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GROUNDWATER-KALAMAZOO RIVER INTERACTION
NEAR THE PARCHMENT CITY WELLFIELD,
PARCHMENT, MICHIGAN

by

W. Richard Laton

A Dissertation
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
requirements for the
Degree of Doctor of Philosophy
Department of Geology

Western Michigan University
Kalamazoo, Michigan
June 1997

GROUNDWATER-KALAMAZOO RIVER INTERACTION
NEAR THE PARCHMENT CITY WELLFIELD,
PARCHMENT, MICHIGAN

W. Richard Laton, Ph.D.

Western Michigan University, 1997

A detailed hydrogeologic study of the Kalamazoo River and its interaction with the groundwater was completed near Parchment, Michigan. The Kalamazoo River between Portage Creek and Allegan Dam is a Federal superfund site due to PCB contamination trapped in its sediments. The City of Parchment pumps all of its drinking water from a glacial aquifer 850 feet from the Kalamazoo River. This study focused on the hydrogeology and groundwater/surface interaction of the area through the use of surface and downhole geophysics, installation of monitoring wells and piezometers, seepage meters and chemical sampling. It was determined that the Kalamazoo River is receiving recharge from the adjacent aquifer, however, it was seen in the seepage meter results that this recharge can fluctuate with pumping rates and river stage. The chemical sampling data demonstrated the interaction of the river with the wellfield and the variability of groundwater movement. Although the data does not show impact to the wellfield, it does show that pumping in the wellfield does cause shifts in the hydraulic gradient in the aquifer and in the distribution of chemical species. These pumping induced gradients coupled with high stream stage appear to induce river water to flow towards the wellfield.

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CHAPTER I

INTRODUCTION

Definition of Problem

Interaction between waters of the Kalamazoo River (Figure 1) and groundwater in the adjacent alluvial and glacial sediments has not been well documented. Allen and others (1972) suggested that such interaction was minimal at the time of their study because waste clay from paper industries was thought to have effectively sealed the riverbed, even though no supporting data were available. In fact, control of clay-rich paper mill waste from adjacent landfills entering the river, coupled with erosion of the streambed below Comstock, strongly suggests that the river water and adjacent groundwater are in hydraulic communication. This interaction, combined with documentation of extensive Polychlorinated biphenyl (PCB) contamination of sediments associated with the Kalamazoo River, have raised the level of concern regarding the quality of water being pumped from glacial aquifers adjacent to the river. A study of the Kalamazoo River fish population shows high concentrations of these carcinogens in their flesh. The PCB contamination has also been detected predominantly in the sediment of the Kalamazoo River and Portage Creek. Elevated levels of PCBs have also been detected in the water column and fish due to physical, chemical and biological interactions with the contaminated

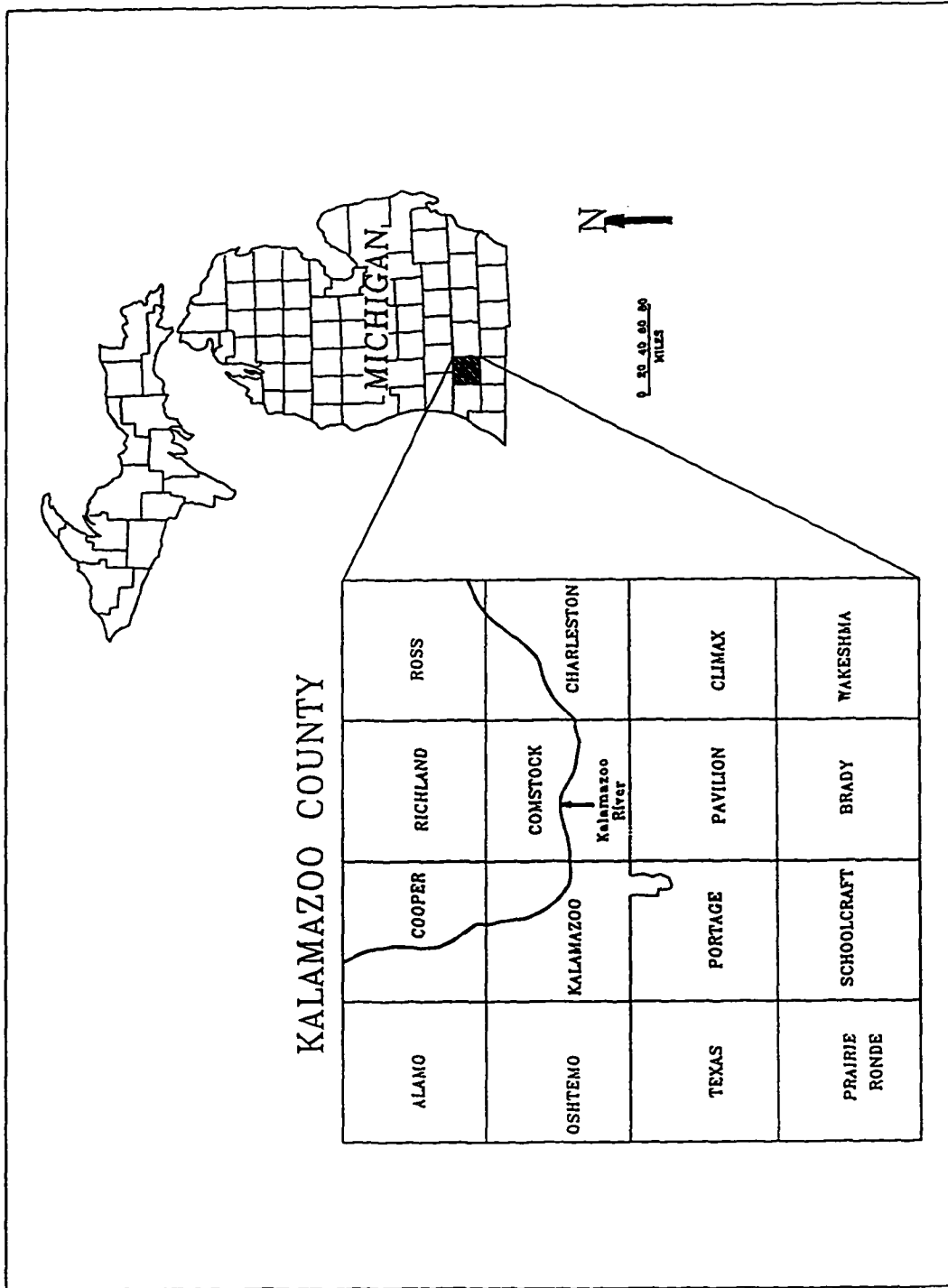


Figure 1. County Location Map.

sediments. The primary historical source of this contamination is thought to be paper mill wastewater, which contained an estimated 160,000 kilograms (352,000 pounds) of PCBs discharged from the paper industries located along these waterways from 1950-1970 (Hanshue, 1993). Sampling and analysis by the Michigan Department of Environmental Quality (In 1994, the environmental section of the Michigan Department of Natural Resources was renamed the Michigan Department of Environmental Quality, MDEQ.) suggest that the majority of the PCBs that have been released are redeposited along the banks of the Kalamazoo River and in the bottom sediments of the impoundments behind the six major dams or spillways along the river (Hanshue, 1993) (Figure 2). Currently, erosion of poorly constrained sediments in landfills adjacent to the river is suspected of causing continued contamination. Recent evidence suggests that the river continues to be polluted by at least one major source upstream of its confluence with Portage Creek, as well as one source upstream Portage Creek (Yeast, 1986).

Surface waters of Kalamazoo County are predominantly calcium bicarbonate type, although dissolved sulfate concentrations are slightly higher in streams in the southeastern and northwestern parts of the county. The water in most streams is hard to very hard (>121 mg/l) (Allen and others, 1972; Rheume, 1990). Sampling and analysis for PCBs in the segment of the river near the study site have shown relatively low levels of contamination. Aquatic life in the river is considered to be environmentally stressed because of the close proximity to the Kalamazoo Wastewater Treatment Plant (KWTP) and James River Paper Company (JRPC)

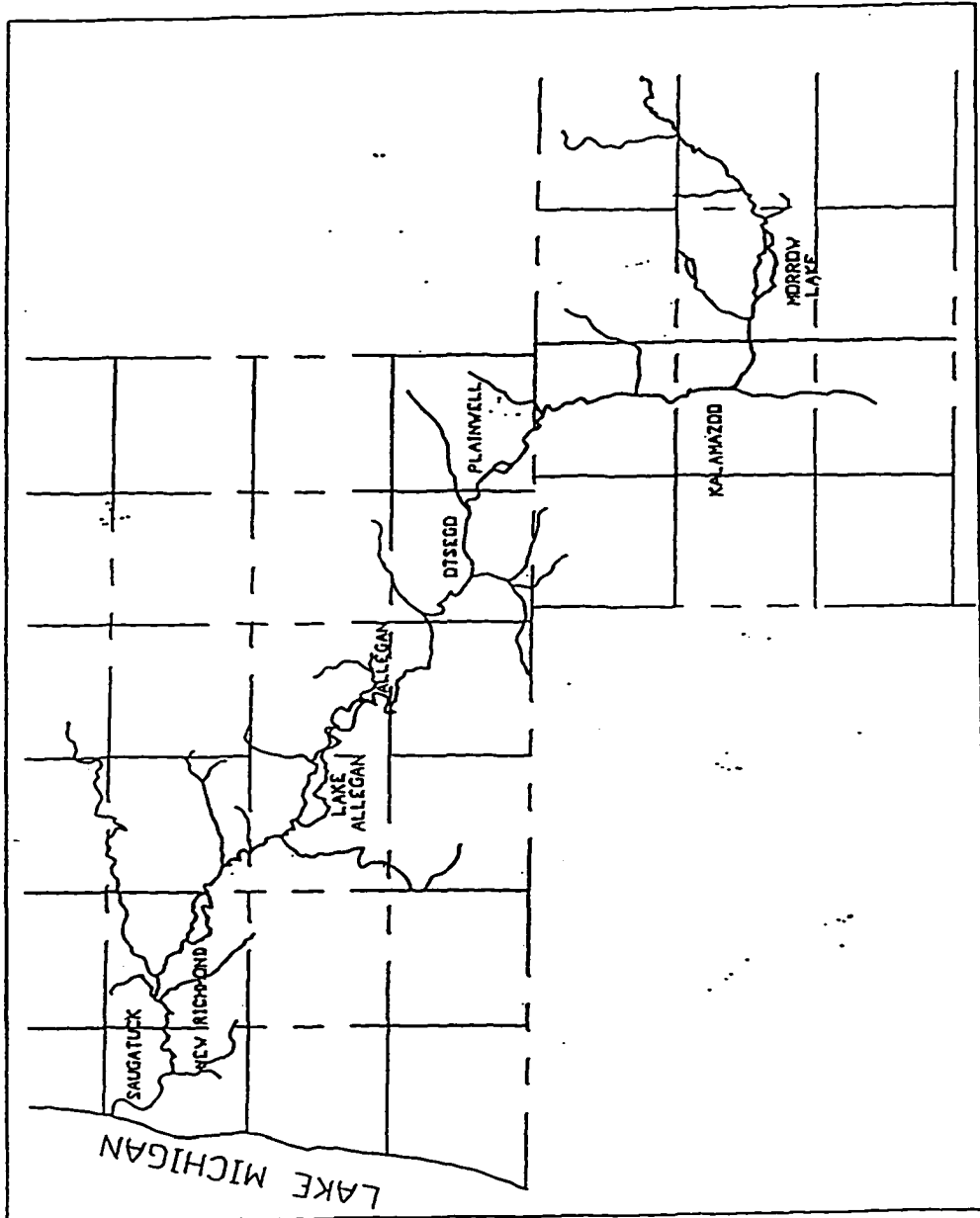


Figure 2. Kalamazoo River From the City of Comstock to Lake Michigan.

outfall (Yeasted, 1986). Since 1977, the Michigan Department of Public Health has issued an annual advisory warning people against eating fish from the Kalamazoo River downstream of the City of Kalamazoo because of PCB contamination (Hanshue, 1993).

Surface sediment samples taken between the mouth of Portage Creek and Main Street in Plainwell, Michigan, had average PCB concentrations of 9.0 parts per million (ppm) in 1976, 36.2 ppm in 1982, and 13.0 ppm in 1984 (Yeasted, 1986). No general trends can be detected from these annual averages. However, based on the upstream-downstream location of each of the samples, some spatial distribution trends are apparent (Figure 3). All of the concentrations in the 1976 data were less than 15 ppm and the PCBs were observed to be distributed throughout the entire river. In the 1982 and 1984 data, the PCBs were no longer evenly distributed, but instead they were apparently concentrated upstream near Michigan Avenue (Figure 3). The Kalamazoo River adjacent to the study site is considered to be undergoing erosion and as a result, upstream sediment is not expected to be deposited in this area. A PCB concentration of 57 ppm was reported at Patterson Avenue in the 1982 results. Downstream, values reported for samples taken at D-Avenue and Commerce Street were as low as 1.6 and 1.0 ppm respectively (Figure 3) (Yeasted, 1986).

According to Yeasted (1986) the effects of Portage Creek's PCB discharge to the Kalamazoo River could have been partially masked by the proximity of the KWTP discharge, an additional historical source of PCBs. In spite of the

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interference, however, he considered the discharge concentrations of PCBs from Portage Creek to be significant.

Only 242 surface and core samples were taken for the entire reach of interest [approximately 135 kilometers (80 river miles)] between 1971 and 1985 (Figure 2). Given this number of samples over such a large study area, it is difficult to calculate representative averages and to draw fully supportable conclusions. PCB concentrations in sediments may also vary greatly within a small area. Therefore, the locations of the samples within a segment of the river valley may give non-representative average values for that particular area (Yeasted, 1986).

The Kalamazoo River is a Federal Superfund site in the 60-kilometer (35-mile) stretch between the mouth of Portage Creek inlet and the Allegan Dam (Figure 2). This stretch is also a site under Part 201 of the Natural Resources and Environmental Protection Act, Michigan Public Act 451 of 1994 as amended, between Allegan Dam and Lake Michigan.

Basic questions concerning the hydrogeological interaction between the Kalamazoo River and groundwater need to be addressed in this "Area of Concern", especially at such locations as the stretch of river adjacent to the City of Parchment where groundwater is used as the sole source of municipal water. Possible major concerns to the City of Parchment wellfield include, but are not limited to, the following: (a) the close proximity of the wellfield to the Kalamazoo river; (b) the relatively shallow depth of the municipal wells, less than 21 meters (71 ft); (c) the undetermined extent of a confining clay layer throughout the area; (d) the close

proximity of the JRPC landfill; (e) the proximity of the North American Aluminum plant and landfill; and (f) the physical location of the wellfield (downstream of the City of Kalamazoo). These factors raise questions about how future clean-up efforts would affect the City of Parchment's municipal water supply. These possible impacts and concerns can be best addressed by an extensive hydrogeological study of this precariously placed municipal wellfield.

The hydraulic connections between groundwater and surface water systems are critical in the management of water resources. An incomplete understanding of shallow groundwater flow systems and their influence on the surface waters, which depend on groundwater discharge, can result in drastic reductions in flow, water availability for direct withdrawal (municipal, industrial and private water supply), and habitat loss during drought periods. Improved understanding of these factors can facilitate development of basic water management strategies to cope with periods of abnormally high and low precipitation. A thorough investigation of these basic hydrogeological parameters should precede any efforts to clean up the problems associated with contamination in the Kalamazoo River. The data necessary for such an understanding can be generated through an investigation of the watershed contributions made to the Kalamazoo River from direct precipitation, runoff, and the relationship and interplay of the surface water with groundwater. Results of this study must include a detailed analysis of groundwater interaction with the river system/wellfield and provide a basis for the long-term watershed/wellfield management.

CHAPTER II

BACKGROUND

Location of Study and Historical Background

Location of Study

The main focus of the study is the Kalamazoo River floodplain and the upslope area adjacent to and within the City of Parchment, Cooper Township (Sec. 34, T. 15 S., R. 11 W.), Kalamazoo County, Michigan (Figure 4). The primary study area is owned by Consumers Power Company and is located between the Kalamazoo River, the JRPC (formerly the Brown Company) and the City of Parchment's Wellfield. The City of Parchment Wellfield is approximately 260 meters (850 ft) from the east bank of the north-flowing Kalamazoo River and south of the confluence of Spring Brook with the Kalamazoo River (Figure 5). The northern border of the JRPC property lies 300 meters (977 ft) to the south of the study area and city wellfield. Cultural features at the site include several north-south overhead power lines situated along the river and the abandoned Penn Central railroad grade which is located between the Kalamazoo River and the City of Parchment's Wellfield (Figure 4).

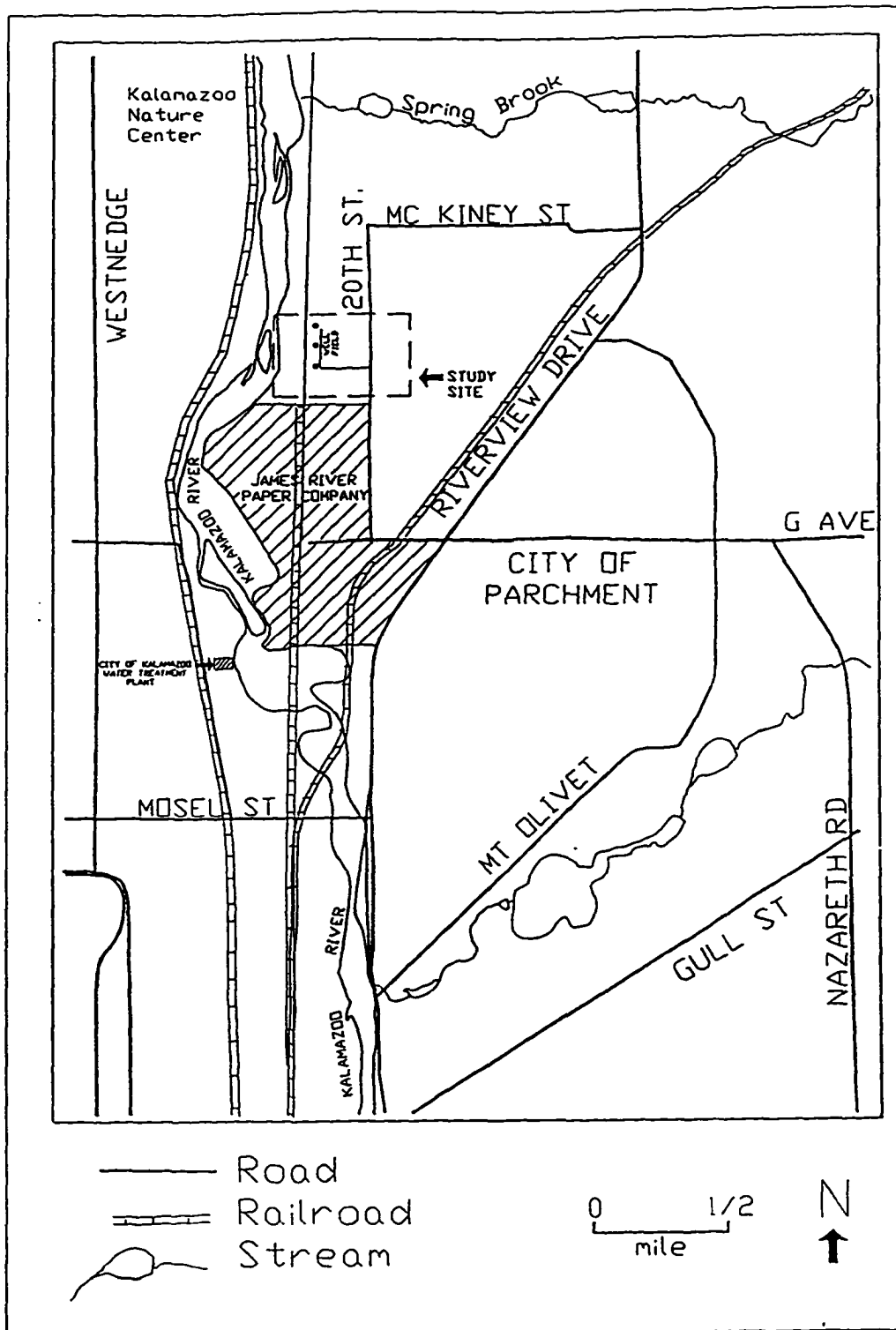


Figure 4. Location of Study Site.

