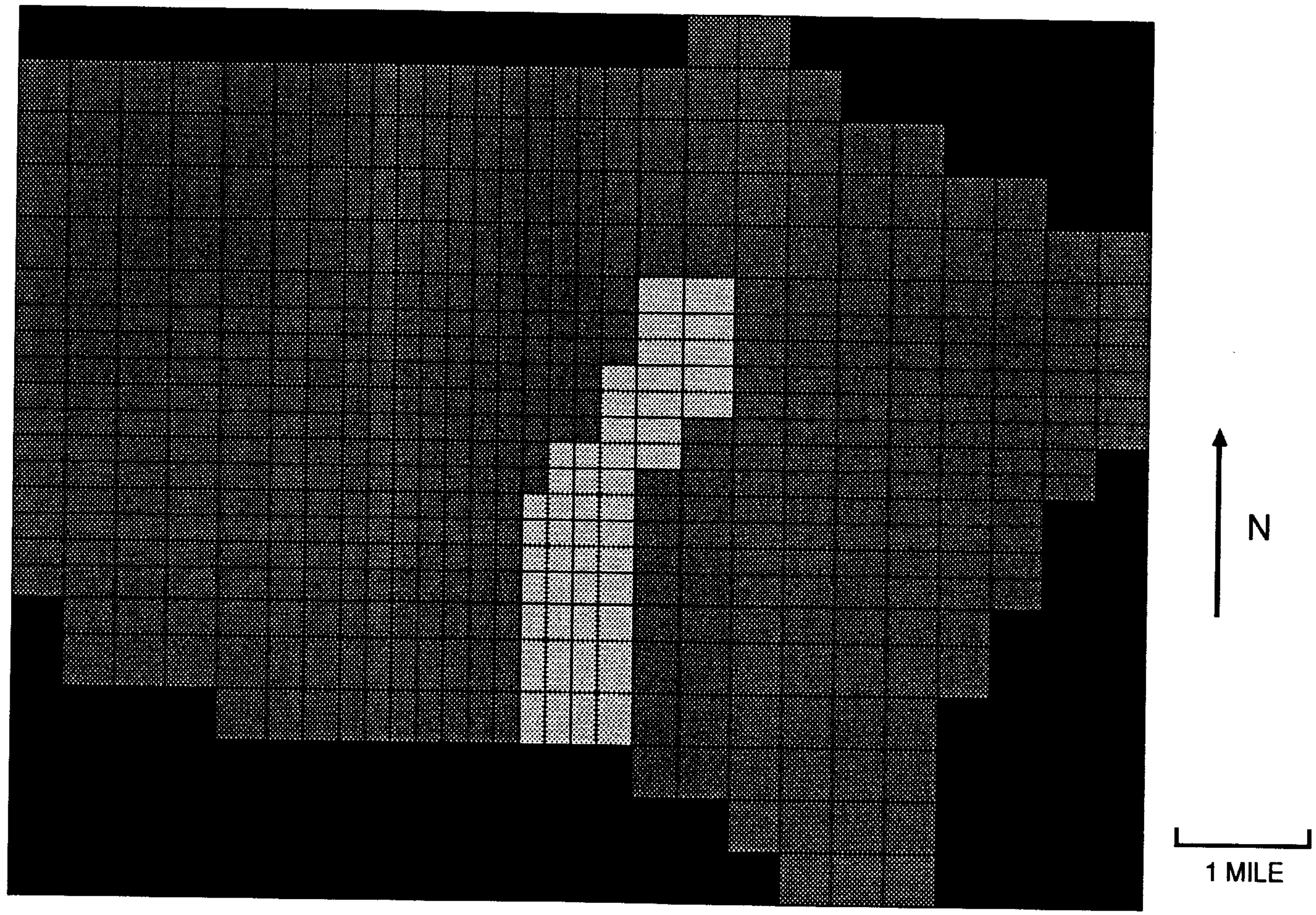
LAYER 1: ☐ DRIFT ⊞ GALENA-PLATTEVILLE + DRIFT


N
1 MILE
LAYER 2: DRIFT ST. PETER SANDSTONE

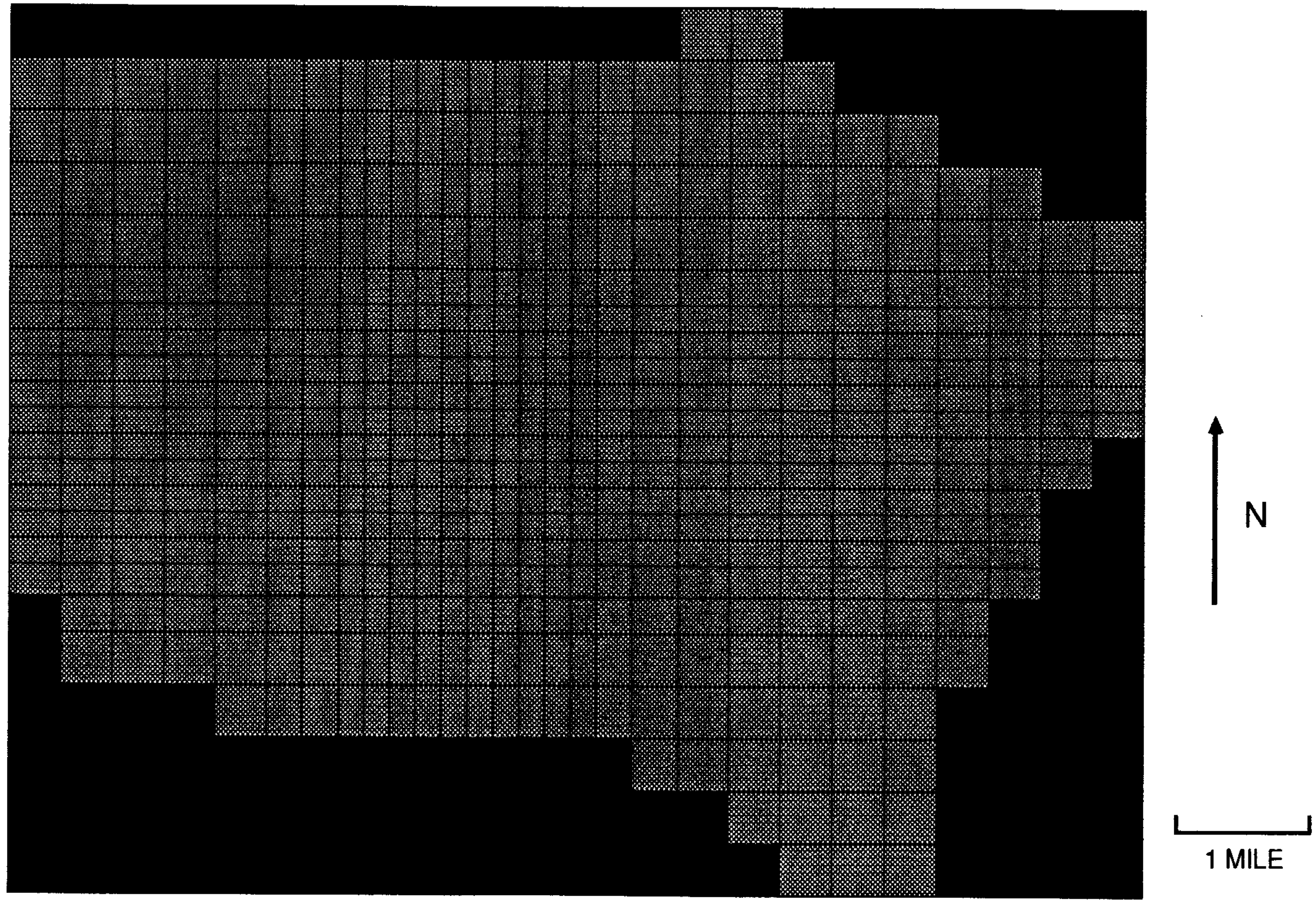

N
1 MILE
LAYER 3: DRIFT ST. PETER SANDSTONE PRAIRIE DU CHIEN GROUP



LAYER 4: ☐ DRIFT ▩ ST. PETER SANDSTONE ▨ TREMPEALEAU GROUP



LAYER 5: ST. PETER SANDSTONE TUNNEL CITY & ELK MOUND GROUPS



LAYER 6: TUNNEL CITY & ELK MOUND GROUPS

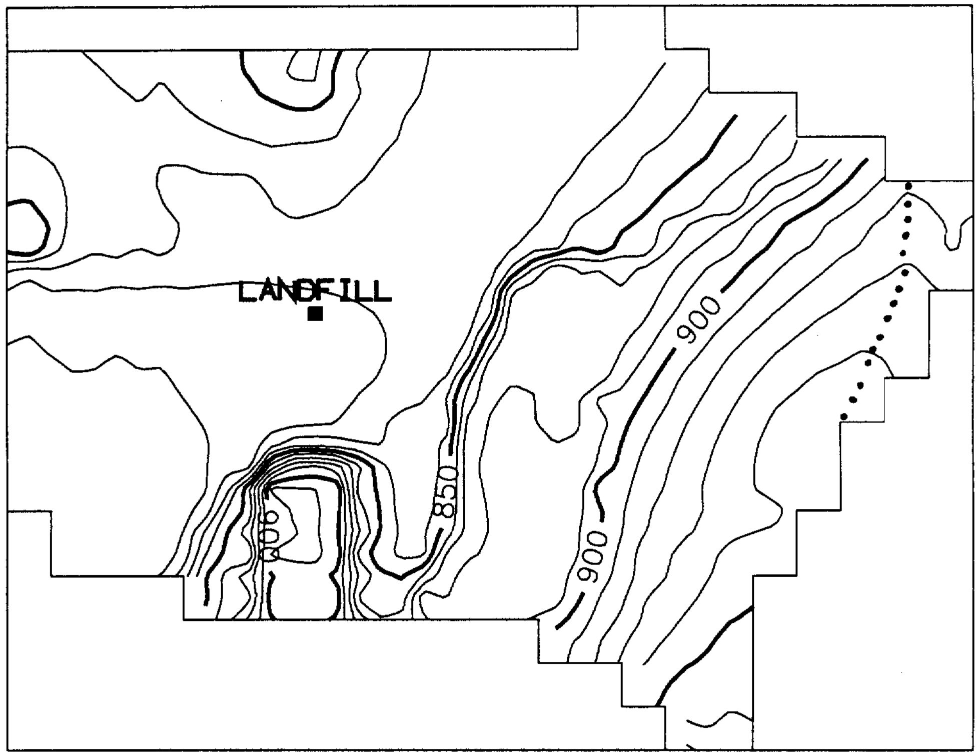
APPENDIX D
HEAD CONTOURS

Contours of head solutions for all six model layers were produced using the code SURFER (Golden Software, INC., 1990). Head data from the MODFLOW output were converted to SURFER-compatible format with a simple FORTRAN code. Results for the models with and without pumping of the municipal wells are presented in the following pages. The locations of the groundwater divide near the eastern boundary are shown by dotted lines.