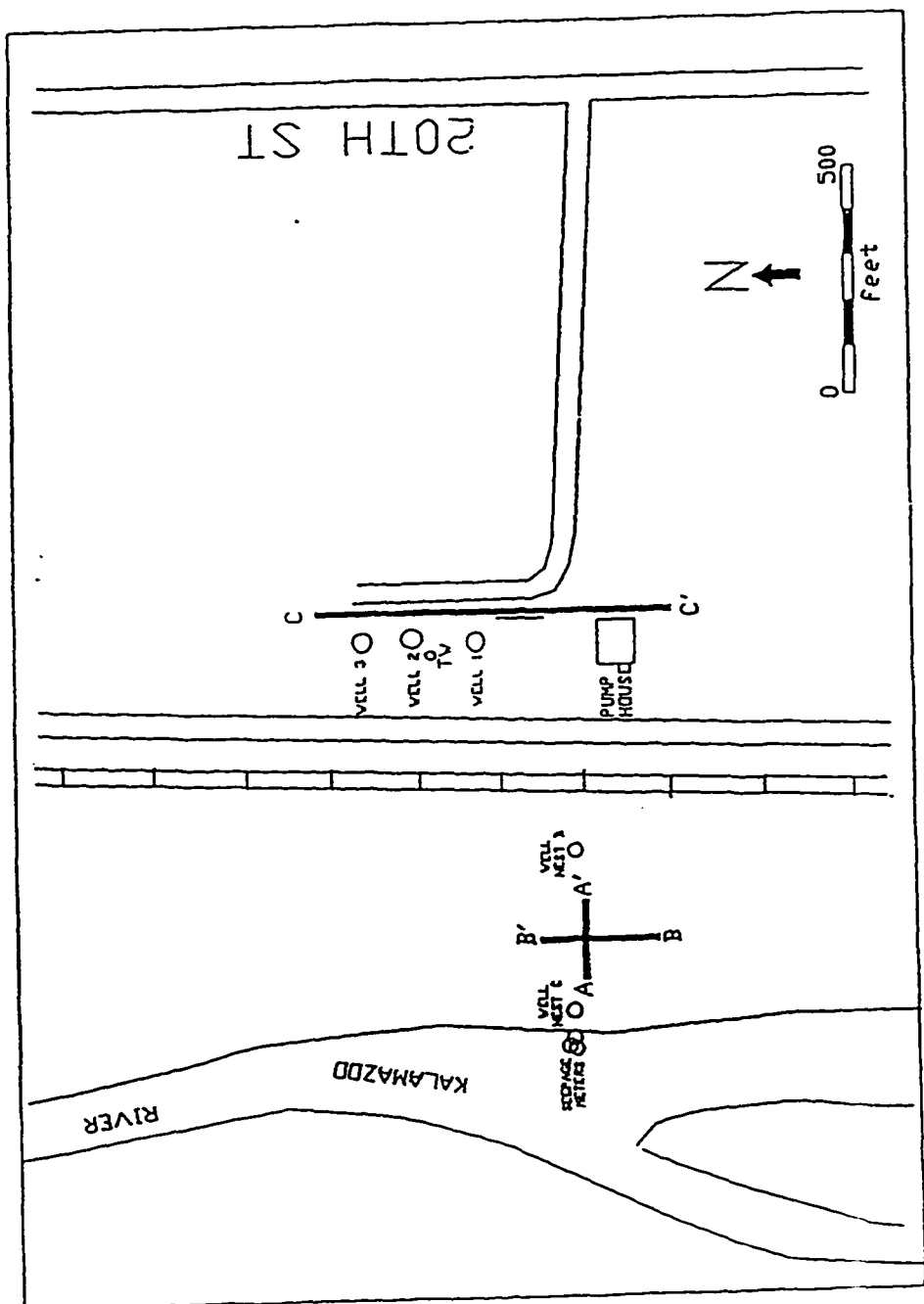


Figure 5. Detailed Map of Study Area, Including Monitoring Wells and GPR Profiles.

Kalamazoo River Area of Concern

By 1986, the Michigan Department of Natural Resources had identified several PCB contaminated areas along the Kalamazoo River between the City of Kalamazoo and its mouth at Saugatuck, Michigan, on Lake Michigan. Reported data clearly indicated that PCBs had migrated downstream from the mouth of Portage Creek and that upstream Portage Creek sources owned by the Potentially Responsible Parties (PRPs) have continued to cause contamination. Based upon these data, the MDEQ expanded the Remedial Investigation and Feasibility Study (RI/FS) to include approximately 135 kilometers (80 miles) of the river from Morrow Lake Dam to the mouth of the Kalamazoo River (Figure 2).

The PCB contamination was apparently caused by paper mills, which recycled carbonless copy paper containing PCBs. Waste from these operations was dumped into Portage Creek and placed in landfills adjacent to this stream and the Kalamazoo River between 1957 and 1971 (Hanshue, 1993). On August 30, 1990, based on the severity of the contamination, the Environmental Protection Agency (EPA) officially placed the site on the National Priority List (NPL) pursuant to the Comprehensive Environmental Response, compensation and Liability Act (CERCLA) or Superfund, 1980 PA 96-510 (Hanshue, 1993). The State of Michigan has identified 3 PRPs located several kilometers upstream: HM Holdings, Inc./Allied Paper Company, Georgia-Pacific Corporation, and Simpson-Plainwell Paper Company. This group of PRPs signed an Administrative Order by Consent to fund and conduct a Remediation Investigation and Feasibility Study (RI/FS) (1992).

The major site of concern to the MDEQ is the Allied Paper, Inc./Portage Creek/Kalamazoo river area. This site includes the Allied Paper, Inc., property; a 4.8 kilometer (km) (3 mile) stretch of Portage Creek where the creek meets the Kalamazoo River; and a 56.3 km (35 mi.) stretch of the Kalamazoo River, which involves extensive PCB contamination of the soil, sediment, water column, and biota (Hanshue, 1993). The main study area of focus is located within this 56.3 km (35 mi.) stretch.

Historical Facts

Kalamazoo County, located in southwest Michigan, has a population of 223,411 according to the census data of 1990. Cooper Township, which lies in the north-central section of the county, has 8,442 residents, most of who live in the City of Parchment (Figure 4). Vulnerability of the drinking water supplies due to surface contamination is of great interest to county and township residents because all are dependent on groundwater as their sole source of drinking water. The MDEQ has confirmed four organic chemical contaminated wellfields within Kalamazoo County. Several other wellfields in the county are approaching the regulated contaminant levels due to elevated levels of nitrates (Cousins-Leatherman, Foust, and West, 1992). At the present time the City of Parchment's Wellfield is not listed as one of the contaminated sites or as a site that is approaching regulated levels.

As of 1992, the MDEQ had identified 107 sites of environmental contamination in Kalamazoo County under Part 201 of Natural Resources and

Environmental Protection Act, Michigan Public Act 451 of 1994 as amended. Of the 107 sites, 88 are known to be sites of groundwater contamination. The MDEQ had also identified 157 locations under Part 213 of Natural Resources and Environmental Protection Act, Michigan Public Act 451 as amended (March 1992), with confirmed releases from underground storage tanks and other sources. Of the 157 sites, 48 locations have confirmed groundwater contamination (Cousins-Leatherman, Foust, and West, 1992).

Wellhead Protection Report

In 1992, the City of Parchment spearheaded a Wellhead Protection Area (WPA) program (Jones, 1992). The initiation of the Wellhead Protection Program came out of the 1986 amendments to the Safe Drinking Water Act (SDWA), 1974, 42.U.S.C, Section 1428(E). The purpose of the amendment was to establish a program to prevent future risks and manage existing risks to public water supplies. The federal government placed the responsibility for implementing this program on the individual states. In Michigan the responsibility falls to the MDEQ, Public Health Division.

The leading agency of the wellhead protection program in Cooper Township was the City of Parchment in cooperation with the local township government. This cooperation was vital because (a) the wellfield, which is owned and operated by the City of Parchment, provides water to both City of Parchment and Cooper Township

residents; and (b) the wellfield is located in Cooper Township outside the City of Parchment.

The WPA program requires the identification of a wellhead protection area for the wellfield (Figure 6). The area and the hydrogeological parameters considered were defined in the Well Head Protection Report as "...the surface and subsurface area surrounding a water well or wellfield, supplying a public water system, through which contaminants are reasonably likely to move toward and reach such water well or wellfield" (Jones, 1992). The wellhead area was based upon a number of hydrogeological and well parameters. These parameters included the direction of groundwater movement, the travel time of groundwater flowing to the well, pumping rates, geologic and hydrogeologic aquifer boundaries, and the degree of aquifer confinement.

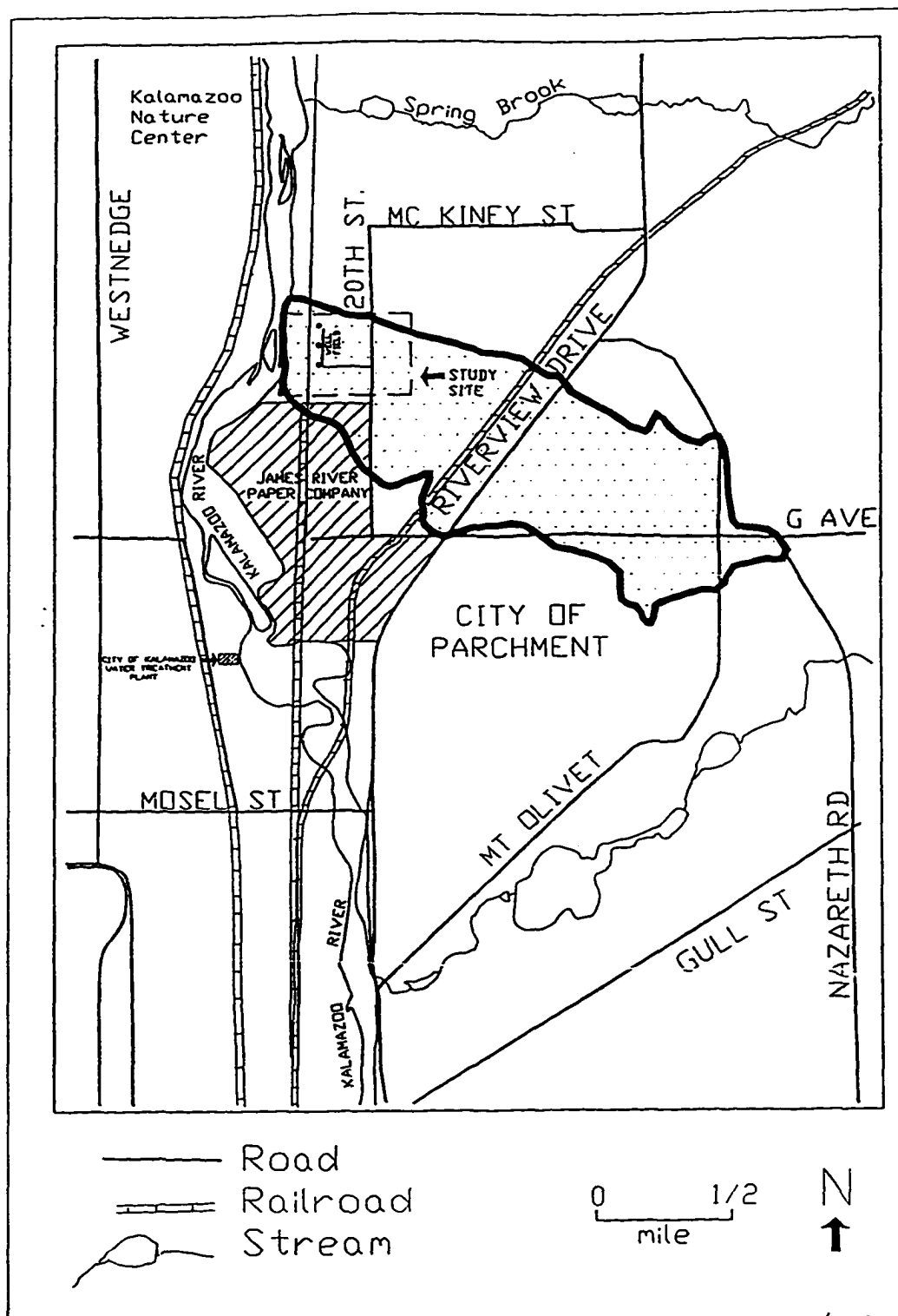


Figure 6. Wellhead Protection Area Showing the 10 Year Capture Zone. Modified From Jones, 1986.

CHAPTER III

GEOLOGY

Soils, Glacial Geology, Bedrock, Stratigraphy and Geophysics

Basic topography of the study site is flat with a gradual increase in slope eastward away from the river (Figure 4). Most of the area has been topographically altered within the last forty years (Williams & Works, 1980). A steep slope approaches the river from the west (Figure 4) where the river borders the west valley wall of the north-south oriented Kalamazoo River valley. The study area is underlain by unconsolidated materials that consist of glacially-derived deposits (glacial drift) of Pleistocene age and alluvial deposits of Holocene age (Rheaume, 1990). The Kalamazoo River in the vicinity of the study site has reworked the glacial material. The sediments next to the river are interbedded with old river channels and deposits associated with possible flooding events.

Soils

Three soil types are present in the study area (Figure 7): Glendora Sandy Loam (Gn), Brady Sandy Loam, 0 to 3% slope (BdA), and Gilford Sandy Loam (Gd) (Austin, 1979). Although the Gilford soil (Gd) is the principal soil type in and adjacent to the main study area, the dominant soil type along the river is the Glendora

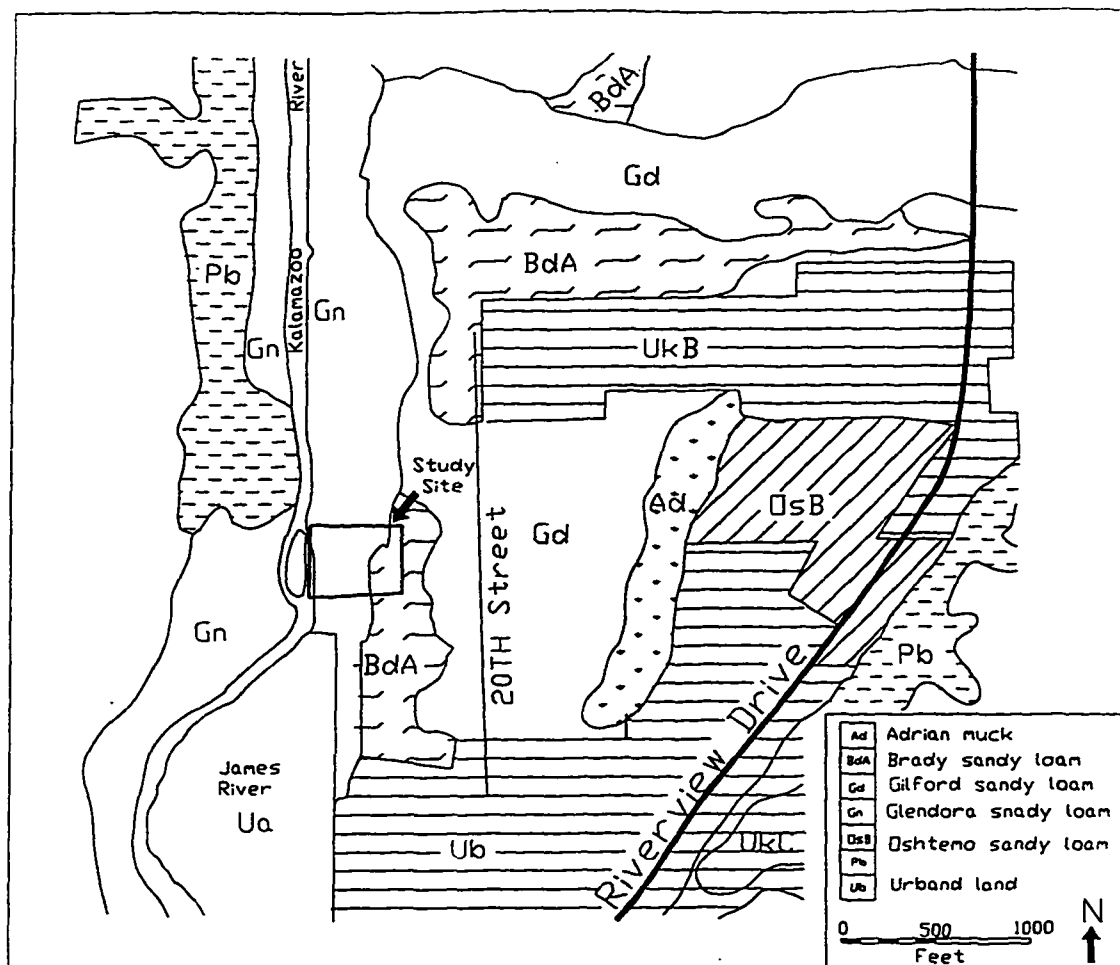


Figure 7. Soils Map. Modified From Austin, 1979.

(Gn). The Brady Sandy Loam soil (BdA) is present over most of the wellfield property.

A transect from the east margin of the Kalamazoo River eastward across the river valley (Figure 8) crosses these soils in the following sequence: Gn-Glendora sandy loam; BdA-Brady sandy loam (0 to 3% slope); Gd-Gilford sandy loam; Ad-Adrian muck; OsB-Oshtemo sandy loam (1 to 6% slope) or Ub-Urban land; OsB-

Oshtemo sandy loam (12 to 18% slope); and the UkB-Urban land-Kalamazoo complex (0 to 6% slope).

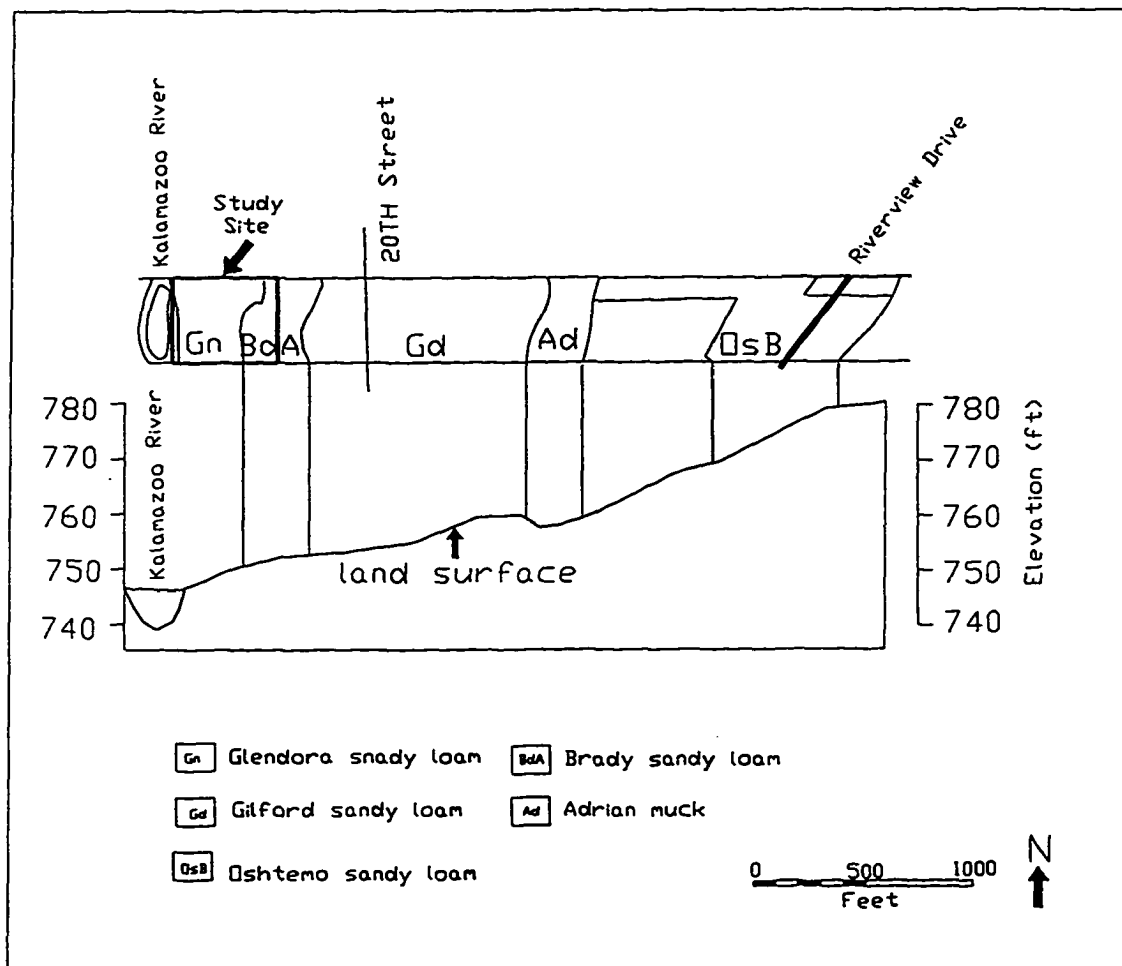


Figure 8. Transect of Soils Across the Kalamazoo River Valley.