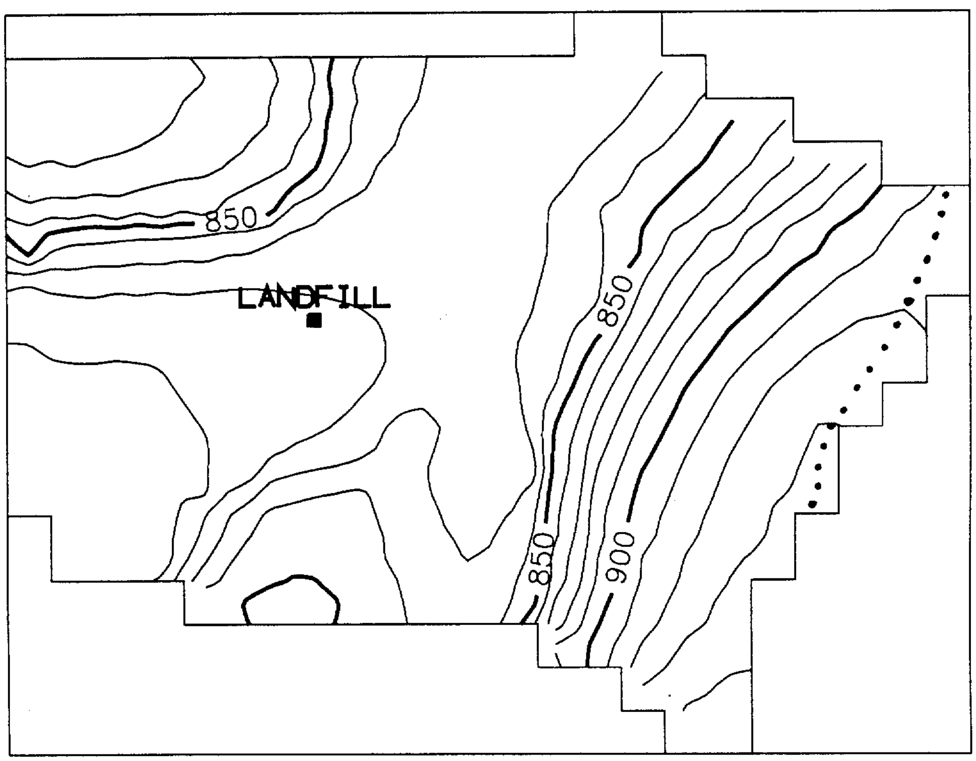
In both cases, layers 1 - 3 have a 10-foot contour interval, while layers 4 - 6 have a 5-foot contour interval. It should also be noted that in the northwest corner of the model area, the first layer was inactive for all solutions. Water levels in the cells in this area dropped below the cell base during the initial model iterations. As a result, the second layer heads are the water table in this area. Also, since the inactive nodes are included in the contoured area, the contours near the margins will be distorted a small amount. This is an unavoidable result of the code and the methods it uses to produce such maps.

Further discussion of these results is found in Chapter 3.

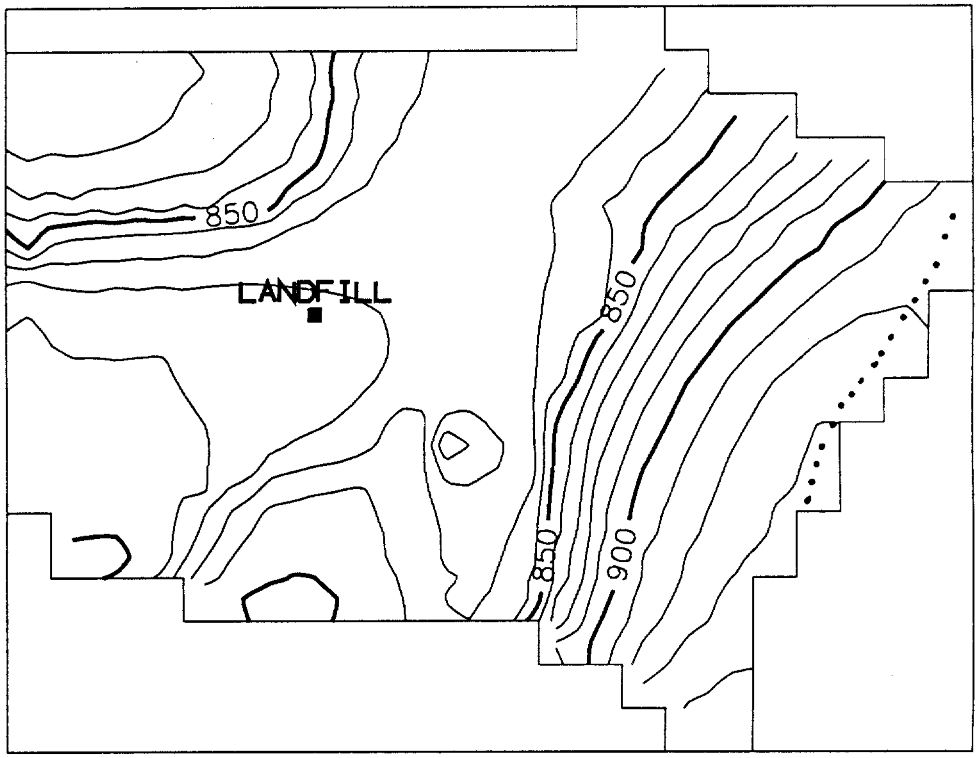
LAYER 1 HEADS -- WITH PUMPING



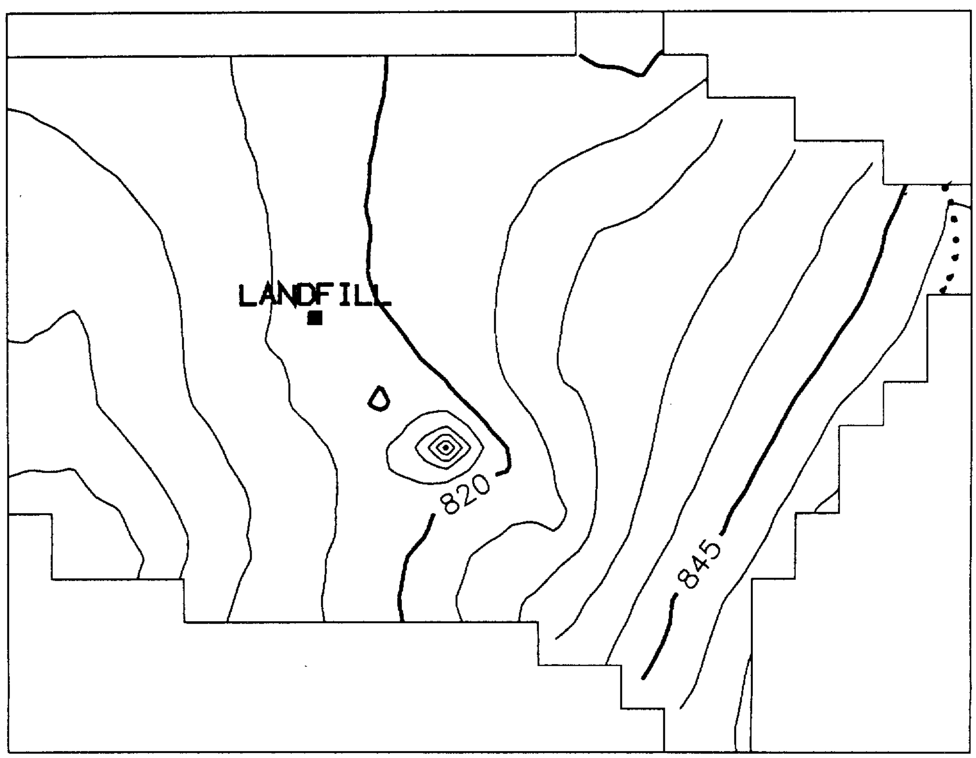
LAYER 2 HEADS -- WITH PUMPING



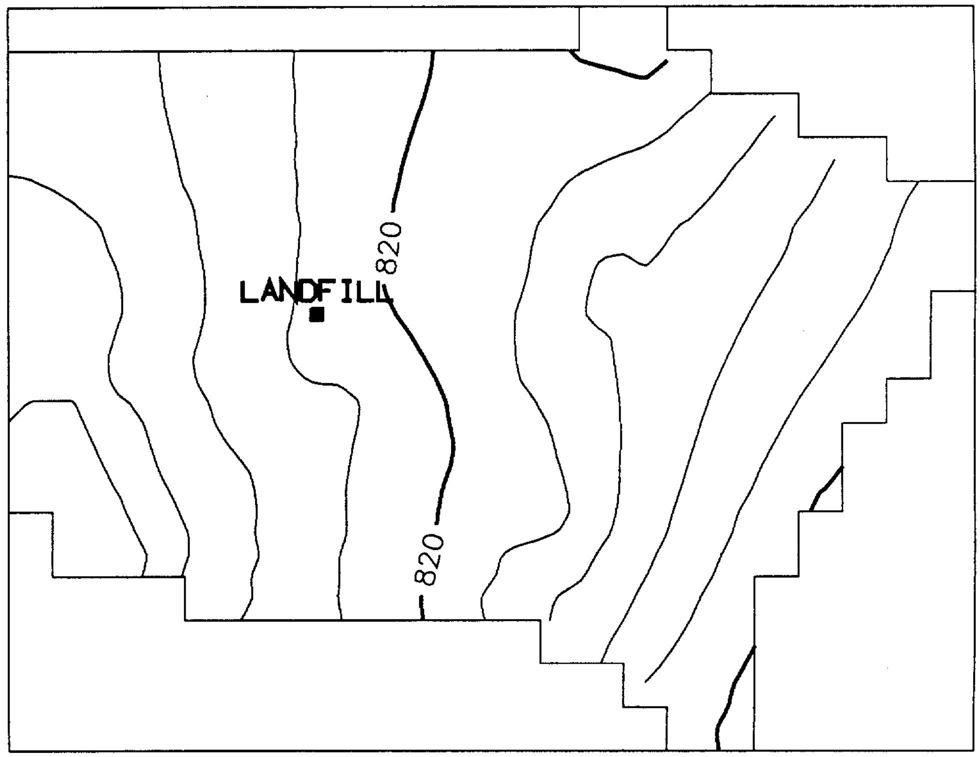
LAYER 3 HEADS -- WITH PUMPING



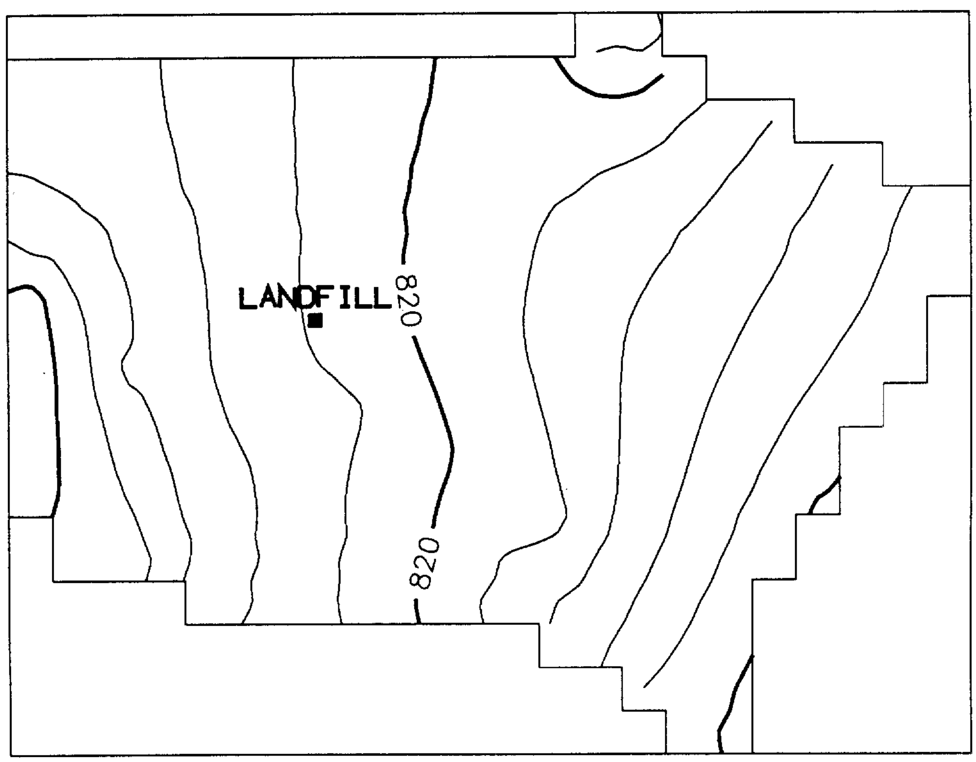
LAYER 4 HEADS -- WITH PUMPING



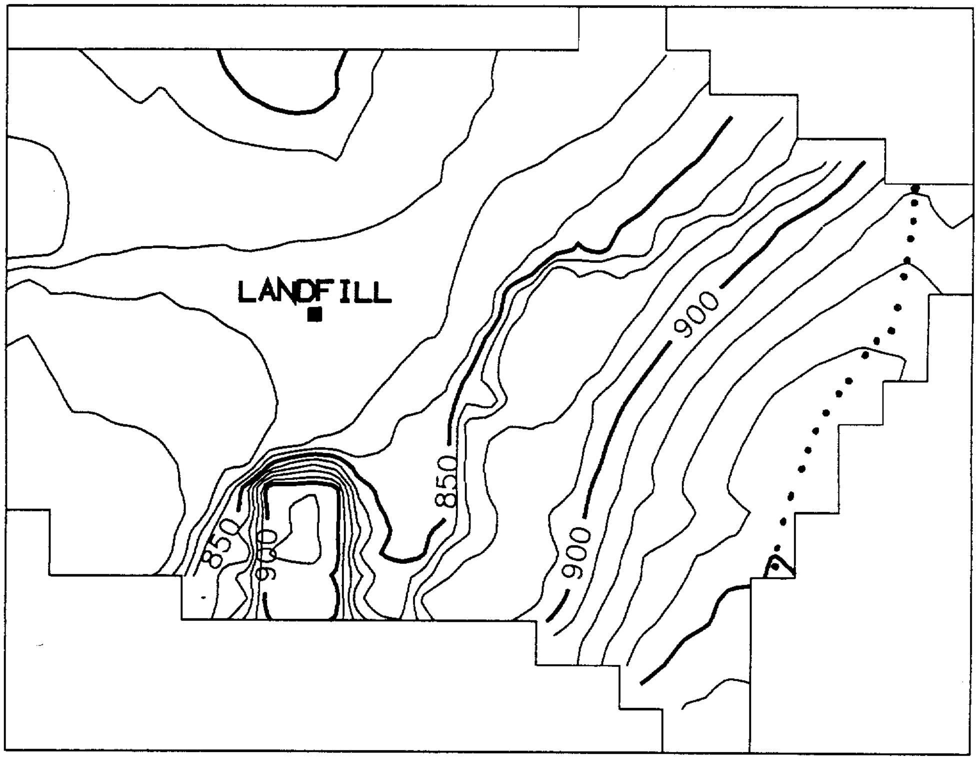
LAYER 5 HEADS -- WITH PUMPING



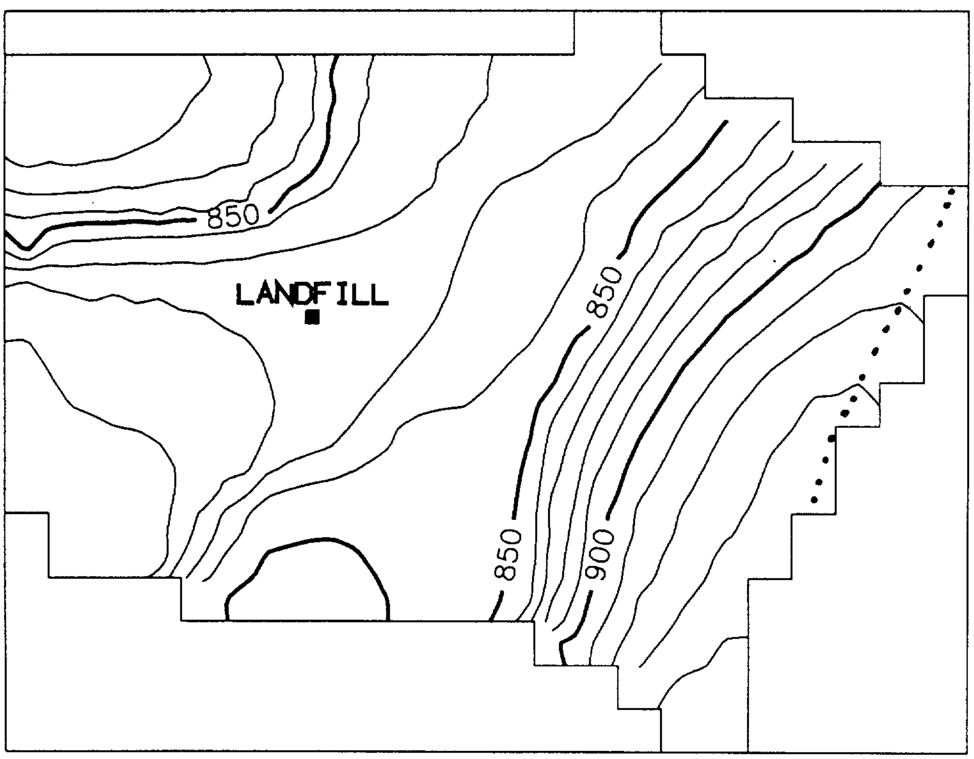
LAYER 6 HEADS -- WITH PUMPING



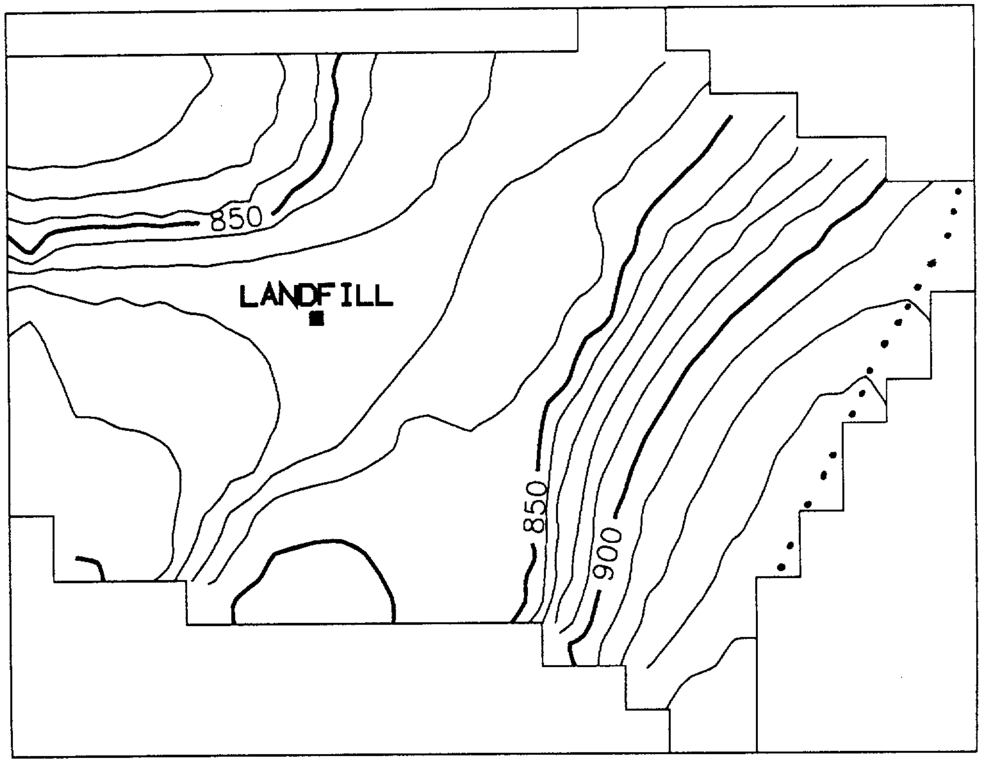
LAYER 1 HEADS -- NO PUMPING



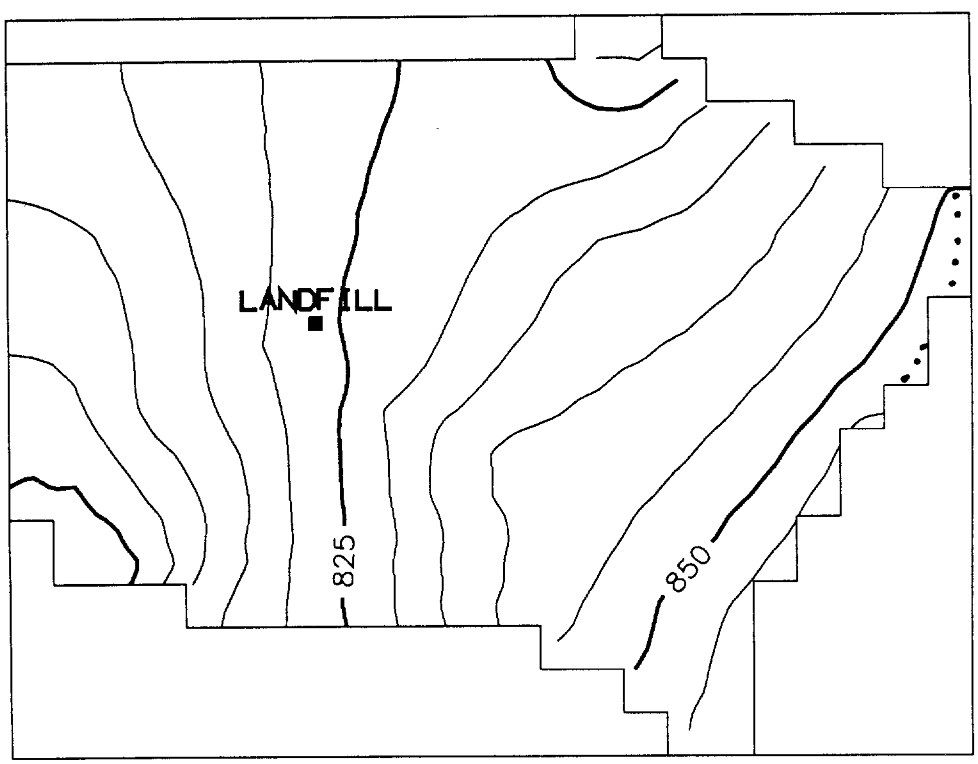
LAYER 2 HEADS -- NO PUMPING