The soil in the area below the JRPC landfill is categorized as Ua-Udipsammments, level to steep, a very sandy soil with a high permeability. This is significant because the landfill is only 300 meters (977.5 ft) from the main transect

line through the study area (Figure 5). The landfill area consists of level to steep, moderately well-drained or well-drained, soils that have been disturbed by man. As mapped, this unit includes sanitary landfills, flood plains, and lowlands that have been filled with various types of natural and manmade debris. The fill material is primarily paper mill waste and is normally 0.3 to 3.0 meters (1 to 10 ft) thick and commonly is covered with sandy or loamy material. To date, no permanent impermeable cover has been placed over the material. Runoff, which depends on the slope, for this particular area is relatively low due to the high water retention capacity of the waste. Some ponded water is present at the northern end of the landfill and within wetlands adjacent to the landfill.

Glacial Geology

The glacial drift consists of material left by continental glaciers which covered Michigan as recently as 15,000 years ago (Straw and Kehew, 1995). The glacial material within the study area consists of till (a mixture of boulders, sand, and clay that is released directly from melting ice), outwash (sand and gravel which is washed and deposited by meltwater flowing away from a glacier) and lacustrine deposits (sand, silt, and clay which settles out in the ponded water of glacial lakes).

During the retreat of the continental ice sheet across this area, ponded waters near the center of Kalamazoo County that had been draining to the south began to drain to the north through a topographic low in the moraine in Cooper Township. This change in direction of drainage resulted in downcutting of the outwash plain by

24.4 to 30.5 meters (80 to 100 ft) (Deutsch and others, 1960). The downcutting of the glacial-drainage channels of the present-day Kalamazoo River valley (Martin, 1957) resulted in the deposition of the material which now is present within the main study area. Most of these deposits have a grain size of medium to very coarse sand to gravel with some layers of clayey silt (Monaghan and others, 1983; Rheume, 1990). The Kalamazoo River valley cuts through this glacial material and is about 1.6 kilometers (1 mile) wide in the study area. The present Kalamazoo River appears to be too small to have carved this broad river valley (Straw and Kehew, 1995). It is thought that the river flow through the valley was much greater in the past and that a glacial outburst flood (or floods) may have cut the shallow gorge that now forms the present Kalamazoo River valley. An outburst flood is thought to have originated northeast of Kalamazoo County, apparently connecting a series of topographic lows formed by the melting of buried ice blocks along the present course of the Kalamazoo River valley (Straw and Kehew, 1995).

Bedrock

The bedrock in the area is the Lower Mississippian Coldwater Shale. The topographic surface on the underlying bedrock has a low to moderate relief and reflects the erosional surface that existed prior to glaciation (Williams & Works, 1980). Well logs from the JRPC (Appendix A) show that the shale was encountered at a depth of 25 meters (85 ft). This correlates with other maps that approximate the depth to bedrock to be 25 to 30 meters (85 to 100 ft) (Williams & Works, 1980). The

Coldwater is a gray, micaceous shale that has been truncated by erosion and is approximately 150 meters (500 ft) thick in the area of study (Western Michigan University, 1981). The Coldwater Shale has been interpreted as being part of a deltaic sequence. The thicker, more proximal portion of the delta occurs in eastern Michigan and limestone is interbedded in the relatively thinner central portion that is present in the study area (Lilienthal, 1978). The significance of the presence of the Coldwater Shale is that the shallow bedrock surface provides a base for the useable aquifer in this area. The Coldwater Shale in this area makes an excellent confining layer due to its low permeability. Because of the low permeability, municipalities prefer not to use it for producing water. However with fracturing and where interbedded sands are present, potable water wells can be constructed (Western Michigan University, 1981). Locally, only one family uses water derived from bedrock. This well, which is 55.5 meters (182 ft) deep, is located within a water-bearing section of the Coldwater Shale (Figure 4).

Stratigraphy

Stratigraphic units were depicted in well logs from JRPC, City of Parchment Wellfield and monitoring wells installed for this study (Figure 5). Split spoon, GeoProbe®, and grab samples were taken at specific sampling sites within the study area to aid in the geologic description of the study site. A series of units within the glacial drift are described in the following paragraphs starting with the shallowest unit.

Running north-south through the study area is an old railroad grade (Figure 5) built up approximately one meter (3.3 ft) and is comprised of a mixture of cinders, ashes and other fill material. Also running north-south through the area is a road maintained by Consumers Power (Figure 5) for maintenance on their overhead power lines. This road stands several meters higher than the surrounding land surface. Both roadways help protect the wellfield from being flooded by the Kalamazoo River during high water periods.

The top 3 to 5 meters (9.8 to 16.4 ft) of the native material can be grouped together as one unit. This encompasses the top reworked organic soils, and the underlying sand, gravel, silt and clay. For the most part this unit coarsens downward, except in areas of buried river channels or where it is intermixed with silty-clay lenses. In areas surrounding the study site, some fill material has been deposited. The water table is in this unit and lies at a depth of 0.0 to 1.83 meters (0.0 to 6.0 ft).

The next lower stratigraphic unit is of major importance to the overall hydrology of the study area. This layer is a bed of low permeability clay that is locally interbedded with layers of sand and gravel. The clay layer ranges in thickness from 1.83 to 32 meters (6 to 105 ft), with the maximum known thickness being reported in a local residential well (Figure 5) (Appendix A). Lying directly on top of this layer is a coarse lag deposit of gravel with material as large as 10 centimeters in size. This unit is present in all the well logs throughout the area except in one monitoring well on the south end of the JRPC property.

This underlying unit was described in the Brown Company report of 1980 as an aquiclude (Williams & Works, 1980). An aquiclude as defined by Fetter (1994) is a low-permeability unit that forms either the upper or lower boundary of a groundwater flow system. A more proper term to be used for this layer is aquitard, which is defined by Fetter (1994) as a layer of low permeability that can store groundwater and also transmit it slowly from one aquifer to another. In well "C-Deep", which is 6.1 meters (20 ft) from the Kalamazoo River, drilling problems were encountered. A loss of water was recorded as the hollow stem augers began to penetrate the lower aquifer. This suggests that the clay layer is confining at this point but that the lower aquifer is not necessarily under constant artesian conditions. Another possible explanation for this lack of artesian condition is that pumping by the City of Parchment from wells some 260 meters (850 ft) away had reduced the hydraulic head in the lower aquifer at this location. It seems likely that this layer plays an extremely important role in the protection of the lower aquifer from surface contamination from the JRPC landfill, Kalamazoo River and other possible sources.

Under the clay-rich confining layer is the main producing aquifer unit. This layer consists of beds of coarse gravel with some interbedded sand layers. Both the City of Parchment and JRPC use this unit as a source of water supply. The deposits in this unit probably originated from glacial outwash deposited by meltwater that flowed away from a melting ice front to the northeast (Williams & Works, 1980). Near the north end of the JRPC property this unit thins to 3.35 meters (11 ft)

(Williams & Works, 1980). The unit ranges from 4.0 to 7.9 meters (13 to 26 ft) in the area of the City of Parchment Wellfield (Appendix A).

Underlying the main aquifer unit is a layer of glacial till. This unit is reported on drilling logs throughout the area. Beneath the JRPC property, several monitoring wells penetrated approximately 12 meters (40 ft) of material described as being predominantly clayey (Williams & Works, 1980). The City of Parchment wells were completed above this layer, but mention hard sandy clay or clay layer at the bottom of the borings. Logs for other wells in the area suggest that this layer is even thicker than the 12 meters (40 ft) reported by the JRPC (Appendix A).

Gamma-Ray Logging

Two monitoring wells were logged using the KECK Model SR-3000 gamma-ray logging system. Gamma-ray logging measures the naturally occurring radiation being emitted from the materials within a short distance of the borehole. It has been estimated that 90 percent of the gamma rays detected during logging originate within 152 to 305 millimeters (6 to 12 inches) of the borehole wall. Thus, a relatively small and roughly spherical volume of material contributes most of the natural radiation that is detected (Driscoll, 1986). This record of naturally emitted gamma radiation is commonly used as a qualitative guide for stratigraphic correlation and permeability (Driscoll, 1986). Gamma radiation is emitted from certain elements within the geologic material that are unstable and decay spontaneously into other, more stable, elements. Clays and shales generally contain high concentrations of radioactive

isotopes, usually potassium (^{40}K). In contrast glacial sand and gravel is generally composed of the resistant mineral quartz, which is composed of the stable elements silicon and oxygen, and as a consequence emit only very low levels of radiation.

Gamma-ray logging is the correlation tool of choice for the environmental consulting industry and State Health Departments, because it can penetrate high-density material such as casing and cement-based grout. The principal advantage gamma-ray logging has over standard electrical logging, is that it can be used in either cased wells or in open boreholes containing air, water, or drilling fluid. Electrical logging can only be done in uncased boreholes filled with a fluid.

Wells "B-Deep" and the City of Parchment monitoring well "TW" were gamma-ray logged (Figures 9 & 10). A time constant of 10 seconds and a scale of 1000 counts per minute (cpm), full scale were used. Well "B-Deep" had a total depth of 12.1 meters (39.7 ft). At the surface (0.0 to 1.2 m; 0.0 to 4 ft), topsoil can be seen in the high gamma kick to the right. Below this, a sandy clay layer, approximately 2.43 meters (8 ft), can be identified. The local clay-rich layer is represented in the log from 4.26 to 8.53 meters (14 to 28 ft). The bottom portion of the gamma-ray log shows the producing aquifer to be a sand and gravelly formation (Figure 9). Well "TW" has similar stratigraphy to that of the well "B-Deep", but, the total length of the log is only 17.22 meters (56.5 ft). The confining layer is represented in the gamma logs by only 3.05 meters (10 ft) of clay-rich material (Figure 10) at this location. Overall, it was found that the gamma-ray logs correspond closely to the driller's logs for these particular wells (Figure 9 & 10).

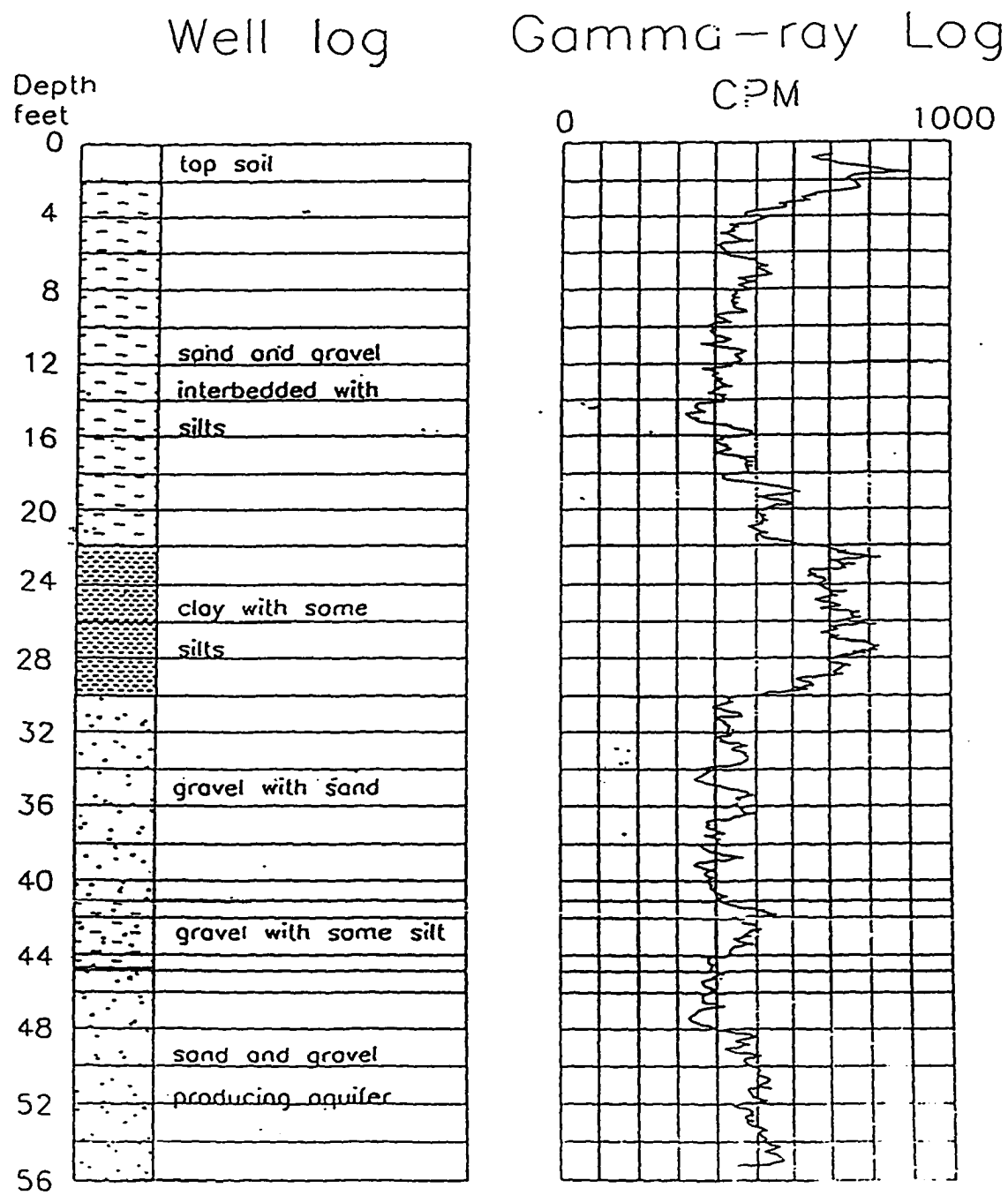


Figure 9. Well and Gamma-Ray Log of City of Parchment Well "TW".

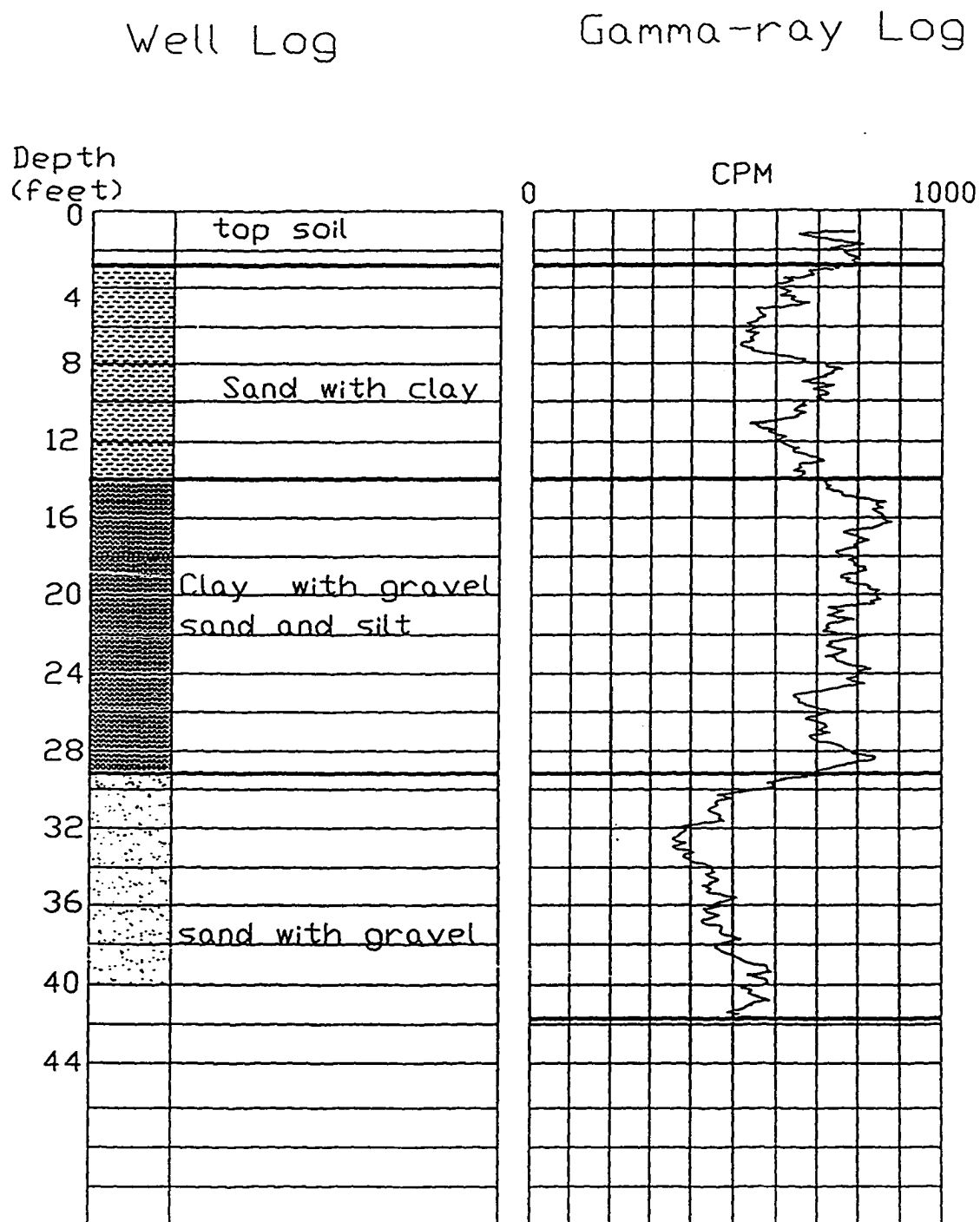


Figure 10. Well and Gamma-Ray Log of Monitoring Well "B-Deep".

Geophysics

Due to overhead power lines and other obstacles, soil borings were not appropriate in most locations throughout the study area; consequently, geophysics was deployed to map the underlying geology. These studies were integrated to map the local confining layer that is present throughout much of the area in the well logs. A ground-penetrating radar (GPR) survey was conducted in conjunction with surface resistivity profiles [vertical electric soundings (VES)]. The survey lines were laid out both perpendicular and parallel to the river. The information derived from these studies was used to formulate the geologic history of the site, and its overall importance to the hydrogeological processes contained within the study area.

Ground Penetrating Radar

Several GPR profiles were run across the study area to document the position of the water table and the location of underlying clay layer(s). The downward looking radar was used to detect the subsurface disturbances that are in electromagnetic contrast with the surrounding media (Daniels, 1989). Changes in water content, grain size, porosity, and sedimentary structures can commonly be detected using GPR. The profiles are vertical representations of the subsurface, and clearly show the various interfaces defined by contrasts in the electromagnetic properties: (a) conductivity, (b) relative permittivity, and (c) magnetic permeability (Daniels, 1989, Sauck, 1995). In this sedimentary environment, conductivity and relative permittivity are most important (σ and ϵ_r , respectively) because they are

controlled by the water content. Thus, even fairly small changes in water content, as can occur at boundaries between layers having different grain sizes or textures, can produce appreciable reflector coefficients. This is true in both the vadose zone and the saturated zone. The permittivity controls the radio wave velocity, with velocity proportional to the free space velocity (c), and inversely proportional to the square root of ϵ_r . The conductivity controls the attenuation, or loss of signal strength with depth. Higher conductivity soils are less penetrable by the radio pulses.

GPR Results and Interpretations

Three profiles were run through the study area and city wellfield (Figure 5). Two were north-south trending and one ran west-east. The first two of these profiles were run between well nests *B* and *C*. *A-A'* runs west-east from the river's edge under the north-south oriented power lines to well "B-Deep". *B-B'* runs north-south under the power lines crossing the *A-A'* profile at the 35 meter (114.8 ft) mark. This corresponds to the 40 meter (131 ft) mark on *B-B'*. The third profile (*C-C'*) runs north-south inside the City of Parchment's Wellfield between wells #3 and #1. The Geophysical Survey Systems Incorporated (GSSI) SIR-10 GPR unit with 100 MHz bistatic antennas and a 15 m (49.2 ft) cable was utilized for this study. The GPR velocity versus depth function has been interpreted from the sand-clay interface at 5.49 m (18 ft) in well "B-Deep". This resulted in an average velocity of 0.078 m/nsec, corresponding to a relative permittivity of 14.6. Using the average velocity, the total depth of penetration is interpreted as 9.36 m (30.7 ft) for a 240 ns scan

length. The following describes each of these profiles and its significance to the geology of the study area.

Profile A-A'

A-A' (Figure 11) starts 10 m (32.8 ft) from the river's edge and runs eastward for 55 m (180.5 ft). This profile was run October 19, 1994 with a range of 240 nanoseconds at 512 samples/scan. The field acquisition parameters were: (a) a 3 stage vertical low pass filter of 80 cycles/scan, (b) a 3 stage vertical high pass filter of 10 cycles/scan, and (c) a horizontal smoothing filter set to do a running average of 5 scans. The post processing filters included a vertical boxcar high pass filter of 33 sample window length and a low pass filter of 7. The horizontal boxcar smoothing filter was 3 scans wide. The post-processing filters were run only on samples 256 through 512 (i.e., the lower half of the displayed section.)

The A-A' profile crosses the B-B' profile at the 35 m (114.8 ft) mark. Well "C-Deep" is located at the 10 m (32.8 ft) mark, and well "B-Deep" is located at the 65 m (213.3 ft) mark. Using these wells as controls for the profile, the description of depths to reflectors and interpretation of those reflectors are as follows.