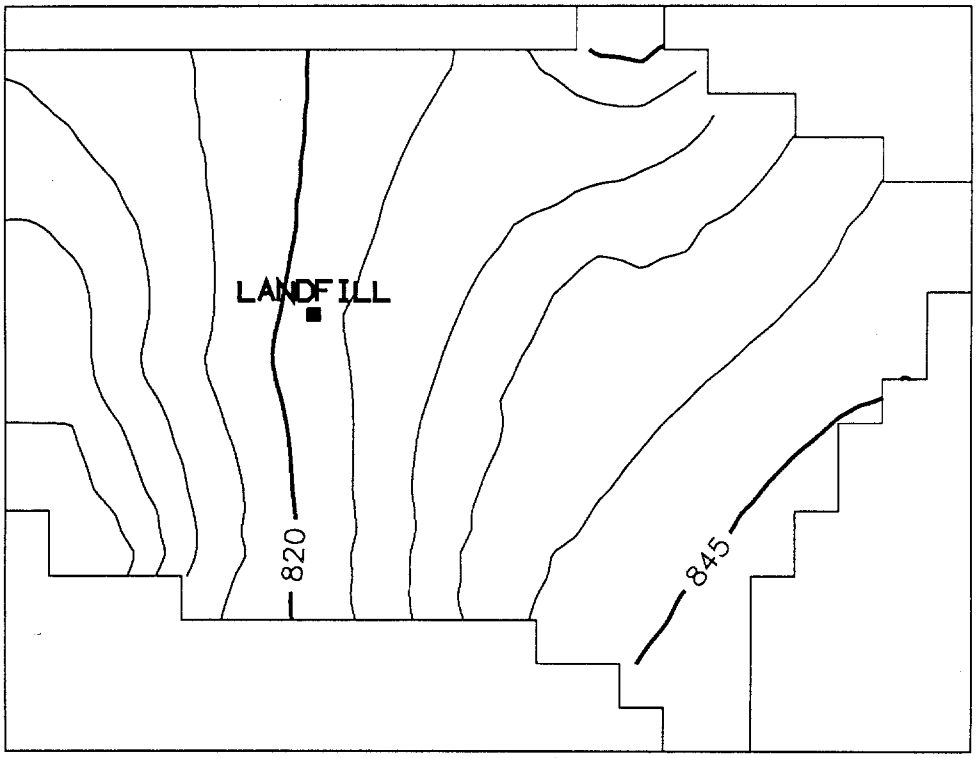
LAYER 3 HEADS -- NO PUMPING



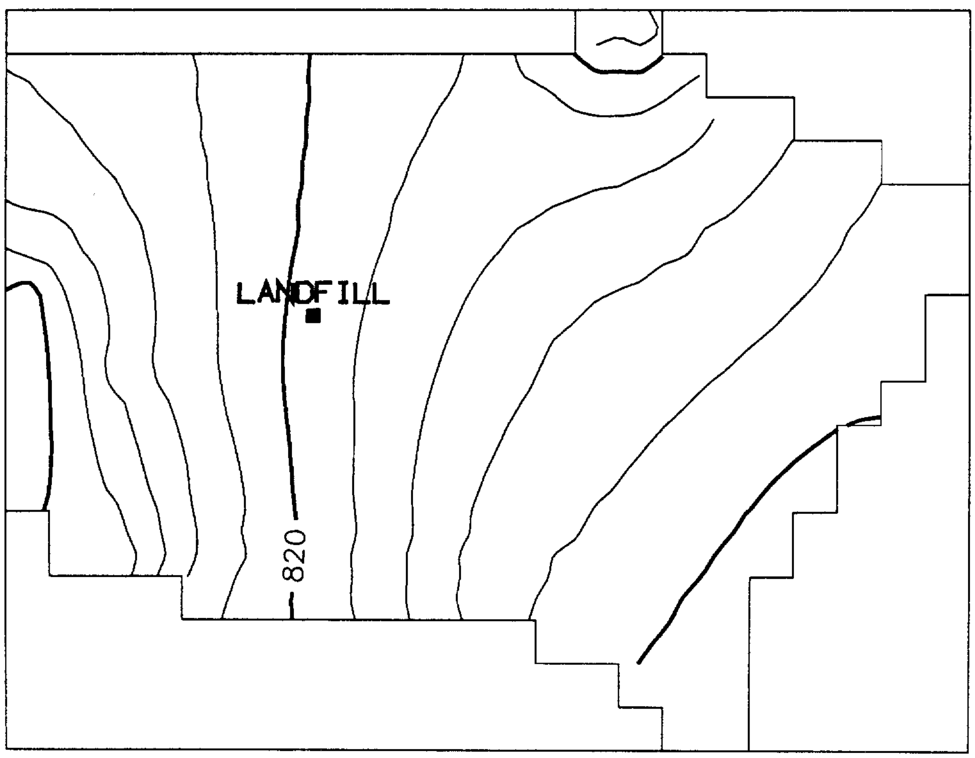
LAYER 4 HEADS -- NO PUMPING



LAYER 5 HEADS -- NO PUMPING



LAYER 6 HEADS -- NO PUMPING



APPENDIX E
PUMPING TEST

A. Procedure

From May 3 to May 7, 1991, a recovery and pumping test utilizing municipal well #9 was conducted. The municipal well was the pumping well, open to the Cambrian Tunnel City and Elk Mound Groups. All three MW-1 wells plus MW-3A and MW-3B served as observation wells. The MW-2 nest was monitored from time to time during the test.

Except for MW-1S, all data were collected with pressure transducers and data loggers. MW-1S was monitored with an electric tape and stopwatch because its recovery and drawdown exceeded the limits of the pressure transducers. Wisconsin Power and Light Co. provided hourly flow rates and cumulative volumes for the pumping test and the period preceding the recovery test.

Testing began with the recovery phase. Municipal well #9 was shut off at 1 P.M. on May 3 and recovery was monitored for 24 hours. After this, the pumping well was left off for another 42 hours prior to the pumping test. Monitoring of water levels in the 18 hours prior to the resumption of pumping showed only a slight steady rise of about 0.1 feet. Pumping began at 8 A.M. on May 7. Again, monitoring of water levels continued for 24 hours.

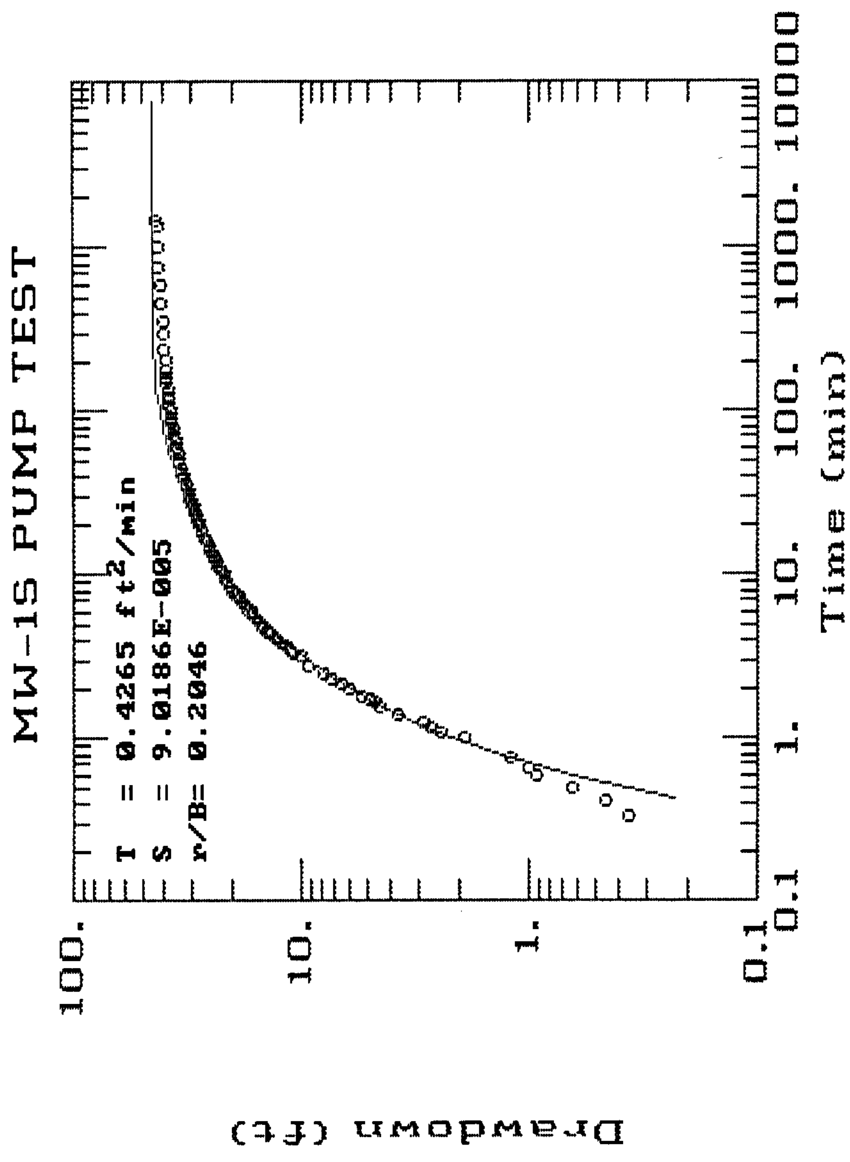
The municipal wells in Ripon normally operate concurrently for a six hour period each day. As a result, the recovery data could be affected by the continued pumping of the other wells. The pumping data may also be affected by the shut down of the other wells during the day of May 7. Based on observations at MW-2, however, it is likely that such effects were negligible. MW-2 is approximately 0.5 miles from municipal well #9 and all the observation wells are at least 2 miles from the next nearest municipal well. During recovery, levels at MW-2 rose an average of 1 foot, while during pumping they fell an average of 1.8 feet. Given this and the distance to the next nearest pumping well, it would be difficult to identify any effects produced by pumping of the remaining municipal wells.

B. Results

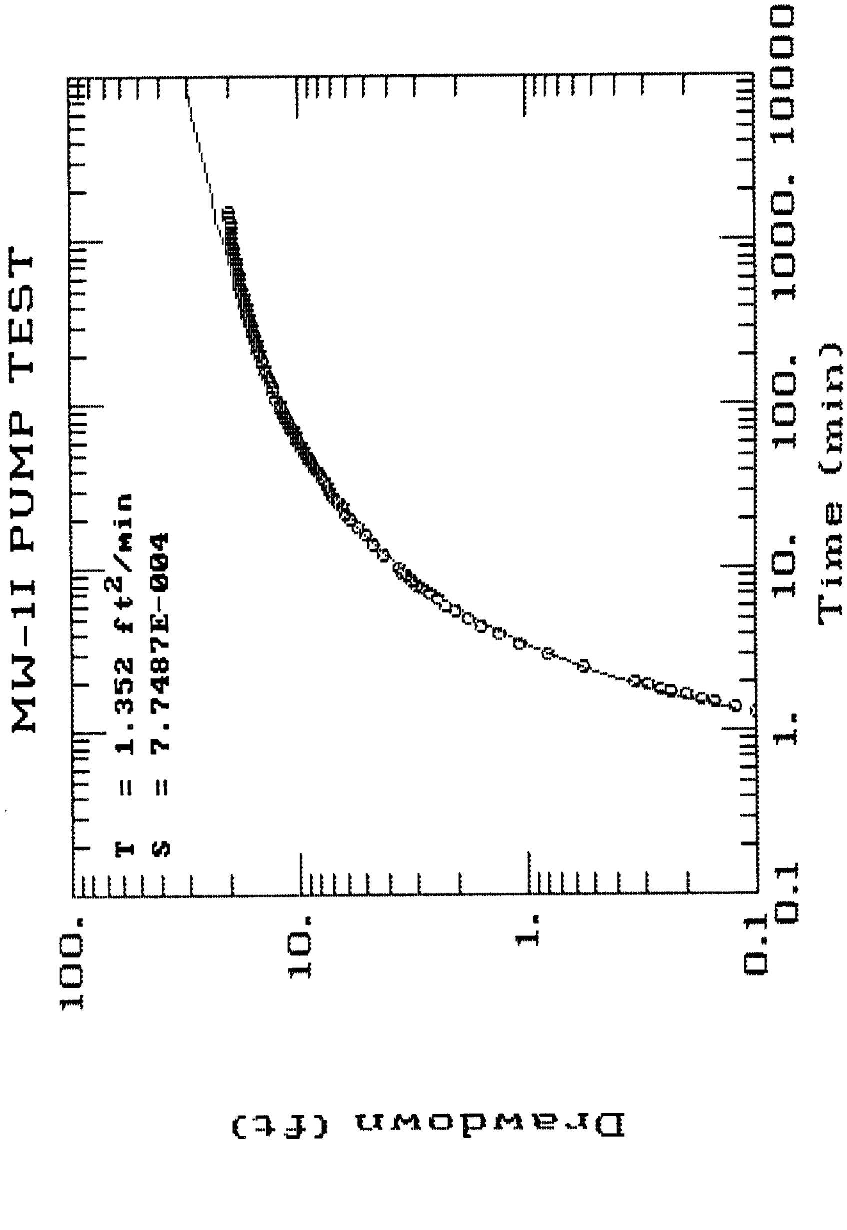
Data from both pumping and recovery were analyzed using the AQTESOLV computer code (Duffield and Rumbaugh, 1989). This code allows curve matching utilizing several different solution methods, including methods involving partial penetration and leaky confining units. AQTESOLV will fit curves to data and automatically calculate transmissivity and storage coefficient. More importantly, visual fitting of the type curves is also possible, and this was done for all of the following curves. In all cases, visual fitting provided better fits with the early time data.