The main reflector running through the profile is located at a depth of 5 m (16.4 ft) on the west and rises to a depth of 2.1 m (6.9 ft) on the east end of the line. The sloping of this layer towards the river represents a fairly recent position of the river channel. This reflector defines the top of the clay-rich confining layer that

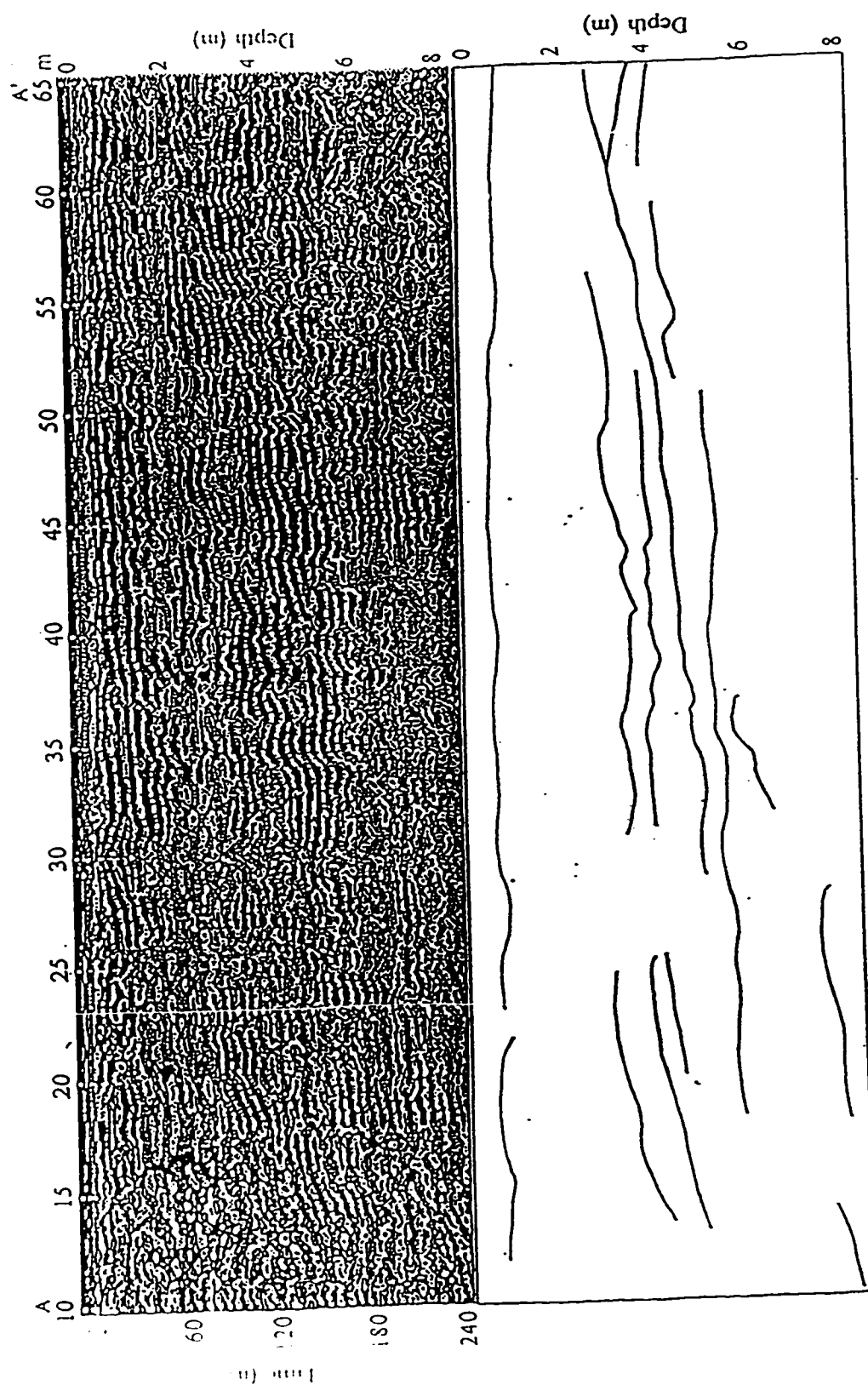


Figure 11. GPR Profile and Interpretation A-A'.

separates the upper aquifer from the producing aquifer. However, since there appear to be reflectors represented below this layer, the continuity of the confining layer is not confirmed. That is, the GPR profiles show that some areas away from the wells may not be as well defined while the well logs from both "C-Deep" and "B-Deep" show that the clay-rich layer is not only present but also well defined. The water table is quite close to the surface in the area [less than 1.5 m (4.9 ft) on average]; the relatively horizontal reflector at the top of the profile represents this.

Profile B-B'

B-B' (Figure 12) runs 40 m (131.2 ft) south of A-A' and north for 35 m (114.8 ft) for a total length of 75 m (246 ft). This profile was run October 19, 1994 with a range of 240 nanoseconds at 512 samples/scan. The field acquisition parameters were: (a) a 3 stage vertical low pass filter of 80 cycles/scan, (b) a 3 stage vertical high pass filter of 10 cycles/scan, and (c) a horizontal smoothing filter set to do a running average of 3 scans. The post processing filters included a vertical boxcar high pas filter of 33 sample window length and a low pass filter of 7. The post processing filters were run only on samples 256 through 512, i.e. the lower half of the displayed section.

Power lines run overhead parallel with this profile. This profile crosses the A-A' profile at the 40 m (131 ft) mark. Using wells located at the ends of the A-A' profile as controls for this profile, the description of depths to reflectors and interpretation of those reflectors are as follows.

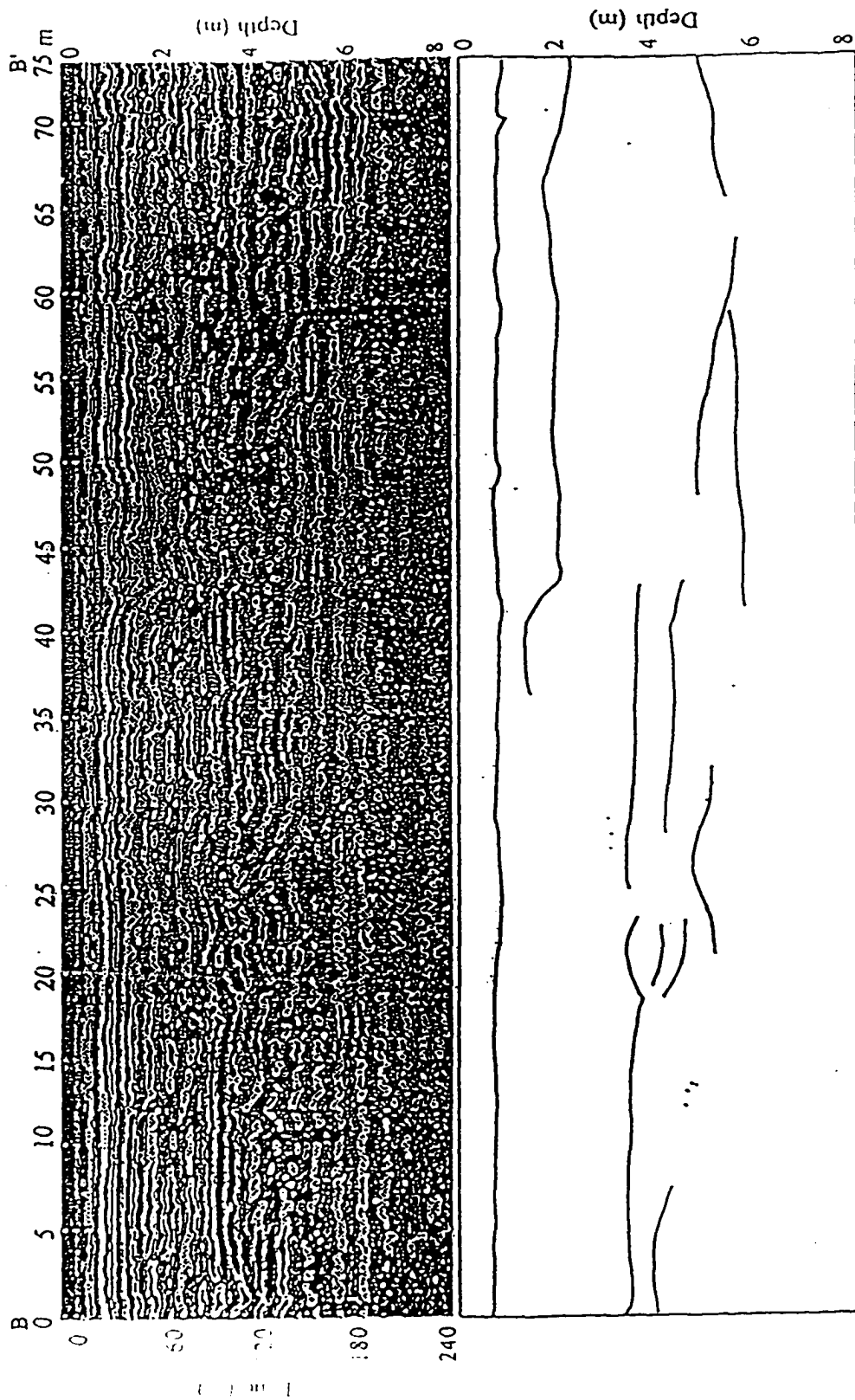


Figure 12. GPR Profile and Interpretation B-B'.

The main reflector running through the profile is located at an average depth of 3.5 m (11.5 ft). Using the information from well "B-Deep" and line A-A', this reflector is interpreted as the top of the clay-rich layer. The reflector separates at 20 m (65.6 ft) into two separate reflectors paralleling each other through the rest of the profile. From 42 m to 78 m (137.8 to 255.9 ft) the main reflector is absent shallow, but shows at a depth of 5.8 m (19 ft). This is interpreted as an old river channel that cuts through the area. Steep dipping reflector near the surface supports this interpretation. The water table appears in the upper part of the profile with an average depth of 0.75 m (2.5 ft).

Profile C-C' (a and b)

C-C' starts adjacent to the City of Parchment Well #3 and runs southward toward Well #1 for a total length of 240 m (787.4 ft). For interpretation and presentation purposes this profile is broken into two sections C-C'a (Figure 13) and C-C'b (Figure 14). C-C'a is 125 m (410 ft) and C-C'b is 115 m (377.3 ft) long. This profile was run January 22, 1997 with a range of 240 nanoseconds at 512 samples/scan. The field acquisition parameters were: (a) a 4 stage vertical low pass filter of 70 cycles/scan, (b) a 3 stage vertical high pass filter of 8 cycles/scan, and (c) a horizontal smoothing filter set to do a running average of 5 scans. The post processing filters included a vertical boxcar high pass filter of 27 sample window length and a low pass filter of 5, with a horizontal boxcar smoothing filter of 5 scans wide.

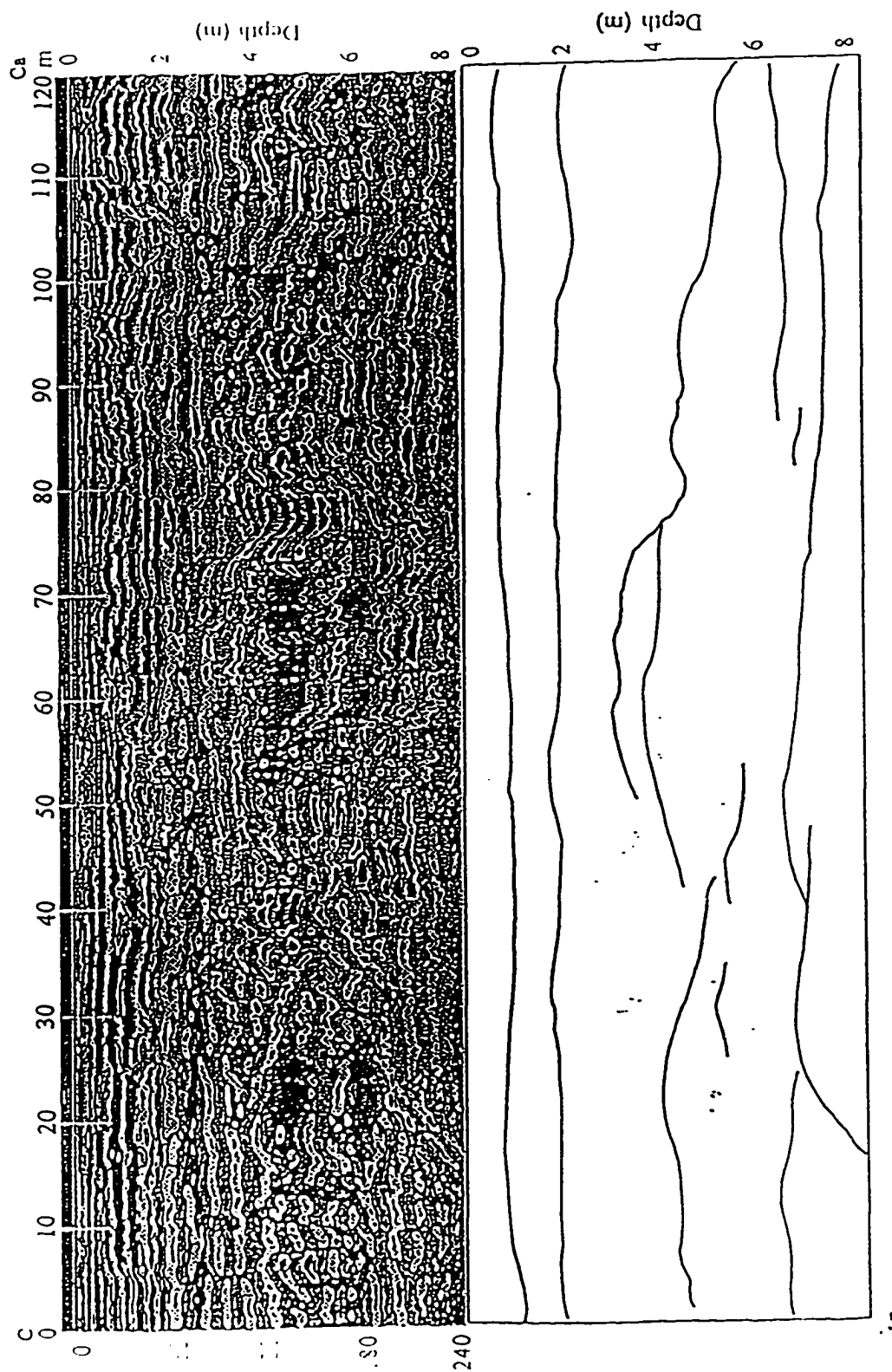


Figure 13. GPR Profile and Interpretation C-C'a.

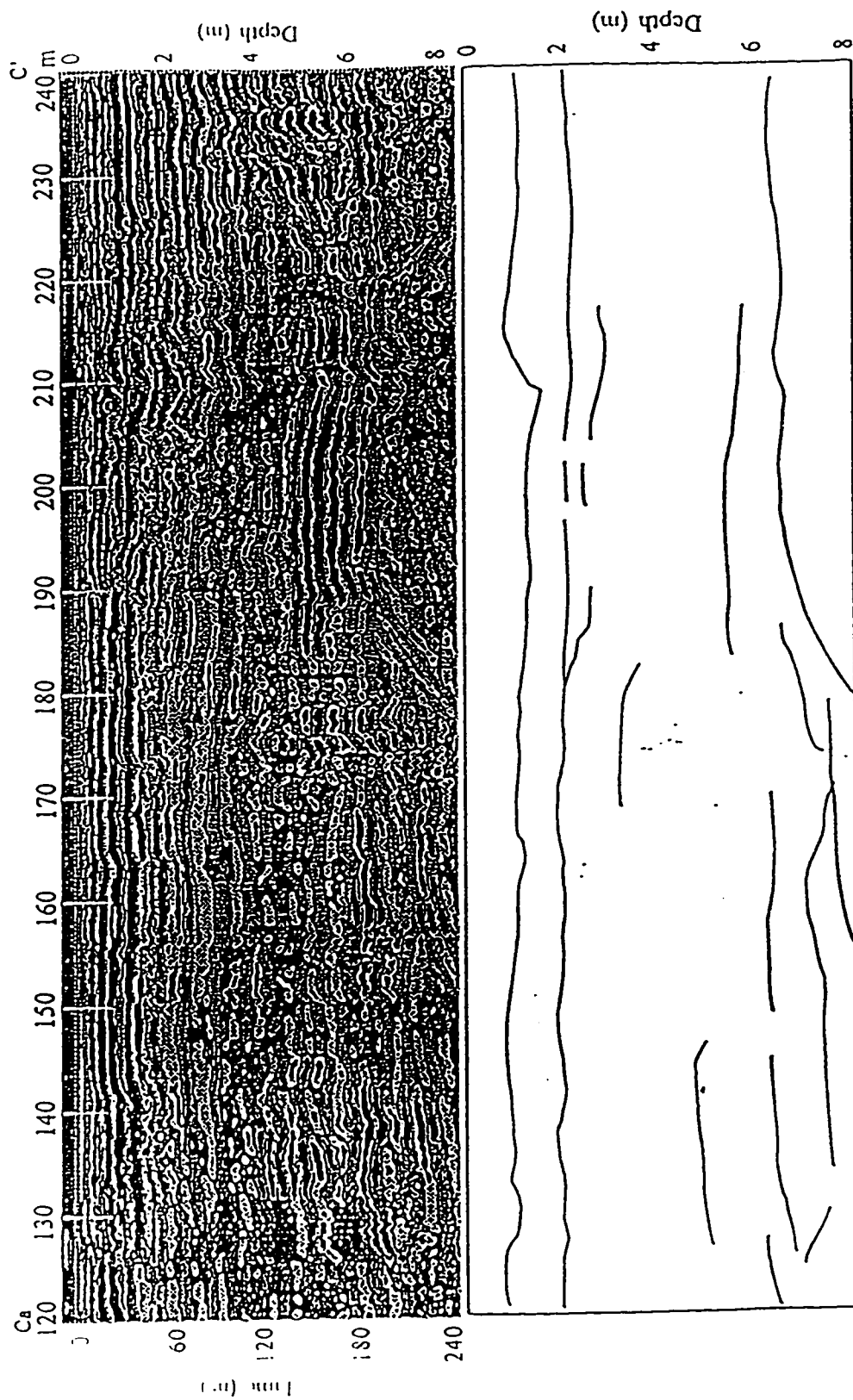


Figure 14. GPR Profile and Interpretation C-C'b

There are several wells located along this profile. Conditions during data collection were sloppy with snow cover, and it should be noted that this profile was run on a built up utility road. City Well #3 is located at the 0.0 m (0.0 ft) north, Well #2 at 113 m (370.5 ft), Well TW at 123 m (403.6 ft) and Well #1 at the 235 m (771 ft) marks. Using these wells as control for the profile the following description of depths to reflectors and interpretation of those reflectors are as follows.

Three major reflectors are present in profile C-C'a. The top reflector, which averages 1.2 m (3.9 ft) in depth, is the base of the maintenance road. The next reflector, which ranges in depth from 3.5 to 5 m (11.5 to 16.4 ft), represents the water table reflector. The third reflector averages 6 to 7.5 m (19.7 to 24.6 ft) in depth and correlates well with the well logs as the clay-rich layer. At 15 m (49.2 ft) south, a steeply dipping reflector is present, representing an old river channel cut. This same reflector is less defined past the 100 m (328.1 ft) south area.

Profile C-C'b is a continuation of profile C-C'a. The road base reflector is still present throughout the profile. However, the water table reflector is not as well defined through this portion of the profile. The bottom reflector representing the clay-rich confining layer has several steep dipping reflections, one at 150 m (492 ft) south and the other at 180 m (590.6 ft) south. These represent old river channel terraces.

GPR Interpretation Conclusion

Several possible sources of error must be discussed. One possible error is that all or part of the antennae lifting-up over obstacles caused decoupling and ringing in the record. Another cause of error that was encountered at the study site was the crossing of power lines perpendicular to the profile. This may cause large hyperbolas, which could be misinterpreted as steeply dipping geologic structures. Along profile B-B' several grounded steel structures (power line poles) were passed which caused hyperbolas on the depth section. Along C-C' the metal casing from the wells could cause a similar problem. The change in surface soil conductivity along C-C' could change the attenuation/brightness of deeper reflectors. This would account for the lack of water table definition in the southern portion of the C-C' profile.

The GPR profiles give an indication of the continuity (or lack thereof) of the clay-rich confining layer within the study area. From the profiles it is seen that the clay-rich layer is not as defined as one is led to conclude by the well logs. This lack of definition is probably due to buried river channels formed over time during the development of the Kalamazoo River valley. The mapping of these buried river channels over the area surrounding the City of Parchment Wellfield is vital to its overall wellhead protection plan.