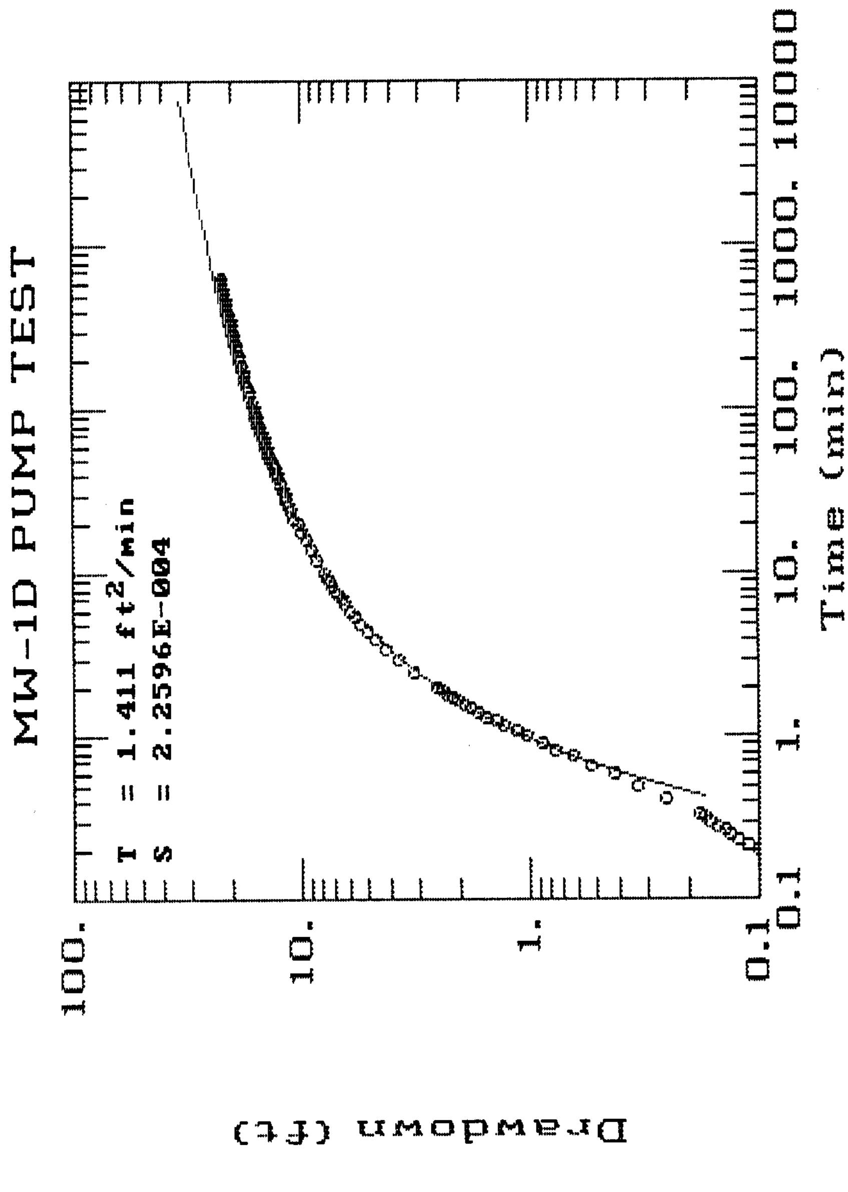
All pumping data except for MW-1S were analyzed using the Theis (1935) method with corrections for partial penetration as described by Hantush (1961). MW-1S was analyzed with the semiconfined method of Hantush and Jacob (1955). For all cases involving pumping, the plots which follow are log - log. All recovery data were analyzed with the Theis (1935) method. In this case, the plots are semi-log, and follow the pumping data.

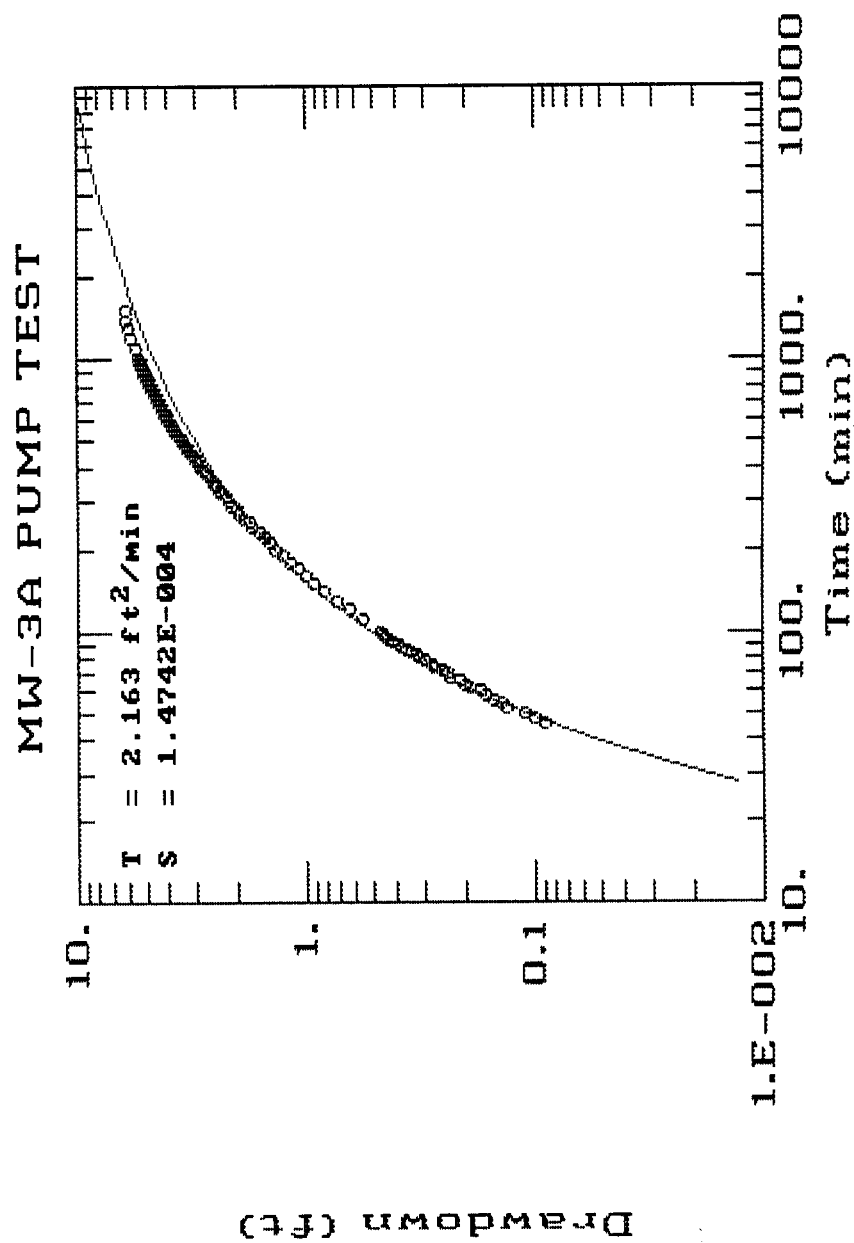
All plots are screen dumps from the AQTESOLV program. For a representation of the data as it applies to the model, see Chapter 3.