Vertical Electric Soundings

Geophysical earth resistivity was used in conjunction with the ground penetrating radar. This method utilized a pair of current electrodes that were driven into the ground, activated, and the resulting potential difference measured between a pair of potential electrodes using a sensitive voltmeter. By applying a known current over a known separation of electrodes (which is increased in a stepwise manner) the potential distribution (proportional to the apparent resistivity) and the path of the current flow, was calculated. Through the use of a vertical sounding, horizontal layers of high/low conductivity/resistivity can be mapped, although with ambiguity of layer thicknesses and resistivities. Clay minerals generally tend to decrease resistivity because the clay minerals can adsorb cations in an exchangeable state on their surfaces, and/or desorb and contribute to the supply of free ions in the soil electrolyte. For details of this and interpretation, Telford (1990), Sharma (1986), and Ward (1990) should be consulted.

VES data using the Schlumberger array were collected on October 19, 1994 (Table 1) (Figure 5). The AB/2 (AB is the current electrode separation) spacing was systematically increased from 1.0 to 46.41 meters (3.3 to 152.3 ft), with a MN (MN is the potential electrode separation) spacing ranging from 0.3 to 3.0 meters (1.0 to 9.8 ft). Calculations to obtain apparent resistivity (ρ_a) are made using the standard expression,

$$\rho_a = \pi \frac{(AM \times MN)}{MN} \frac{V}{I} = \frac{KV}{I}$$

where V is the drop in potential, I is the measured current, and k is the conductivity.

This accounts for array geometry (Sharma, 1986) based on the difference in readings taken as the MN distance is increased.

Table 1
VES Data, Calculations, and Corrections

AB/2 (meters)	MN (meters)	K (meters)	V/I (Ω)	$\rho_a - \Omega$ (ohm-m)	Corrected $\rho_a - \Omega$
1	0.3	10.2	380/10	387.6	430.24
1.47	0.3	22.4	186/10	416.64	462.47
2.15	0.3	48.2	77/10	371.14	411.97
3.16	0.3	104	140/10	291.2	Skip
3.16	1.0	30.57	529/50	323.43	323.43
4.64	1.0	66.9	171/50	228.79	228.79
6.81	1.0	145	53.4/50	154.86	154.86
10.0	1.0	313	16.04/50	100.41	100.41
14.67	1.0	675	11.1/50	74.925	74.925
14.67	3.0	223	41.7/100	92.99	Skip
21.54	3.0	484	15.9/100	76.96	62.34
31.62	3.0	1045	6.73/100	66.15	53.81
46.41	3.0	2253	2.74/100	61.73	50.0

Segments of the curve made from different MN separation were adjusted up or down to match the next segment resulting in a smooth VES curve for interpretation.

The Schlumberger VES inversion program (SCHLINV) used a five-layer earth for interpretation (Figure 15). The model fits the field data with a RMS error of 1.124 percent. The constraints put on the model came from well borings from well nest B (Figure 5). The depths 0.22 (0.72 ft), 0.96 (3.15 ft), 3.38 (11.10 ft) and 12.01 (39.4 ft) meters match favorably with these logs (Appendix A).

	Resistivity (ρ)	Depth (m)
layer 1	224	0.22
layer 2	706	0.96
layer 3	201	3.28
layer 4	67	12.01
layer 5	46	

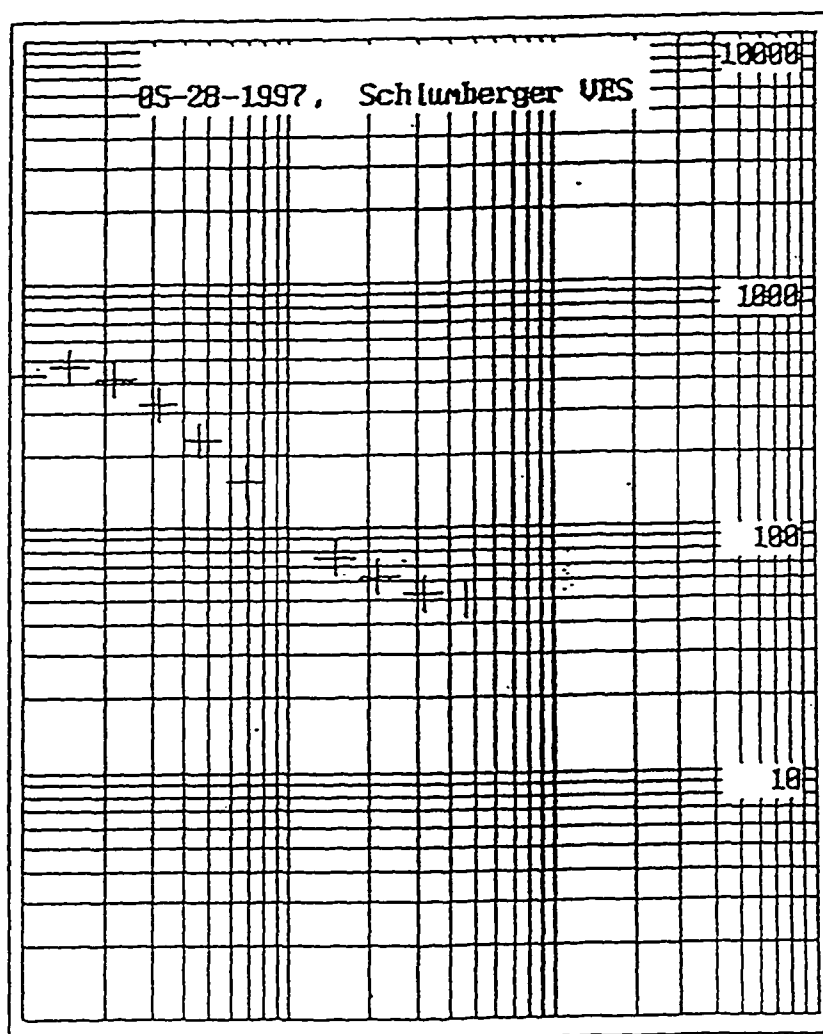


Figure 15. Schlumberger VES Data and Model Results.

The water table in the area ranges in depth from 0.78 to 1.52 meters (3.0 to 5.0 ft), which fits the second layer of the model. The first layer correlates with the topsoil or disturbed surficial material. The layer below the water table in the model is thought to represent a layer of sand and gravel with some clay lenses. Lying under this layer is the semi-confining clay layer that was reported in both the drilling logs and sample borings. The last layer in the model is the coarse sand and gravel unit that forms the aquifer in which the City of Parchment obtains its water.

CHAPTER IV

HYDROLOGY

Climate, Groundwater Flow, Surface Water and Water Budget

The main surface water features in the study area are the Kalamazoo River, which flows north and Spring Brook, which enters the Kalamazoo River from the east (Figure 4). Within the study area, the water table is typically within a few meters [1.0 to 3.0 m (3.28 to 9.84 ft)] of the surface. In Kalamazoo County, with an average rainfall of 86.4 cm (34 in) per year, approximately 27% of the total precipitation infiltrates the ground and as much as 70% is lost to evaporation and transpiration. The remaining 3% is taken in by plants and direct runoff out of the watershed. An understanding of the hydrologic parameters and the interaction of the climate to the surface water and groundwater are important to watershed/water budget studies.

Climate

Kalamazoo County, Michigan, is located in the lower southwest climatic division of the state, about 56 km (35 mi.) north of the Indiana border and about 56 km (35 mi.) east of Lake Michigan. Kalamazoo County is also located in the “Lake Effect Snow Belt”. This “Lake Effect” is caused by three fundamental differences between the land surface and Lake Michigan. First, the lake temperatures “lag”

behind the land temperatures with large differences occurring at certain times of the year; second, the lake increases the availability of moisture to be evaporated into the air during the cold season; and third, the surface of the lake is smoother than the land (Eichenlaub, 1990). The lake effect on Kalamazoo's climate is quite strong. The prevailing winds in the county are southwesterly, averaging 16 kph (10 mph). These southwest winds cross Lake Michigan producing the lake effect which increases cloudiness and snowfall during the fall and winter, and moderates the temperature throughout most of the year. Northeasterly to southerly winds may produce clearing skies with the associated colder temperatures more common to areas to the far east of the county (Nurnberger, 1994). The temperature lag affects the Kalamazoo area by producing milder falls and cooler springs.

Summers in Kalamazoo County are dominated by moderately warm temperatures with a 1951 to 1980 average of eighteen days per year exceeding 32°C (90°F). During the same period, seven days in three different years had maximum daily temperatures of 37.8°C (100°F) or higher. The lake influence was reflected in the minimum temperatures. An average of 136 days per year experienced minimum daily temperatures of 0°C (32°F) or lower and an average of six days per year had maximum temperatures of -17.8°C (0°F). Only two years were entirely above -17.8°C (0°F). The following temperature extremes have been recorded for southwest Michigan: (a) maximum, 42.8°C (109°F), recorded July 13, 1936; (b) minimum, -31.7°C (-25°F), recorded February 10, 1885; (c) warmest monthly mean, 25.7°C

(78.2°F), recorded July 1955; (d) and coldest monthly mean, -10.4°C (13.3°F), recorded January 1977 (Nurnberger, 1994).

Based on the 1951 to 1980 period, the average date of the last freezing temperature in the spring was May 1, while the average date of the first freezing temperature in the fall was October 13. The freeze-free period, or growing season, averaged 164 days annually.

Precipitation is well distributed throughout the year with April-September receiving an average of 52 centimeters (cm) [20.47 inches (in)] for the 1951-80 period (59% of the average annual precipitation). During this same period the average wettest month was June with 9.8 cm (3.83 in), while the average driest month was February with 4.24 cm (1.67 in). Summer precipitation comes mainly in the form of afternoon showers and thundershowers. Annually, thunderstorms will occur on an average of 36 days. Precipitation that owes its origin to Lake Michigan during the winter is 15 to 20% of the total precipitation and 8 to 12% in the summer (Machavaram, 1993).

Michigan is located on the northeast fringe of the Midwest tornado belt. The lower frequency of tornadoes occurring in Michigan may be, in part, the result of the colder water of Lake Michigan during the spring and early summer months, a prime period of tornado activity. During 1950 to 1987, Michigan averaged 15 tornadoes a year. During this same period, only 17 tornadoes occurred within Kalamazoo County.

The 1950 to 1951 through 1979 to 1980 average yearly snowfalls were 186.9 cm (73.6 in). During this period, 71 days per season averaged 2.54 cm (1 in) or more of snow on the ground, but varied greatly from year to year. The following snowfall extremes, based on the time period of record (Nurnberger, 1994), are: (a) greatest observation-day total, 45.7 cm (18.0 in), recorded January 26, 1978; (b) greatest monthly total, 139.7 cm (55.0 in), recorded December, 1903; (c) greatest seasonal total, 307.85 cm (121.2 in), recorded during 1903 to 1904; (d) least seasonal total, 38.1 cm (15.0 in), recorded during 1901 to 1902; and (e) greatest snow depth 106.7 cm (42 in), recorded February 9, 1905.

Evaporation data from a Class "A" pan [a device used to measure free-water evaporation (Fetter, 1994)] was not available for the Kellogg Biological Station, but data for this area should be similar to observations at South Haven, Michigan, which is approximately 50 km west of the City of Kalamazoo. During 1952 to 1980, the pan evaporation in South Haven, for April through October exceeded the average precipitation by 58%. Therefore, soil moisture replenishment during the fall and winter months plays an important role in the success of agriculture for this area. While drought occurs periodically, the Palmer Drought Index (Nurnberger, 1994) indicated drought conditions reached extreme severity only 1% of the time.

Aquifer Tests

Aquifer tests have been conducted on the Kalamazoo River aquifer since the mid-1950's by both the City of Parchment and the Brown Company. These tests are

important in determining the groundwater interaction with adjacent surface water bodies. The derived data from these tests also help to determine the various aquifer parameters such as hydraulic conductivity, transmissivity and storage coefficients.

In 1950, the Kalamazoo River aquifer was developed for industrial and municipal use. At that time an aquifer performance test was run. A transmissivity value of 240,000 gallons per day per foot, with a storage coefficient of 1.8×10^{-4} was calculated (Williams & Works, 1980). Using information generated by the aquifer test they determined that the aquifer would yield 5,000 gallons per minute (gpm) or 7.2 million gallons per day (mgd) because of the high transmissivity and good recharge from the river. Moreover, they determined that this could be done with only two to three feet of drawdown in the 35-acre wellfield area (JRPC property, south of the study area) adjacent to the river. Drawdown in the wells maintained by JRPC has been known to approach the bottom of the aquiclude (Williams & Works, 1980). However, they suggest that most of this is due to well losses.

The City of Parchment began pumping Wells #1 and #2 of the subject wellfield in 1963. Well #3 came online ten years later in 1973. The wells range in depth from 15.7 to 17.7 meters (51.5 to 58 ft). The wells have specific capacities ranging from 32.1 gpm to 244 gpm. Each well was designed to operate in the range of 600 to 1000 gpm (Table 2).

Since 1987, daily pumping rates have ranged from a low of 0.115 million gallons a day (mgd) in 1989 to a high of 2.222 mgd in 1991. Average daily pumping

rates have ranged from 0.394 mgd in 1993 to 0.518 mgd in 1994 (Jones, 1992) (Table 3).

Table 2

Well Diameter and Specific Capacities (Jones, 1992)

Location	Rated Capacity (gpm)	Diameter (in)	Depth (ft)	Screen (ft)	Drilled (year)	Static Depth (ft)	Specific Capacity (gpm/ft)
Well #1	600	38 x 34 x 12	51.5	15	1963	8	32.1
Well #2	1000	38 x 34 x 12	58	15	1963	8	140
Well #3	1000	42 x 34 x 12	58	15	1973	10	244

Table 3

Water Usage for the City of Parchment Wellfield (1986-1996) (Jones, 1992)

Year	Average Daily (mgd)	Maximum Daily (mgd)	Minimum Daily (mgd)
1987	0.457	1.614	0.161
1988	0.503	1.716	0.147
1989	0.456	1.077	0.115
1990	0.434	1.476	0.200
1991	0.438	2.222	0.135
1992	0.413	1.276	0.237
1993	0.394	0.746	0.187
1994	0.518	1.264	0.318
1995	0.499	1.304	0.115
1996	0.515	1.484	0.168

Water-level information from the monitoring and production wells were contoured and compared to the United States Geological Survey (USGS) water table

map of August 1988 (Allen and others, 1972). The shape of the water table thus generated was found to be comparable to that reported by Rheume (1988) and showed groundwater movement to be in a northwesterly direction along the Kalamazoo River (Figure 16). Jones (1992) used well logs (Appendix A) supplied by the Kalamazoo County Human Services Department to develop a water table map that corresponds fairly closely with that of Rheume (1988).

The Well Head Protection Report (Jones, 1992) includes information on a 24-hour pump test conducted by Peerless-Midwest in December 1991. The tests for these wells gave transmissivities from 15,898 ft²/day to 20,232 ft²/day and hydraulic conductivities from 361 ft/day to 460 ft/day (Table 4). The following averages were calculated from the pumping results: (a) the transmissivity equals 17,915 ft²/day (134,004 gpd/ft); (b) the hydraulic conductivity is 407 ft/day (3044 gpd/ft²); and (c) the storativity is 3.72×10^{-4} . These averages are very similar to most producing aquifers within Kalamazoo County. As noted by Jones (1992), the results are reasonably close for each of the wells. It was not possible to determine the storativity of Well #1, because the effective radius of the pumping well is unknown.

The difference between the results of the pumping phase of the test and the recovery phase is likely due to the pumping of Well #3 during the recovery period. Another possible problem was that Well #3 was pumped until the start of the pumping test in Well #1. This would have caused problems with the early time data in Wells #2 and #3. The well recovery data were analyzed using the Cooper-Jacob

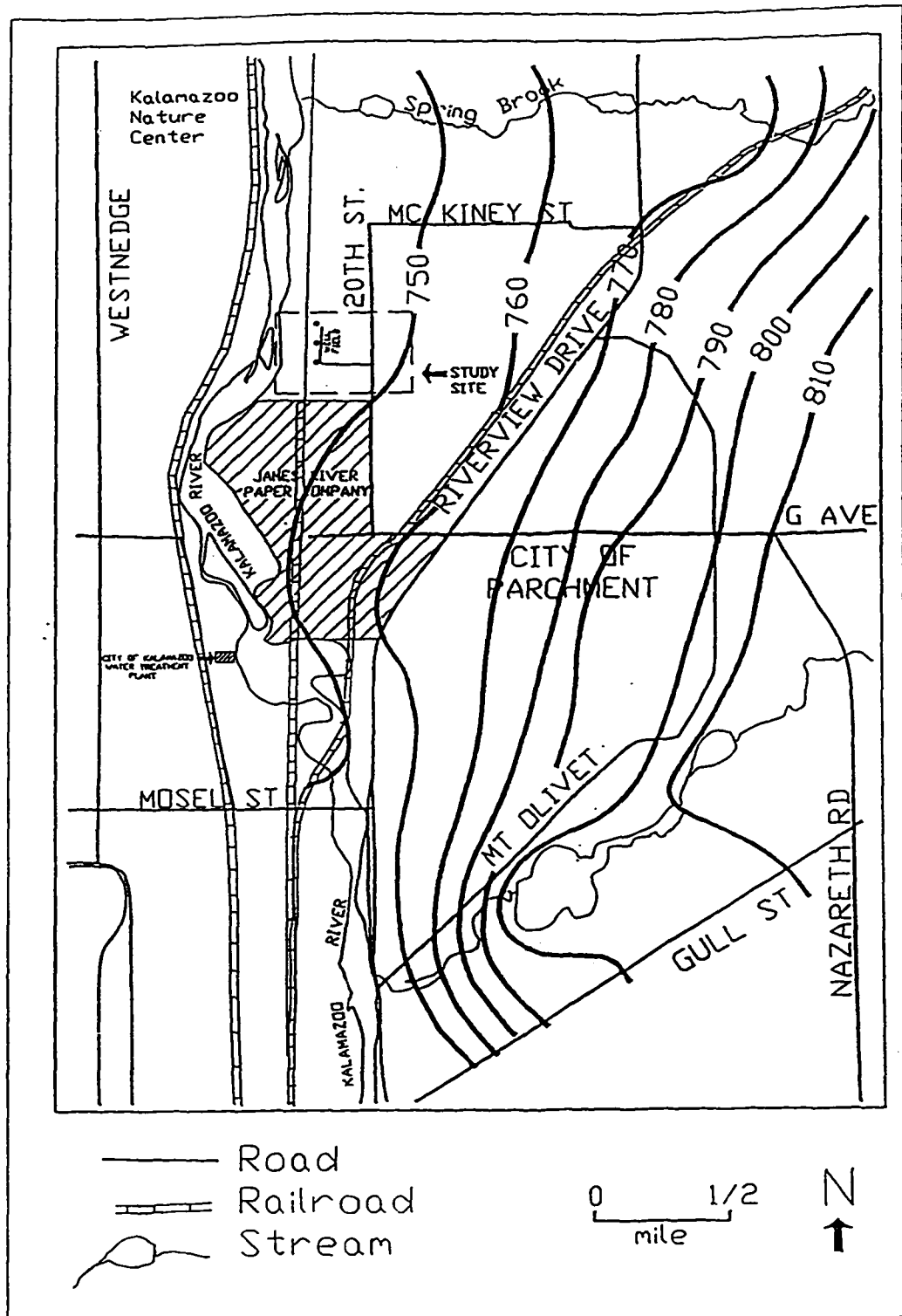


Figure 16. Groundwater Flow Map. Modified from Jones, 1986.

straight-line method and yielded transmissivities from 28,840 to 36,363 ft²/day and hydraulic conductivities of 655 to 826 ft/day (Table 5).

Table 4

Hydraulic Parameters, Well #1 Pumping Test, Parchment, Michigan
(Jones, 1992)

Well ID	Transmissivity (ft ² /day)	Hydraulic Conductivity (ft/day)	Storativity (dimensionless)
Well #1	15,898	361	N/A
TW	20,232	460	4.42×10^{-4}
Well #2	18,855	429	3.54×10^{-4}
Well #3	16,675	379	3.21×10^{-4}
Average	17,915	407	3.72×10^{-4}

Table 5

Hydraulic Parameters, Well #1 Recovery, Parchment, Michigan
(Jones, 1992)

Well ID	Transmissivity (ft ² /day)	Hydraulic Conductivity (ft/day)
TW	29,346	667
Well #2	28,840	655
Well #3	36,363	826
Average	31,516	716

Interpretation of Aquifer Test Results

Jones (1992) discussed the results of the test and the presence of clay in the well logs of Wells #1, #2, and #3 (Appendix A). The well logs report a clay or gravel and clay-confining layer. This clay layer is also present in the well logs of well nests *B* and *C* constructed for this study (Figure 10). The presence of this clay layer

throughout the area of the wellfield suggests that a continuous clay layer is present; but conflicts with the drawdown curves for the pump test indicate that unconfined conditions exist. This suggests that the clay layer is not continuous or it may be that the aquifer is being recharged from some other source.

The pump test data showed some delayed yield which suggests that unconfined conditions exist, but the storativity of 3.72×10^{-4} is indicative of a confined aquifer. Typically storativity of confined aquifers is less than 0.005 (Fetter, 1994). The 1950 pump test data generated values for a storage coefficient of 1.8×10^{-4} (Williams & Works, 1980). They suggest that the low storage coefficient was evidence for a true aquiclude being present over the lower aquifer unit. They further state that under “non-pumping” conditions, an upward pressure gradient exists across the aquiclude which means that any leakage through the unit is upward from the lower aquifer rather than downward into it (Williams & Works, 1980). The combined pumping of JRPC and the City of Parchment most likely causes a reversal in the hydraulic gradient within the study area.

Jones’ (1992) report on the barrier effect of the river indicates that the confining layer does not extend to the river. Cross-section A-A’, (Figure 11) shows a continuous clay layer, but the GPR line reveals possible discontinuous sections along the transect A-A’, as explained in the previous chapter.

Southwest Michigan aquifers have transmissivities ranging from 2,000 to 300,000 gpd/ft (Table 6). Specific capacities for the same aquifers range from lows of less than 1 to a high of 650 gpm/ft. The City of Parchment Wellfield data falls

well within these ranges of aquifer parameters. The Coldwater formation, which underlies the City of Parchment Wellfield, has a very low specific capacity with a transmissivity of 26,700 gpd/ft, which is good enough for private potable wells but not for municipal production (Passero and Straw, 1988). This prohibits the City of Parchment from deepening the wells in order to further protect the wellfield from potential contamination.

In 1951 and 1952, the Brown Company installed six high-capacity, 12-inch diameter, water supply wells south of the City of Parchment Wellfield. When these wells were pumped they influenced the water levels in the shallow aquifer in nearby monitoring wells, thus providing evidence of hydraulic conductivity through the aquiclude (Williams & Works, 1980). From this it is concluded, based on the aquifer performance data, that the aquifers are interconnected and that the clay-rich layers from an aquitard not an aquiclude.

Table 6

Productivity of Glacial Drift and Bedrock Aquifers
(Passero and Straw, 1988)

Aquifer	Well Capacity (gpm)	Specific Capacity (gpm/ft)	Transmissivity (gpd/ft)
Glacial Drift	<5-2,850	<1-550	3,000-300,000
Coldwater Formation	25-975	1-54	26,700

Groundwater Flow

Groundwater levels in Kalamazoo County reflect short- and long-term changes in precipitation and local pumpage. Groundwater levels increase in the late

winter and early spring in response to the infiltration from snowmelt and rain during the early part of the growing season when evapotranspiration is very low. According to Rheume (1990), water levels in Kalamazoo County only fluctuate from 0.6 to 0.9 meters (2 to 3 ft), even during extended dry and wet periods. Generally, the configuration of the water table shows that groundwater moves from topographic high areas to topographic low discharge areas such as ponds, streams, and wetlands (Rheume, 1990; Fetter, 1994). On the east side of the Kalamazoo River near the City of Parchment Wellfield, the slope of the water table indicates that flow in the upper aquifer is toward the river. Rheume (1990) constructed a hydrograph separation of data collected at the Comstock, Michigan gauging station and calculated groundwater discharge rates for the Kalamazoo River of 12.1% or 8.79 in/year, thus demonstrating that the river is a discharge river. Allen confirms this in his report of 1972. Near the river, the water table is controlled by the river's stage (Williams & Works, 1980). The water table is nearly flat in the study area and follows the subdued topography of the site (Figure 16).

In the lower (production) aquifer, based on the hydrogeology of the area and the hydraulic communication with the river seen in the pump test data, it seems likely that under normal and low river flow, the aquifer discharges to the river, as Rheume (1990) and Allen (1986) suggest. As the river stage rises, recharge to the aquifer from the river begins (Williams & Works, 1980). The gradient direction probably swings northward close to the river and with an upward component when discharging

to the river (Freeze and Cherry, 1979). Under the influence of this gradient, the upper and lower aquifers combine to support the baseflow of the river.

Natural groundwater velocity can be calculated by rearranging Darcy's Law, Discharge(Q) equals hydraulic conductivity(K) times the gradient(dh/dl) to Velocity(V) = $K(dh/dl)$. Using the average hydraulic conductivity of 407 ft/day along with a gradient of (20 ft/850 ft), based on distance from the river to the wellfield and the drawdown in the wells the time frame needed for water to move from the river to the wellfield can be calculated. Using the calculated velocity of 9.6 ft/day it would take water from the river 3.2 months to reach the wellfield. This is based on the river being 850 feet from the wellfield. The time can be cut down considerably during flooding events in which the water is dammed by the old railroad tracks 200 feet from the wellfield (.74 months).

With the combined pumping of the JRPC and the City of Parchment, the groundwater gradient may show some local perturbations. However, pumping probably has only a small effect on the overall flow patterns of water in the aquifer.

Surface Water

Surface water bodies of importance to the study include the Kalamazoo River, Spring Brook, and several small ponds and wetlands near the site (Figure 5). The Kalamazoo River is the main drainage system for the county, draining 54 percent of the county. Spring Brook, near East Cooper, has a drainage area of 80.6 square

kilometers (31.1 square miles) and an average discharge of 0.5 m³/sec [17 cubic feet per second (cfs)] (Passero and others, 1978) (Table 7).

Table 7

Gaging Station Locations, Drainage Area and Average Discharge of Streams Near the Study Area (Allen and others, 1972; Passero and others, 1978)

Stations	Location	Drainage Area (mi ²)	Average Discharge (cfs)
1060.00	Kalamazoo River at Comstock	1010	794
1067.30	Spring Brook at CD Avenue	22.4	Not known
1067.50	Spring Brook near East Cooper	31.1	17
1067.70	Kalamazoo River near Cooper Center	1250	Not known

Natural discharge from the groundwater system is by seepage to springs, streams and some lakes, and to a lesser extent by evapotranspiration from the water table. During dry periods, the base flow of streams is almost entirely maintained by groundwater inflow. During wet periods, stored runoff in lakes and marshes help recharge the aquifers. Some streams lose water in areas where pumping has lowered water levels thereby allowing additional induced recharge into the aquifers (Allen and others, 1972; Rheaume, 1990). With the combined long-term pumping of both the City of Parchment (500,000 gpd) and the JRPC (2,360,000 gpd), the possibility of induced recharge from the Kalamazoo River exists.

Ten significant dam structures exist in the study area including eight dams or dam spillways on the Kalamazoo River and one each on Portage and Pine Creeks.

Two existing dams create significant impoundments on the Kalamazoo River. One is located at the upstream end of the study area near Comstock, (Morrow Dam-mile 69.5) which forms Morrow Pond, and the second in the downstream portion of the reach which forms Lake Allegan (Allegan Hydro Dam or Calkins Dam-mile 21.0). On the Kalamazoo River, there are several simple overflow dams that create backwater at low flows to control water supply depths or partially direct river flow through parallel side channels around islands. These overflow dams are located just upstream of Plainwell (Plainwell Diversion Dam-mile 51.3), in Otsego (Otsego City Dam-mile 46.1), and in Allegan (Allegan Diversion Dam-mile 28.5). Kalamazoo River water also flows through the spillways of three inactive hydropower dams with flow gates removed and minimal backwater effects located below Plainwell (Plainwell Hydro Dam-mile 48.0), Otsego (Otsego Hydro Dam-mile 42.8), and between Otsego and Allegan (Trowbridge Dam-mile 38.9) (Figure 2). The future of these structures is uncertain because of conflicting proposals to remove them for fish passage, aesthetics, and PCB concerns.

River Hydrographs (Historical)

Most floods occur in the spring as a result of snowmelt and spring rains in combination with frozen or saturated soils (Allen and others, 1972). The 100-year flood elevation for the site reports an elevation ranging from 229.5 to 230.3 m (753 to 755.5 ft)(USGS datum)(Williams & Works, 1980). The area below this datum is referred to as the 100-year floodplain (Figure 17). As seen in Figure 17 the City of

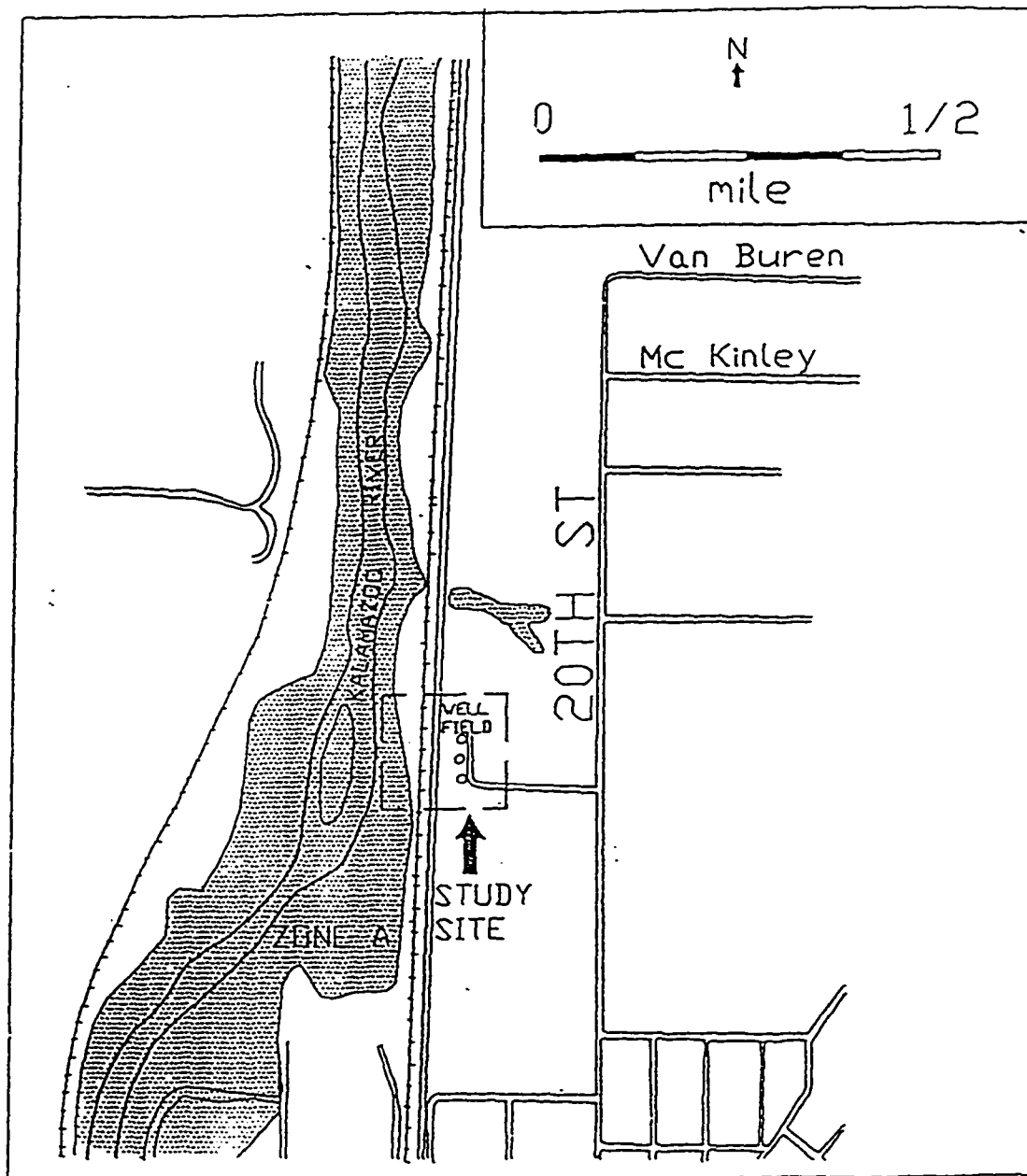


Figure 17. FEMA Map Displaying in the Shaded Area the 100 Year Flood Plain.

Parchment wellfield is protected by the abandoned railroad and Consumers Power road from river flooding.

Water Budget

Analysis of general water budgets can yield insight to the hydrologic system at work within a specific site. Water budgets take into consideration various parameters, some known and some not. These parameters include soil characteristics, weather (precipitation and temperature), surface waters and groundwater flow and infiltration. To calculate a budget for the study site it is necessary to combine past region-wide water budgets with known site-specific parameters.

The average rainfall in Kalamazoo County as reported at the Kalamazoo-Battle Creek International Airport is 86.4 cm (34 in) per year. The range of precipitation is from a low of 53.3 cm (21 in) to a high of 106.7 cm (42 in). Evaporation ranges from a low of 61 cm (24 in) to a high of 73.7 cm (29 in). This is approximately 70 to 85 percent of the total precipitation. The range of surface runoff (depending on soil type and slope) is 2.54 to 7.62 cm (1 to 3 in) or 3 to 8 percent of the total precipitation. Of the remaining precipitation, 5 to 22.9 cm (2 to 9 in) or 7 to 27 percent infiltrates into the ground. The countywide average groundwater recharge rate is estimated to be 23.67 cm (9.32 in) per year (Passero, 1978; Rheaume, 1990). Hydrograph separations done by Allen and others (1972) suggest that 65 to 73% of the total flow in the Kalamazoo River consists of groundwater discharge. Previous water budgets have focused on a countywide scale (Allen and others, 1972; Passero,

1989; Rheaume, 1990). Passero (1989) estimated that an average of 55 mgd or an amount equal to approximately 22% of the total infiltrated water is pumped in Kalamazoo Township (Table 8).

Table 8

Kalamazoo County Water Budget Calculations (Passero, 1989)

Parameter	Range of Parameter (inches)
Precipitation	34" (Ave.) 21"-42" (Range)
Evaporation	24"-29" (70-85%)
Surface Runoff	1"-3" (3-8%)
Infiltration	2"-9" (7-27%)

A water budget for the study area was calculated using a water budget equation (Figure 18) adapted from Fetter (1994). Assuming that there is no change in storage within the study area, then the only input of concern is precipitation. Because of the small scale of the water budget study, the river inflow is assumed to be equal to the river outflow. Due to the flat terrain and onsite observations during and following heavy rains, it can be assumed that no overland flow is coming into or leaving the

<p style="text-align: center;">Inflow = Outflow ± Changes in Storage</p> <p style="text-align: center;">Inflow: Precipitation, river inflow</p> <p style="text-align: center;">Outflow: Evaporation, surface runoff, infiltration, river outflow</p>

Figure 18. Water Budget Equations.

study area, except for the Kalamazoo River. Water budget values for the study site were calculated based on onsite observations and field measurements (Table 9).

Table 9

Calculated Water Budget Measurements of Study Site

Parameter	Calculated Values
Precipitation	86.36 cm (34 in)
Evaporation	73.66 cm (29 in)
Surface Runoff	2.54 cm (1 in)
Infiltration	10.16 cm (4 in)

Precipitation was taken as the average for the area which is 86.36 cm (34 in) a year. The National Council for Air and Stream Improvement (NCASI) maintained a weather station on the James River Paper Company landfill for several years preceding this study and found this to be a good average (Personal communication). Evaporation, which accounts for the greatest loss of water in the system, is hard to calculate. However, combining evaporation with the transpiration, 73.66 cm (29 in) a year becomes a good estimate for the site. Within the study area vegetation is plentiful. Trees line the river on both sides with an absence of trees only under the power lines and within the City of Parchment Wellfield.

The Glendora (Gn) soil is the predominate soil within the study area. It typically has a slope of 0 to 2 percent and resides along perennial rivers and streams. Surface water runoff is very slow and permeability is rapid. Recorded permeabilities are in the range of 5.08 to 50.80 cm (2.0 to 20.0 in) per hour (Austin, 1979). This

provides the justification for using such a low surface runoff of 2.54 cm (1 in) and a high infiltration value of 10.16 cm (4 in).

Using an average discharge from the wellfield (170 million gallons per year) along with the saturated thickness of 100 feet and a porosity of 0.2, we can calculate the area of influence of the wellfield. Based on the equation of radius of influence equaling discharge (Q) divided by effective porosity (n_e) times saturated thickness (h), 2π and the natural velocity (v). This will give a capture zone of 3.6 miles over the course of one year. This capture zone is based upon no recharge from precipitation or groundwater.

The proposed adjustment to the region-wide water budget is significant in that it allows for a more detailed analysis of the hydrogeologic system at work. Given the low slope and high permeabilities of the soils within the study area in association with the wellfield pumping, the possible necessary recharge of water from the river becomes less. However, if the clay-rich confining layer is continuous throughout then this infiltration of precipitation will ultimately filter towards the river and not recharge the producing aquifer. Based on this water budget and the pumping rates of both the City of Parchment and JRPC it is apparent that the wellfields receive water from more sources than just regional groundwater.

CHAPTER V

GROUNDWATER-SURFACE WATER INTERACTION

Seepage Meters and Analysis

Determining the groundwater interaction with the surface waters of the Kalamazoo River is important because of the effect interaction may have on the City of Parchment wellfield. Seepage meters were used to study the interaction of the Kalamazoo River and the upper aquifer adjacent to the river.

Seepage Meters

Modified seepage meters were used to determine the recharge and discharge fluxes across the Kalamazoo River bottom. Seepage meters are devices made from barrels and beach balls (Figure 19) which are placed into the nearshore of a water body in order to define the amount and rate of movement of water across the bottom interface. The seepage meters were installed in shallow water along the Eastern Shore of the Kalamazoo River (Figure 20) in conjunction with a monitoring piezometer and stilling well. The combination of these devices permitted the determination of the groundwater flux across the river bottom and adjacent unconfined aquifer.

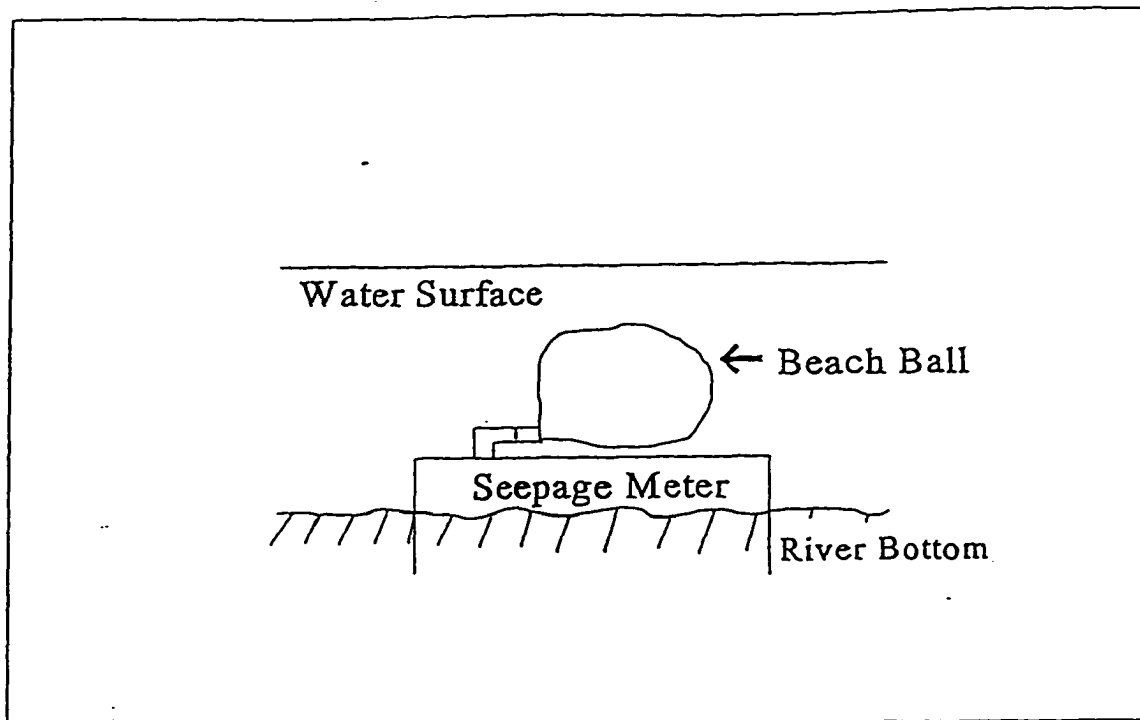


Figure 19. Seepage Meter Design.