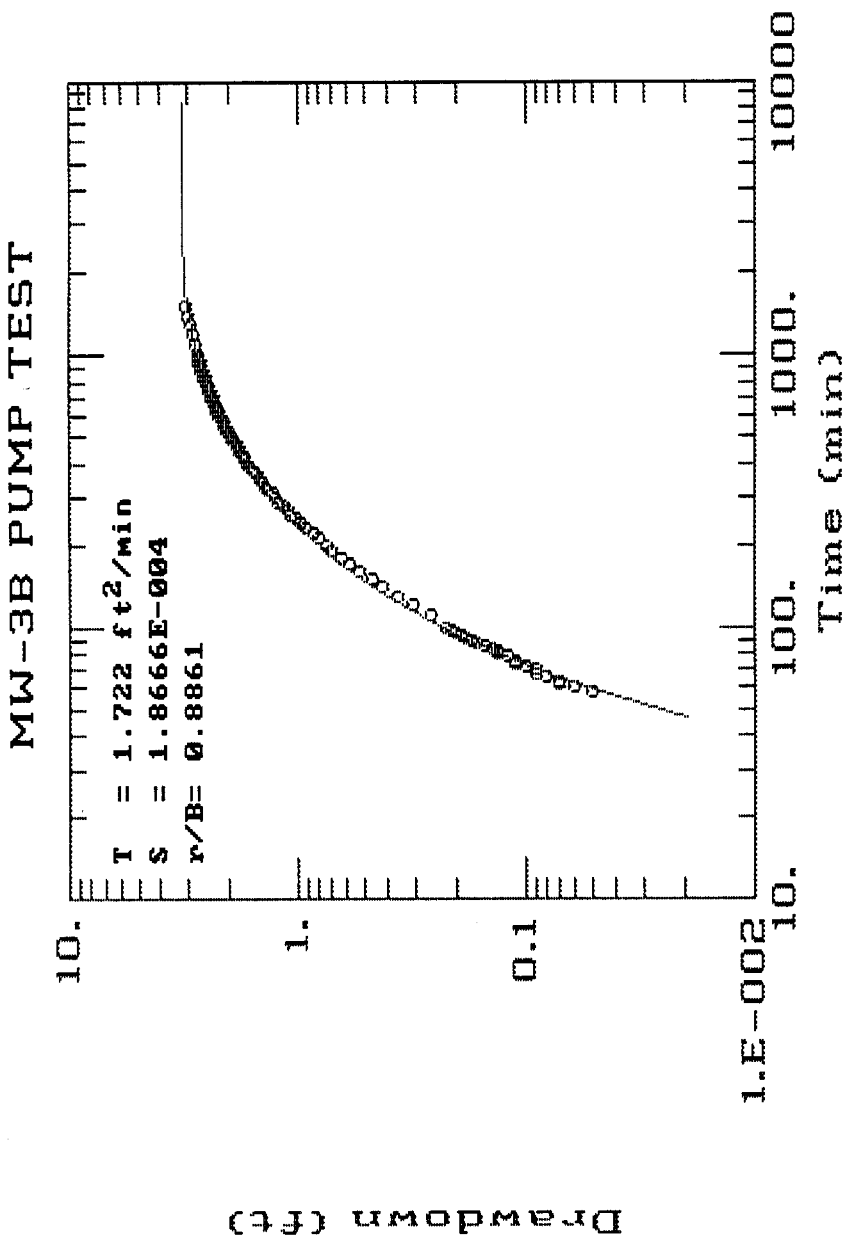


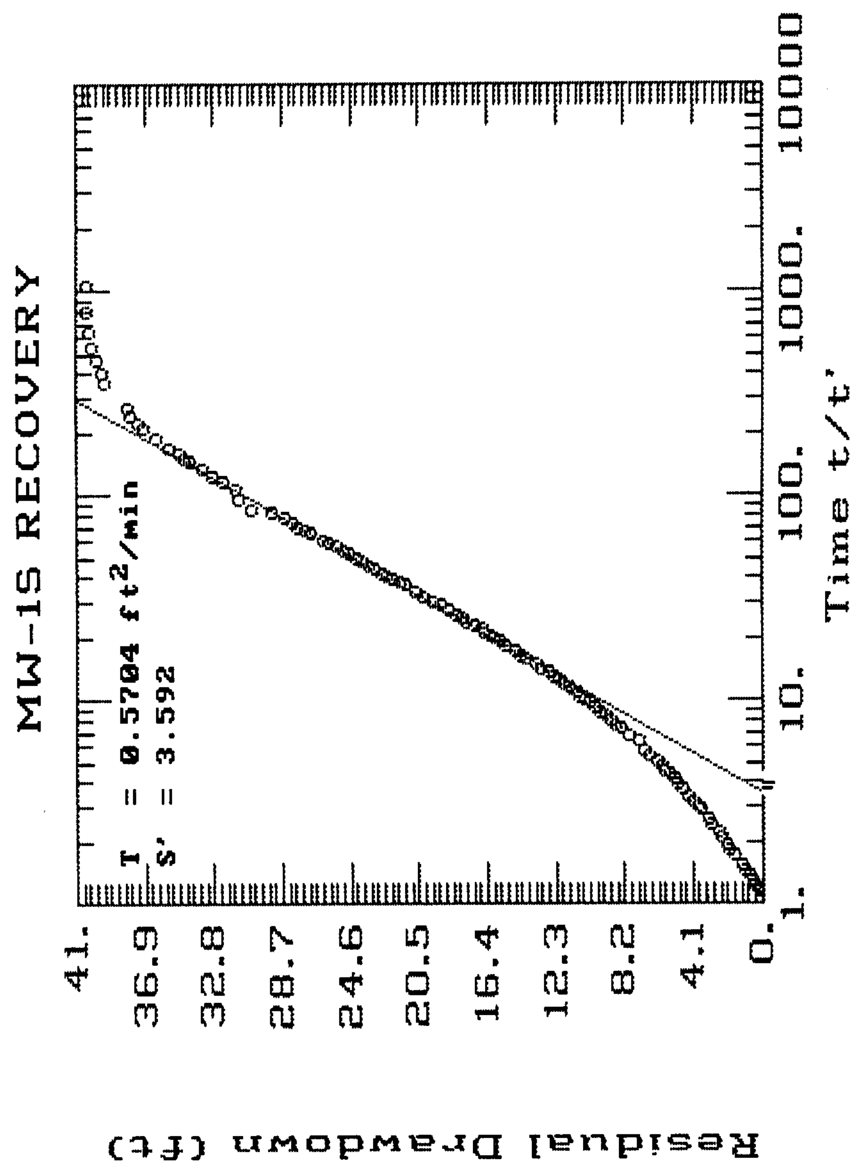
MW-1S PUMP TEST
T = 0.4265 ft2/min
S = 9.0186E-005
r/B= 0.2046
100.
10.
1.
0.1
0.1
1.
10.
100.
1000.
10000.
Time (min)
Drawdown (ft)

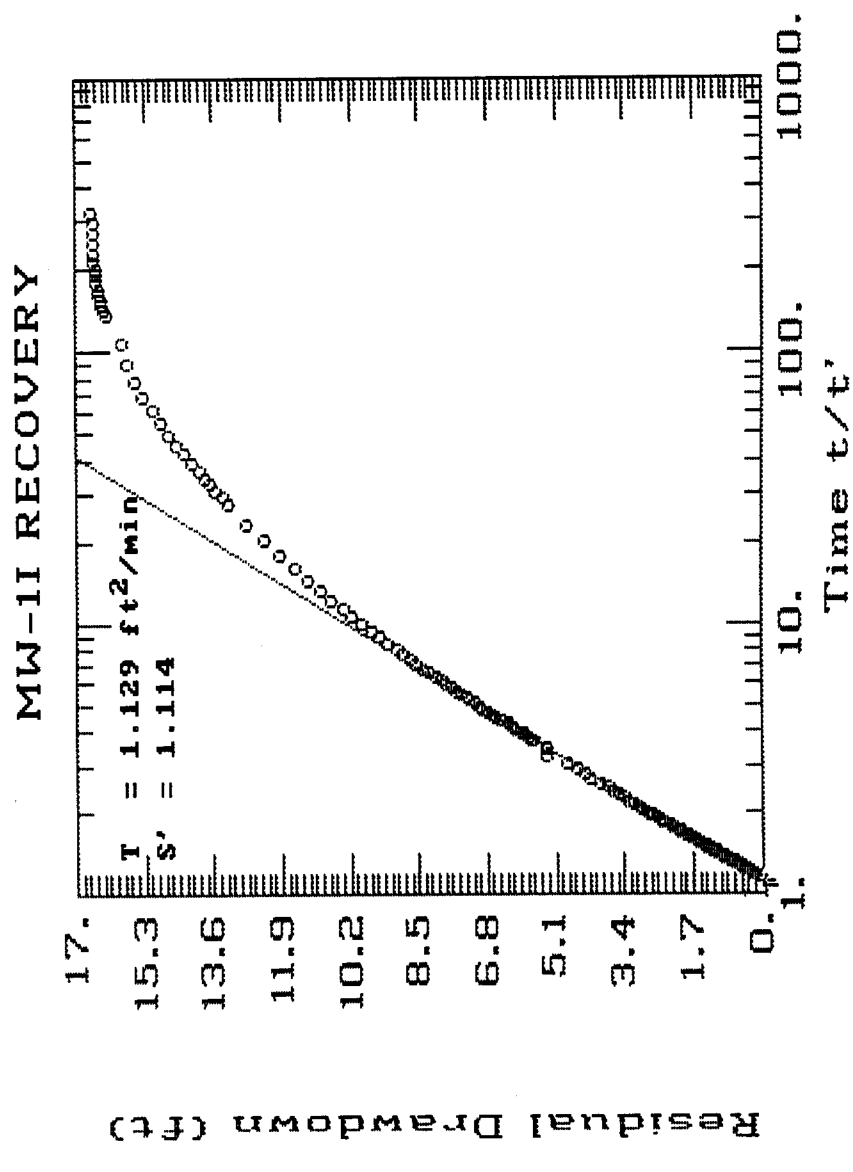

MW-1I PUMP TEST
T = 1.352 ft²/min
S = 7.7487E-004
Time (min)
Drawdown (ft)
0.1
1.
10.
100.
1000.
10000.
0.1
1.
10.
100.


MW-1D PUMP TEST
T = 1.411 ft^2/min
S = 2.2596E-004
Time (min)
Drawdown (ft)
0.1
1.
10.
100.
1000.
10000
100.