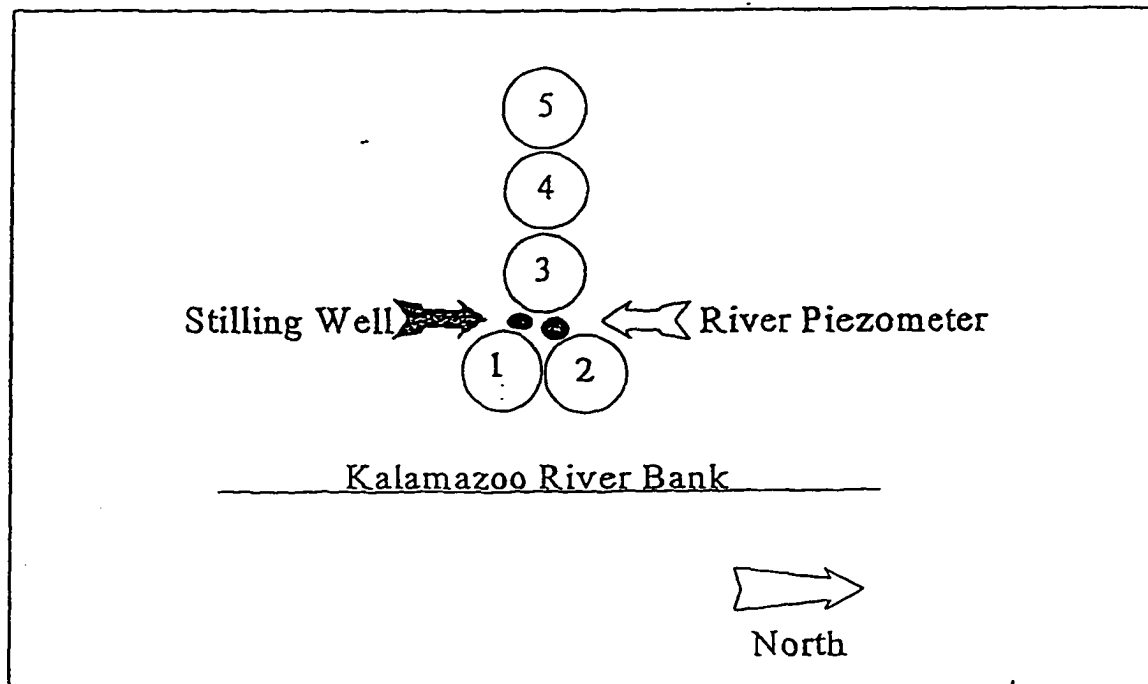


Figure 20. Layout of Seepage Meters, Stilling Well and Piezometer.

The seepage meters were constructed in a modified form from descriptions in Lee (1977) and Lee and Cherry (1978). The seepage meters were constructed by cutting 45.72 cm (18 in) long end sections from a single 55 gallon metal barrel and attaching a deflated beach ball to the top of the divided drum as shown in Figure 19. Water was placed into the beach balls prior to their connection to the seepage meters because results are more consistent if they are pre-charged. The seepage meters were installed by placing them into the bottom sediment below the existing water level by twisting and pushing them into the soft bottom sediments until complete resistance was attained. This commonly establishes the necessary "seal" within the bottom sediments.

Before the seepage meters are set for measurements, they are bled of all air pockets to minimize the trapped air within the meters. The presence of trapped air can be a potential problem with final measurements, due to the compressibility of air.

The seepage flux was calculated using equations presented in Figure 21. The net volume of change refers to the measured amount of water in the beach ball at the time of each reading minus the amount of water that was put into the beach ball at the beginning of each trial. Before each time trial 2 or 3 liters of river water were placed into the deflated beach ball. At the end of each time trial, the water in the beach ball was measured using a funnel and plastic five-liter graduated cylinder.

Sixteen time trials were conducted during two time periods (Table 10). The first time period (K1) was from September 24, 1994, at 2:55 P.M. through October 4, 1994 at 11:28 am (234.59 total hours). The second time period (K2) was from

$$\text{Net volume of change (cm}^3\text{)} = [\text{volume out (L)} - \text{volume in (L)}] \times 1000$$

A **positive** change means groundwater discharge.

A **negative** change means groundwater recharge.

$$\text{Seepage Flux (x } 10^{-2} \text{ cm/hr)} = 100 \times (\text{net volume change} / 2535 \text{ cm}^2) / \text{trial time in hours.}$$

The 2535 cm² is the contact area of the seepage meter with the bottom sediments.

Figure 21. Seepage Meter Equations.

August 24, 1995, at 12:20 P.M. through September 25, 1995, at 4:13 P.M. (747.03 total hours). Table 10 shows the fluxes for the individual seepage meters for each time trial over each trial period. The flux numbers refer to the individual seepage meters as they are oriented in Figure 20. A comparative graph of each sampling period (Figure 22 and 23) shows the variability in the seepage meters with time as discussed below.

Seepage Meter Analysis

The first analytical step was to determine fluxes for the individual time trials. This was accomplished using the equations given in Figure 21. The calculated fluxes for the individual events are listed in Table 10. Column one is the “event” identification. The second column is the trial time, which refers to the duration between collection periods. The third column refers to the accumulated time for the entire sampling

Table 10

Results of Seepage Meter Trials

Trial	Trial Time (hr)	Cum. Time (hr)	Flux 1 ($\times 10^{-2}$ cm/hr)	Flux 2 ($\times 10^{-2}$ cm/hr)	Flux 3 ($\times 10^{-2}$ cm/hr)	Flux 4 ($\times 10^{-2}$ cm/hr)	Flux 5 ($\times 10^{-2}$ cm/hr)
K1 1	2	2	0	2.56	1.38	5.32	16.76
K1 2	18.83	20.83	-0.12	0.18	0.96	1.94	0.64
K1 3	22.16	42.99	-0.21	0.14	1.76	0.94	1.97
K1 4	26.58	69.57	0.32	1.72	1.27	1.45	2.46
K1 5	28.02	97.59	0.94	2.08	1.68	1.05	1.83
K1 6	19.85	117.44	2.52	4.02	1.88	3.12	6.65
K1 7	24.53	141.97	0.41	2.55	0.57	0.69	3.20
K1 8	24.37	166.34	0.71	1.55	0.27	0.71	4.56
K1 9	68.25	234.59	0.04	0.57	0.31	0.20	1.47
K2 1	47.95	47.95	0.65	0.45	0.32	4.11	1.52
K2 2	47.47	95.42	2.45	0.66	0.41	1.12	1.28
K2 3	97.08	192.5	0.54	1.13	1.27	0.50	1.46
K2 4	193.25	385.75	0.44	0.61	0.35	0.12	0.51
K2 5	45.3	431.05	3.48	1.56	1.56	0.34	3.91
K2 6	166.78	597.83	0.49	0.92	0.70	0.43	0.54
K2 7	149.2	747.03	1.13	1.18	0.66	0.56	1.00

period, which is needed to calculate the flux over time. The final five columns are the calculated flux ($\times 10^{-2}$ cm/hr) of the individual seepage meters (one through five) for the given time period. A positive number represents flow into the river or discharge. A negative number refers to surface water recharging the adjacent aquifer.

A comparison of individual seepage meter flux measurements versus others within each sampling period was also made. This comparison was used to help determine if any variations occurred within a given sampling period. Next, river stage (elevation) data was plotted over the same sampling period. A comparison of various river stages to relative values of high flux and low flux was used to determine what effects on bank storage existed. Finally, the changing water elevation data for

the monitoring wells adjacent to the river (Figure 22 and 23) were plotted with the flux and river stage data. This combined to provide information on the surface water (Kalamazoo River) and groundwater (both the upper and lower aquifers) interaction.

Seepage Meter Results

The seepage flux for the first trial ranged from a low of -0.21×10^{-2} cm/hr (indicating that recharge was occurring) to a high of 16.76×10^{-2} cm/hr (showing discharge). The high reading was only for a two-hour time period and equilibrium with the surrounding environment probably had not been established. From prior experience with seepage meters it is known that equilibrium is commonly reached after 24 to 48 hours. Seepage meter #1 showed recharge to the aquifer through the first 43 hours then began to demonstrate discharge for the remainder of the test. This could have been caused by the close proximity to the shoreline or not being properly seated into the bottom sediments. Overall, the seepage meters showed movement of groundwater into the river throughout the trial period, with fluctuations occurring when river stage changed. The second trial period showed less variability than the first trial. This most likely was the result of the meters becoming better seated over time. During this trial the seepage meters constantly demonstrated discharge into the river, with a seepage flux low of 0.12×10^{-2} cm/hr to a high of 4.11×10^{-2} cm/hr.

Based on the average seepage flux of 3.0×10^{-2} cm/hr, it is calculated the discharge of water to the river is 10.34 in/year. Compared to Rheaume (1990),

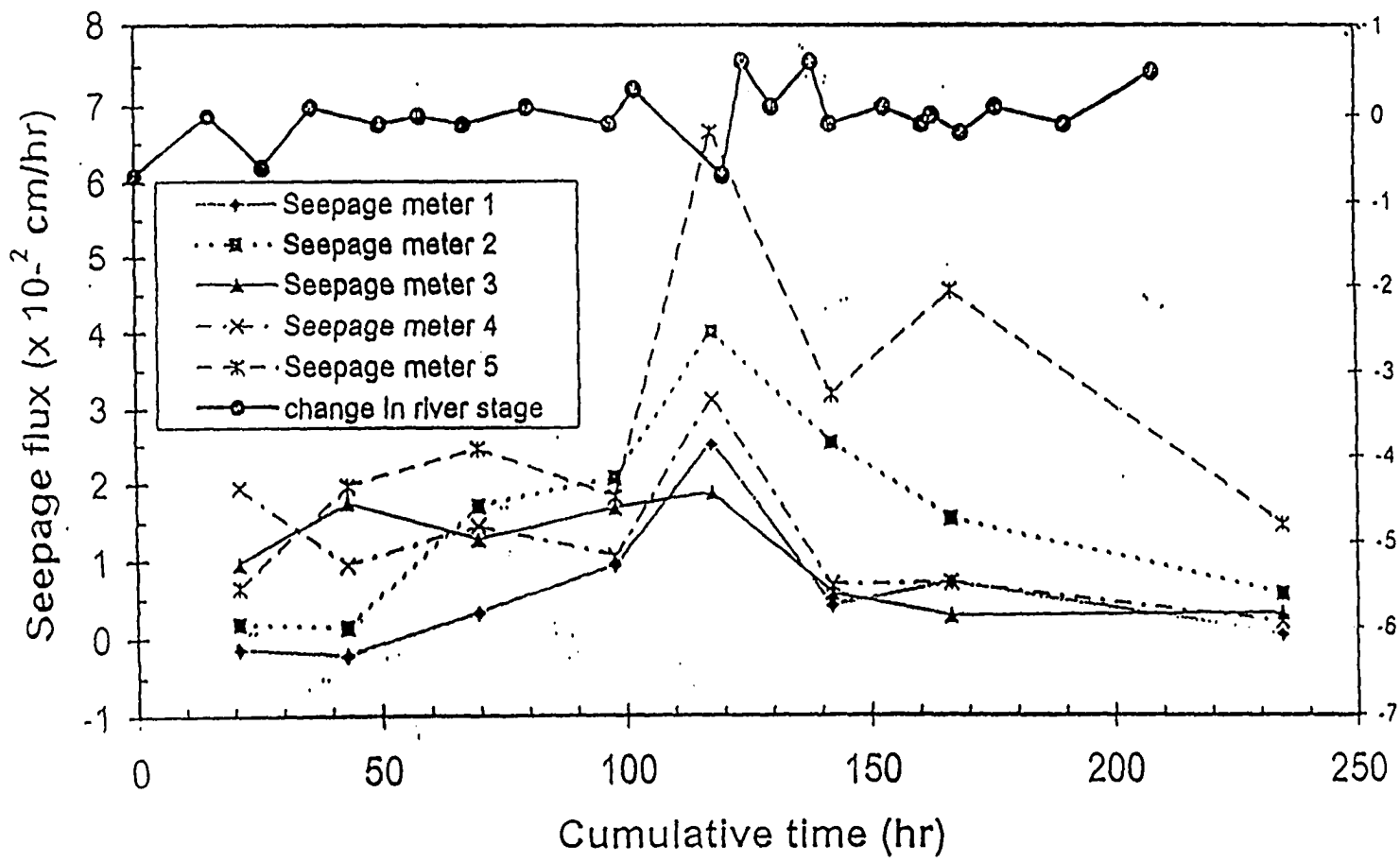


Figure 22. 1994 Seepage Flux Measurements With Kalamazoo River Stage.

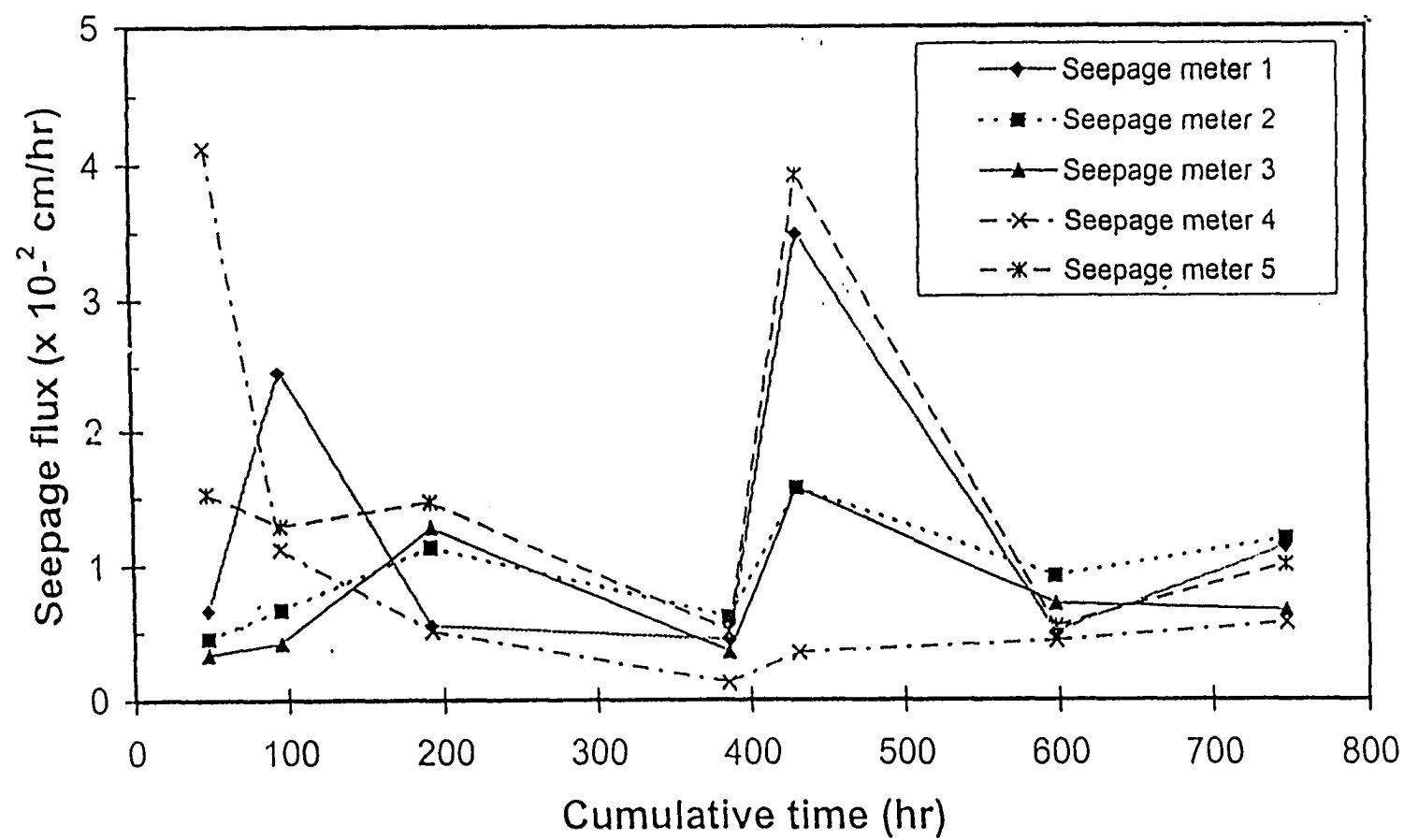


Figure 23. 1995 Seepage Flux Measurements.

through the use of hydrographs of the Comstock, Michigan gauging station the calculated groundwater discharge rates for the Kalamazoo River of 12.1% or 8.79 in/year. This is also comparable to discharge estimates by Allen and others, (1972).

The variability among the flux measurements was probably due to several factors. One being the orientation of the seepage meters with respect to the river/shore (Figure 20). Typically seepage meter #5 being further from shore had a larger flux than meters #1 or #2, closer to shore. Even though the distance between the meters is small, the depth of water ranges from a few centimeters over seepage meter #1 and #2 to almost 1 meter over seepage meter #5. Another possible factor is the pumping from the City of Parchment Wellfield and/or the JRPC. Combined, or by themselves this could have some effect of seepage into and out of the river in the upper aquifer.

The difference in sampling frequency most likely explains the variability in the fluxes. Because the precise optimum sampling frequency for this situation is not known, each of the sample events used a different sampling period. It appears that the optimum sampling time for this site (each site will inevitably be different) is on the order of six to twelve hours. This conclusion was reached because the river fluctuates relatively quickly compared to changes in groundwater levels in the area. A shorter sample period closely related to the river fluctuations might detect short-term changes related to these movements. It is this fluctuation in the river stage and thus the head differences between the river and the adjacent unconfined aquifer that appears to be the major controlling factor in seepage flux variations. As the river

elevation rises the seepage flux decreases and as the river elevation goes down (preceding a storm) the seepage flux increases. Thus, it can be stated that as the river stage increases the discharge to the stream diminishes (but, does not reverse as would be the case in bank storage situation) and when the river stage decreases the discharge to the river by groundwater increases.

CHAPTER VI

HYDROLOGIC AND TRACER MODELING

Chemical Sampling, Inorganic and Stable Isotopes, Tracer Modeling

Hydrologic modeling was used to evaluate the hydraulic interaction of groundwater with the Kalamazoo River. A vertical two-dimensional model was developed for use with Quickflow (Rumbaugh, 1991) to determine surface water-groundwater interaction. Quickflow was also used in conjunction with chemical tracers to model the horizontal flow paths of groundwater and the trajectory of particles from the Kalamazoo River toward the wellfield.

Chemical tracer techniques were employed for two reasons. First, to determine the extent of hydraulic connectivity between the lower aquifer and the river. Second, to determine if chemical species unique to the river could be observed in the lower aquifer and detected in the wellfield. In the tracer technique, chemical species with relatively higher concentrations in the river could be used to directly determine or infer when river water was being drawn into the lower aquifer and could potentially be drawn into the wellfield by pumping. Additionally, concentration gradients of tracers were used to infer preferential flow directions and thus establish if directional mixing from the river and groundwater was occurring.

Inorganic chemical species that were selected for use as tracers were sulfate and chloride because both were at significantly higher concentrations in river water than in groundwater (Allen and others, 1972; Rheaume, 1990). Sulfate concentrations are especially high in the Kalamazoo River, probably due to urban runoff and treatment plant discharge into the river (Allen and others, 1972; Rheaume, 1990). Also, road deicing operations during the winter provide a spiked source of chloride that can be traced through the river-groundwater system.

Stable isotopes of hydrogen and carbon can also be used as tracers in the hydrologic system (Gat and Gonfiantini, 1981). Deuterium/hydrogen ratios in water and $^{13}\text{C}/^{12}\text{C}$ ratios in dissolved inorganic carbon (DIC), i.e., carbonate, bicarbonate, and aqueous carbon dioxide, are proven tracers. In principle, a shift in the stable isotope signature of these constituents in streams can be detected in the groundwater if the stream recharges the groundwater. Thus it is possible that both the hydraulic connectivity and the river's influence on groundwater at the wellfield can be inferred through the use of isotopic tracer techniques. By monitoring both inorganic and stable isotope tracers in the wellfield, the river and groundwater between the two inputs, source/sink and mixing relationships between the river and groundwater can be determined.

Sampling Procedure

Water samples were collected from the Kalamazoo River, the City of Parchment Wellfield, monitoring wells at the site, and two up-gradient residential wells (Figure 5).

Stream water from the Kalamazoo River was collected approximately 4 m (13.1 ft) from the shore on the east side of the river within the study area. Water was collected approximately 25 to 50 cm (10 to 20 in) below the surface. Groundwater samples from monitoring wells (2 inch diameter wells with 2.5 foot, 10 slot screens) were collected after purging. Purging removed stagnant water from the well bore prior to obtaining representative water samples from the formation. At least five well volumes of water were removed from high yield wells prior to sampling using a pumping rate of 2.5 liter/minute. For wells that had low yields, all the water in the well bore was removed, the wells were allowed to recover, and the process was repeated prior to sample collection.

In moving the pump from one sampling location to another, the electric submersible pump was cleaned by immersing it in a bucket of deionized water and recirculating the contents of the pump and tubing for at least one minute. The process was repeated in another bucket of deionized water to ensure proper rinse. Purge pumping prior to sample collection should remove any deionized water remaining in the pump system after rinsing.

Samples for inorganic chemical parameters were collected in polyethylene bottles, stored in ice at 4°C and analyzed within 8-16 hours. Water samples for stable

isotopes of hydrogen were collected in 20 ml scintillation vials which were tightly closed until analysis. Water for dissolved inorganic carbon (DIC) determination were collected in pre-evacuated septum tubes containing a magnetic stir bar and phosphoric acid (Atekwana and Krishnamurthy, 1997).