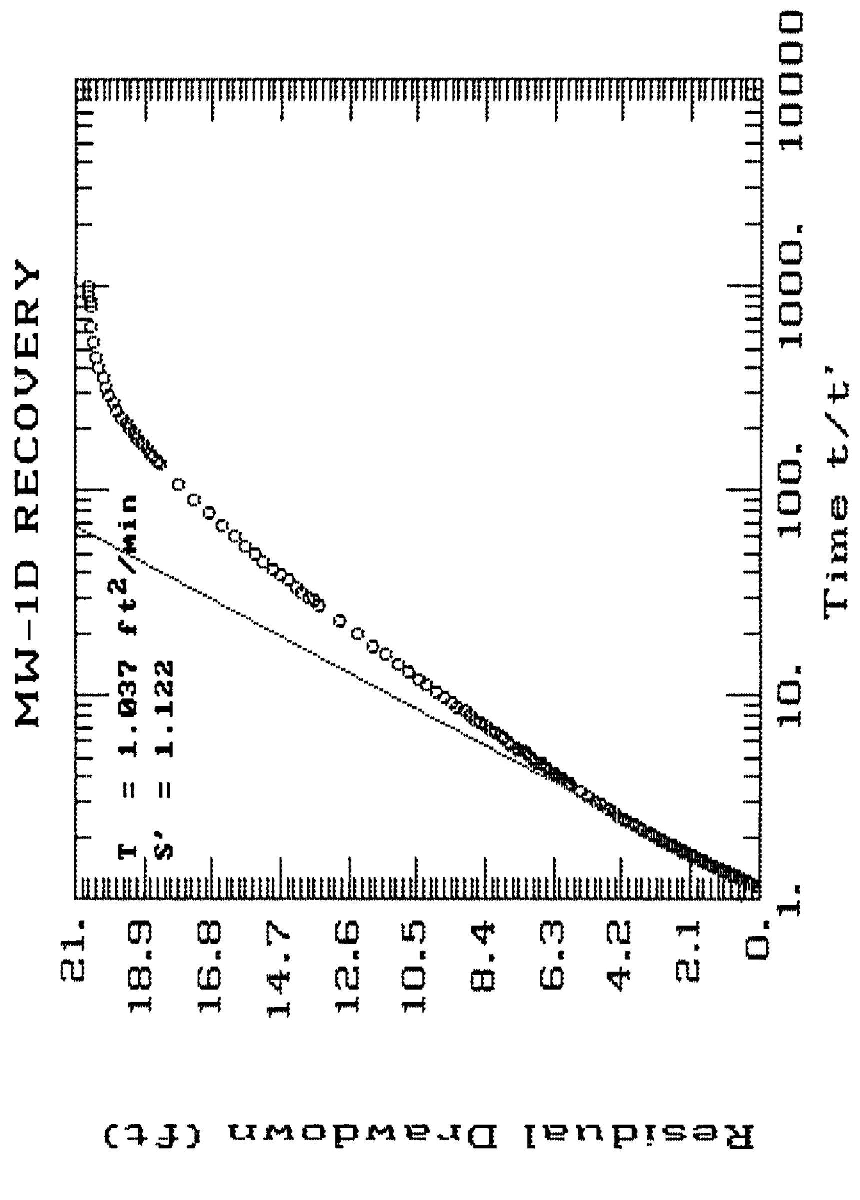

MW-3A PUMP TEST
T = 2.163 ft²/min
S = 1.4742E-004
Drawdown (ft)
10.
1.
0.1
1.E-002
10.
100.
1000.
10000.
Time (min)


MW-3B PUMP TEST
T = 1.722 ft^2/min
S = 1.8666E-004
r/B= 0.8861
10.
1.
0.1
1.E-002
10.
100.
1000.
10000.
Time (min)
Drawdown (ft)

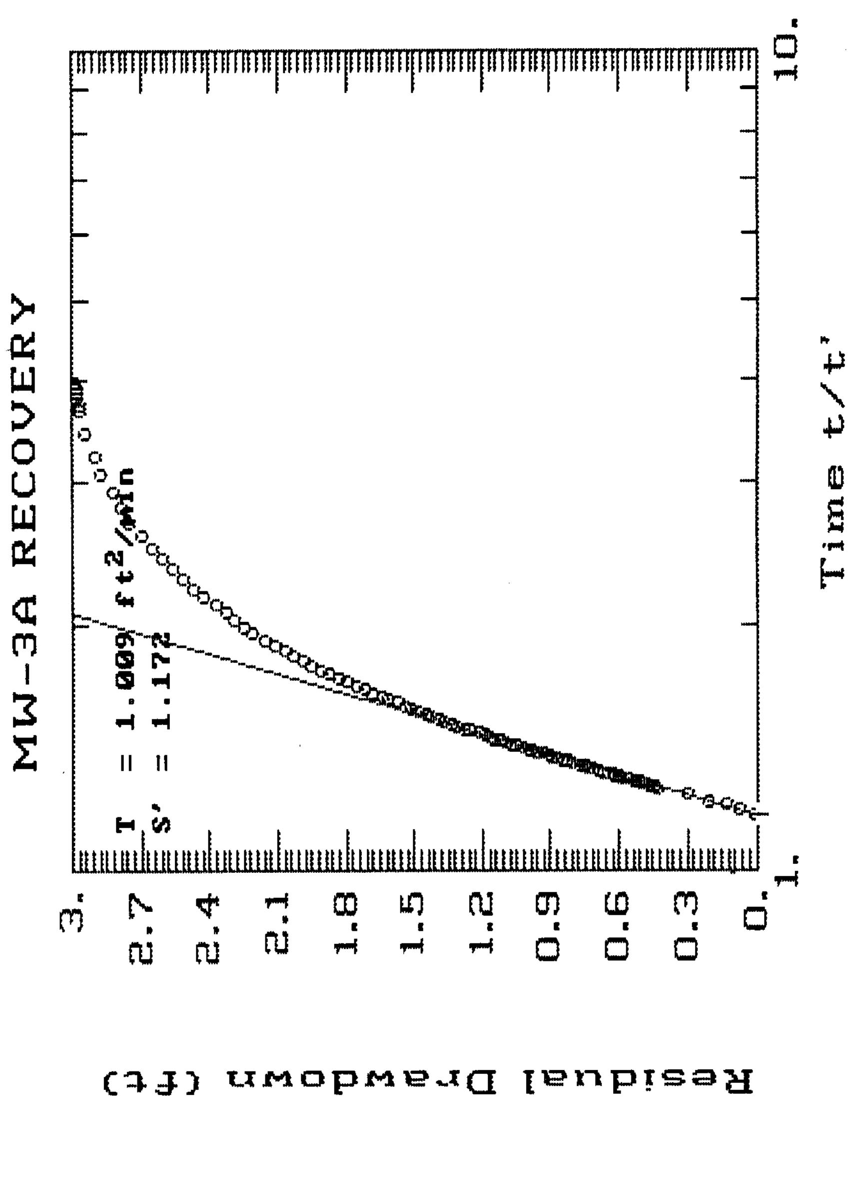

MW-1S RECOVERY
T = 0.5704 ft2/min
S' = 3.592
Residual Drawdown (ft)
Time t/t'
41.
36.9
32.8
28.7
24.6
20.5
16.4
12.3
8.2
4.1
0.
1.
10.
100.
1000.
10000

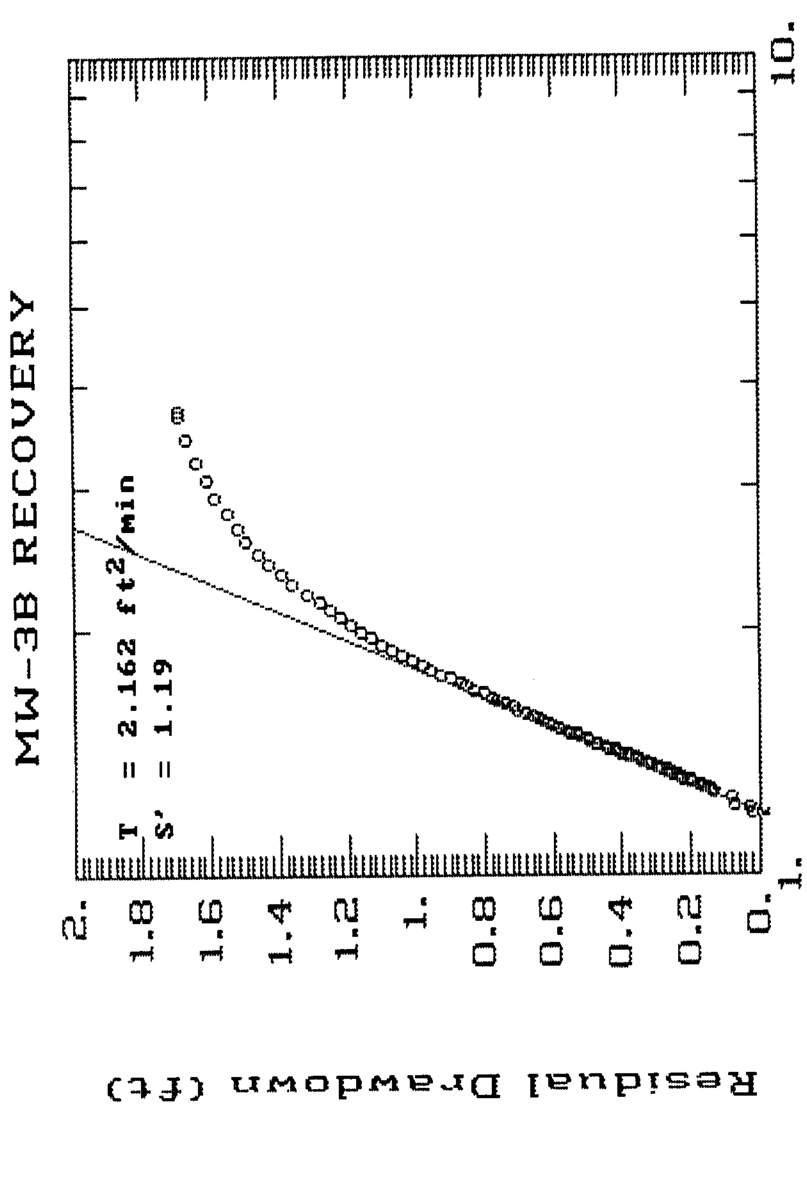


MW-1I RECOVERY
T = 1.129 ft²/min
S' = 1.114
Residual Drawdown (ft)
17.
15.3
13.6
11.9
10.2
8.5
6.8
5.1
3.4
1.7
0.
Time t/t'
1.
10.
100.
1000.



MW-1D RECOVERY
T = 1.037 ft2/min
S' = 1.122
Time t/t'
Residual Drawdown (ft)
21.
18.9
16.8
14.7
12.6
10.5
8.4
6.3
4.2
2.1
0.
1.
10.
100.
1000.
10000.


MW-3A RECOVERY
T = 1.009 ft2/min
S' = 1.172
Residual Drawdown (ft)
Time t/t'
3.
2.7
2.4
2.1
1.8
1.5
1.2
0.9
0.6
0.3
0.
1.
10.


MW-3B RECOVERY
T = 2.162 ft2/min
S' = 1.19
Time t/t'
Residual Drawdown (ft)
2.
1.8
1.6
1.4
1.2
1.
0.8
0.6
0.4
0.2
0.
1.
10.

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Dr. Jean M. Bahr
Assistant Professor of Geology and Geophysics

DATE August 7, 1991
August 7, 1991