Sampling Analysis and Results

Samples collected for inorganic chemical species were removed from the ice chest and brought to approximately 20°C. Alkalinity, chloride and hardness were measured by titrimetric techniques. Silica, sulfate, iron, nitrates, and ammonia were measured by colorimetric techniques (HACH, 1992). Potassium and sodium were determined by inductively coupled plasma emission technique (ICP) and total organic carbon (TOC) was measured by dry combustion after inorganic carbon was removed by the Institute for Water Sciences Water Quality Lab. Specific conductance, total dissolved solids (TDS), dissolved oxygen (DO), temperature and pH were measured in the field using portable meters which were calibrated prior to use.

The result of the chemical analyses conducted on 9/10/95, 4/3/96, and 1/23/97 are shown in Table 11. Analysis for September 10, 1995 show specific conductances ranging from a high of 940 ($\mu\text{S}/\text{cm}$) in C-Deep to a low of 440 ($\mu\text{S}/\text{cm}$) in C-Shallow. The chloride values ranged from a high of 56.8 mg/l in the river to a low of 4.8 mg/l in C-Deep, with the city wellfield measuring 16 mg/l. Nitrate levels were non-detectable in all samples except for the city wellfield, which registered 0.5 mg/l.

Table 11

General Chemistry Data

Sample ID	River	C-Shallow	C-Deep	B-Deep	City
9/10/95					
pH Field	7.89	7.32	7.17	7.08	7.58
Conductance ($\mu\text{S}/\text{cm}$)	770	440	940	800	660
Temp ($^{\circ}\text{C}$)	24.4	17.6	22.3	15.9	25.3
TDS	254.1	145.2	310.2	264	217
DO (mg/l)	7.7	11.3	14.4	17.9	*
Total Hardness	27.6	18.9	41.9	34.1	28.7
Calcium Hardness	17.9	12	26.4	22.5	18.1
Magnesium Hardness	9.7	6.9	15.5	11.6	10.6
Chloride (mg/l)	56.8	5.4	4.8	16.1	16
Alkalinity (mg/l CaCO_3)	202	162	226	287	221
Iron (mg/l)	0.1	1.2	0.9	2.59	0.25
Silica (mg/l)	9	12	16	16	15
Sulfate (mg/l)	70	29	52	55	55
Nitrate (mg/l)	ND	ND	ND	ND	0.5
Ammonia (mg/l)	0.22	0.33	0.6	0.55	0.1
TOC	8.74	4.1	8.05	1.47	2.75
Sodium (mg/l)	38.6	2.68	6.6	7.64	7.9
Potassium (mg/l)	3.38	<1.2	2.78	4.6	3.16
4/3/96					
pH	8.14	7.02	7.13	7.16	7.57
Conductance ($\mu\text{S}/\text{cm}$)	760	650	*	600	575
Sodium (mg/l)	32	28.2	6.04	8.67	8.51
Potassium (mg/l)	1.44	0.924	1.72	1.38	<0.85
1/23/96					
pH Field	7.74	6.6	7.33	6.86	7.33
Conductance ($\mu\text{S}/\text{cm}$)	705	660	485	650	539
Alkalinity (mg/l CaCO_3)	215	243	247	317	232
Chloride (mg/l)	67	34	62	20	18
Sulfate (mg/l)	73	62	80	57	53
Nitrate (mg/l)	1	0.1	0.9	0.9	1.1
Silica (mg/l)	12	11	15	14	15

*Not Measured

ND=non-detect

Results from the April 3, 1996 survey show sodium concentrations in the river of 32 mg/l, with values of 8.67 and 8.51 mg/l in B-Deep and the city wellfield respectively. Analytical results from January 23, 1997 samples showed chloride ranged from 67 to 18 mg/l, sulfate ranging from a high of 73 mg/l to a low of 53 mg/l and alkalinity from a high of 317 mg/l in B-Deep to a low in the river of 215 mg/l.

Water was converted to hydrogen gas for isotopic measurements over hot uranium. A gas evolution technique was used for DIC extraction (Atekwana and Krishnamurthy, 1997). Isotope measurements of both D/H and $^{13}\text{C}/^{12}\text{C}$ were made with a Fison Optima mass spectrometer in the IWS Isotope lab. The isotope ratios are reported in δ notation in per mil where:

$$\delta (\text{‰}) = ((R_{\text{sample}}/R_{\text{standard}}) - 1) \times 10^3$$

R is D/H or $^{13}\text{C}/^{12}\text{C}$. Values are reported relative to SMOW and PDB standards for hydrogen and for carbon respectively. Routine δD , $\delta^{13}\text{C}$ and DIC concentration measurements had an overall precision of 1 ‰, 0.1 ‰ and 1% respectively. The results of the stable isotope measurements are shown in Table 12 and 13.

δD values collectively show no significant difference for these sampling periods. The δD values for Kalamazoo River, the monitoring wells, and samples from the city wellfield are similar. From these isotopic values, it appears a river/groundwater relation is not evident. The lack of difference in the δD isotopic ratio could be attributed to homogenization of the seasonal δD signal observed in precipitation in the Kalamazoo area (Machavaram and Krishnamurthy, 1994). The

attenuation of the precipitation signal could occur through infiltration and rapid mixing with a large isotopically homogenized groundwater reservoir. In addition, the lack of difference could be explained by a dominance of groundwater component in the river. The values obtained in this study are consistent with the annual average value in precipitation (Machavaram and Krishnamurthy, 1994) and to values measured for several groundwater samples in the Kalamazoo area (Atekwana and Krishnamurthy unpublished data). Mixing of river water with groundwater, while possible, cannot be demonstrated by these small shifts in hydrogen isotope values.

Table 12
Collected δD Data

Sample ID	δD ‰ (12/29/94)	δD ‰ (1/9/95)
B-Deep	-60	-61
C-Deep	-53	-61
C-Shallow	-55	-58
River	-58	-60
City	-61	-65
GW #1	-	-61

DIC concentrations ranged from a high of 96.8 mg C/l in C-Shallow to a low of 47.4 mg C/l in the river. During the January 23, 1997 sampling, DIC concentrations ranged from a high of 77.9 mg C/l in the shallow aquifer (CH3) to a low of 43.5 mg C/l in the deeper aquifer (C-Deep). During the two sampling periods, the $\delta^{13}C$ (DIC) ranged from -22 to -25 and -10 to -15 ‰ for 4/5/96 and 1/23/97 surveys respectively.

Table 13
DIC and $\delta^{13}\text{C}$ Data

Sample ID	DIC (mg C/l) 4/5/96	$\delta^{13}\text{C}$ (‰) 4/5/96	DIC (mg C/l) 1/23/97	$\delta^{13}\text{C}$ (‰) 1/23/97
River	50.2	-25.2	49.6	-11.4
C-Shallow	96.8	-22.7	68.5	-14.6
C-Deep	57	-25.2	43.5	-13.5
B-Deep	73.9	-22.8	70.7	-13.7
City	53.5	-25.4	72	-12.4
CHS 1	-	-	55.1	-10.4
CHS 2	-	-	47.4	-13.8
CHS 3	-	-	77.9	-10.5
GW #1	-	-	53	-13.1
GW #2	-	-	62.8	-12.3

Modeling

In order to develop the hypothesis that the city wellfield and the Kalamazoo River are interacting with each other, a groundwater model was designed for the site. This model evaluated flow into the wellfield from three possible sources. These sources included regional groundwater up-gradient from the wellfield, the Kalamazoo River and a combination of the two. The hydrology of the wellfield was assessed through the use of two-dimensional models. Possible flow paths in and around the wellfield and river were evaluated and particle tracing used to interpret the chemical and isotopic data.

The computer program Quickflow was used to track the horizontal flow paths of the groundwater at the site. Quickflow is an analytical model that simulates two-dimensional groundwater flow. The principle of superposition was used to evaluate a

pumping well or river in a uniform regional flow field from multiple analytical functions. The model depicts the flow field using streamlines, particle traces, and contours of hydraulic head. The streamlines are computed semi-analytically to illustrate groundwater flow directions. Numerical particle-tracking techniques were used to compute travel times and flow directions.

In the first step of modeling, the hydrologic flow conditions for the wellfield were analyzed. Data for the aquifer parameters needed as input into the model were obtained from previous aquifer performance tests (Jones, 1992). Geological and recharge information obtained as part of the current study was also used as input for the model. In addition, regional groundwater flow direction (Jones, 1986) and water budget recharge rates were utilized. Hydraulic gradient was estimated from the head distribution.

The following input parameters were used for the hydrologic model simulation: (a) aquifer hydraulic conductivity: 407 ft/day, (b) aquifer top elevation: 745 ft, (c) aquifer bottom elevation: 645 ft, (d) hydraulic gradient: 0.0001 at 110 degree azimuth, (e) uniform recharge rate: 0.00068 ft/day, (f) reference head: 744 ft located at the river, (g) aquifer storage coefficient: 1.8×10^{-4} , (h) porosity: 0.28, and (i) time of simulation 365 days

Other analytical elements used for the model included a pumping well, pumping at a rate of 66,850 gpd (simulating the wellfield pumping well), and a linesink representing the Kalamazoo River. The head distributions and streamlines

for this simulation are shown in Figure 24. The streamlines show the flow of regional groundwater and river water towards the wellfield.

Particle tracing of possible paths of water in and around the wellfield and the river were evaluated. Two scenarios were created to aid in the interpretation of the chemical tracers. The first source placed the particles in the flow path of the streamlines between the river and the wellfield in the southern portion of the site. The second source placed the particles parallel to the river at the site.

The results of the particle tracing are shown in Figure 24. The results show that particle tracks introduced in the flow regime between the wellfield and the river were consistent with the expected trajectory of the regional groundwater flow. Thus the chemical species observed in water samples at the study site should be consistent with the regional evolution of groundwater chemistry, and any perturbations observed. Because the trajectory for particles from the river are drawn into the pumping well indicating possible mixing of river water and groundwater at the location of monitoring well C-Deep and the wellfield, it is possible for river water to enter the aquifer and migrate towards the pumping well. If this scenario is possible, the chemistry of the groundwater at the site should reflect the influence of river water.

The particle traces were compared to chloride, sulfate and carbon isotope results (Figure 25). In these models of the study area, the river is shown on the west and the wellfield to the east. The monitoring wells are shown in their relative positions with respect to the river and city wellfield.

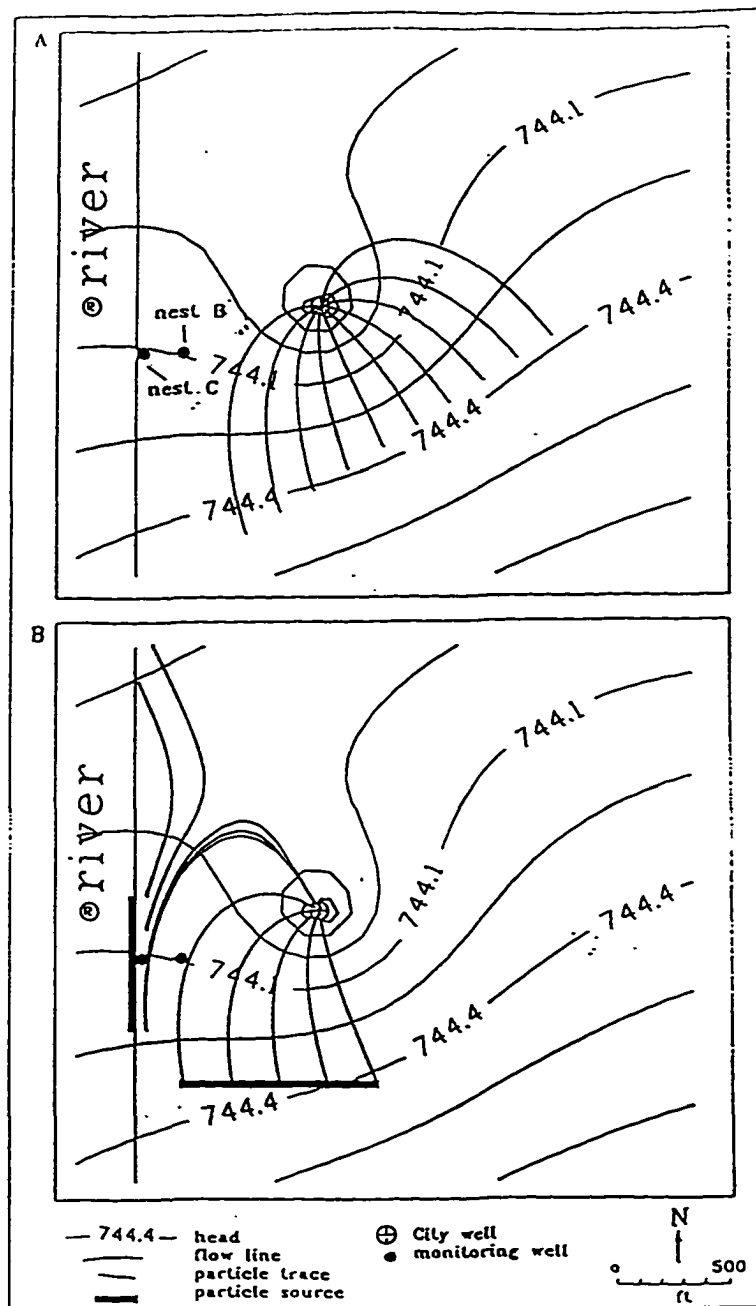


Figure 24. Quickflow Flow Model of Particle Traces and Groundwater Flow Paths.

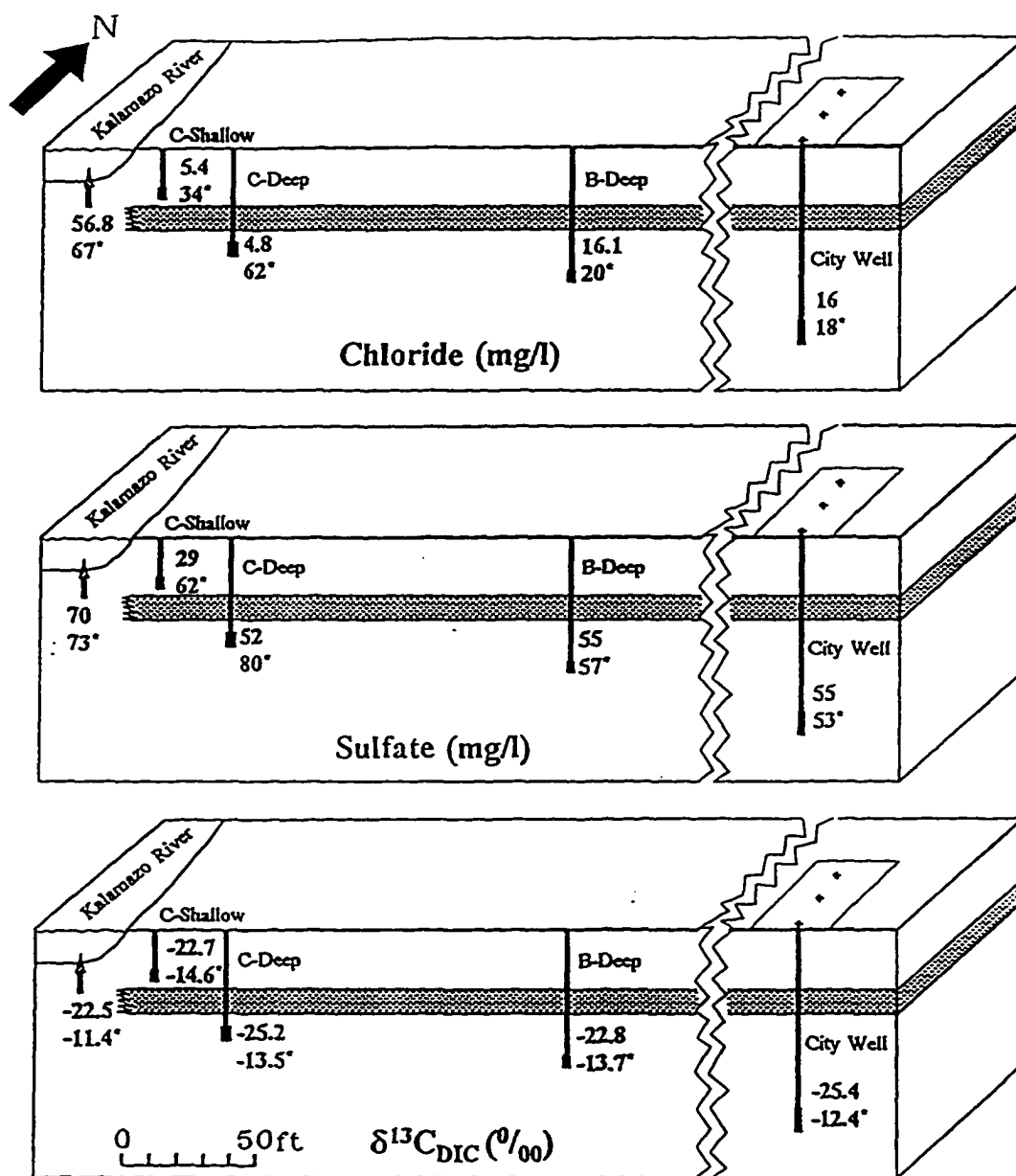


Figure 25. Distribution of Inorganic Tracer Species.

Modeling of basic chemical data in natural unpolluted aquifers is based on the expected evolutionary sequence from areas of recharge to areas of discharge. As groundwater evolves, changes in concentrations of chemical species are observed along the flow path (Freeze and Cherry, 1979). Thus in the study area, disruption of this chemical evolutionary direction can be indicative of alterations in the natural flow paths. At the study site, the regional/local groundwater flow is towards the Kalamazoo River, which serves as a discharge point for groundwater. Thus, the most chemically evolved water within the study area should be groundwater discharging into the river. Precipitation events are expected to have greater influence on the hydrogeochemistry of the river than the aquifer. This influence can result in dilution of chemical species input from baseflow or additional chemical species that are unique to surface runoff from up gradient sources. Such species include chlorides from road deicing operations during the winter months.

Tracer Results

In evaluating chemical tracers the source is important. In the present case, possible sources include groundwater and the Kalamazoo River. Assessing inputs of transient tracer (e.g. chloride from runoff) into the study area along with their temporal distributions are important. During the winter months the application of salt for road maintenance results in elevated chloride levels in the river. These chloride levels, which occur during periods of snow melt, can serve as tracers where streams recharge the groundwater. In these instances, a chloride concentration gradient may

be observed in the groundwater system if the river recharges the groundwater. Results of a chloride survey at the study site (9/10/95) show the lowest chloride concentration in well C-Deep (4.8 mg/l) and higher readings in well B-Deep and the city wellfield (18 mg/l) (Figure 24). The measured chloride concentration for the river sample was 56.8 mg/l. Although the chloride levels in the river were higher than the groundwater in the study area, there appears to be no evidence of river-groundwater interaction based on the observed chloride gradient. However, a subsequent survey conducted on 1/23/97, two days after a snow melt event, high chloride concentration were observed in C-Deep (62 mg/l). The chloride concentration in the river was 67 mg/l. Because the source of the high chlorides is attributed to the river, high chloride levels in C-Deep below the upper clay-rich layer is indicative of river-groundwater recharge. The observed chloride gradient from the river toward the wellfield is consistent with the particle tracer paths from the hydrologic model for the site. In addition, during this period, the river stage was high and thus augmented the hydraulic head toward the wellfield due to the city's pumping. The lack of a similarly observed increase in the chloride concentration in C-Deep during the 9/10/95 survey can be attributed to the transient nature of the river-groundwater interaction at this site. During this period, the river stage is lower and thus it is conceivable that the hydraulic gradient between the river and the wellfield is lower. In this instance, local/regional groundwater dominates the supply to the wellfield. Other chemical data for the same survey period are consistent with this interpretation. From Table 11, specific conductance, alkalinity, and TOC showed

more dilute concentrations in the wellfield water than the down gradient well B-Deep. Dilution of the chemical species is suggestive of river inputs to groundwater and thus mixing along a river groundwater flow path. The sulfate data (Figure 25) showed trends that are similar to those of river-groundwater recharge demonstrated by the chloride data. Water samples for the 1/23/97 survey exhibited high sulfate concentration in the river, 73 mg/l. Well C-Deep shows higher concentrations from the first sampling to the second, 52 to 80 mg/l. This along with the increased concentrations in C-Shallow, 29 to 62 mg/l demonstrates the influence of the river recharge to the groundwater system. However, this shift in concentrations is not present in B-Deep and the city wellfield (53 to 57 mg/l), which remained consistent throughout both sampling periods. In addition, specific conductance and alkalinity measurements are consistent with this interpretation.

The use of the carbon isotopic tracer is based on the temporal evolution of carbon in the groundwater system. Carbon isotopic values for isotopically fully evolved natural unpolluted groundwater in the Kalamazoo area is about -10 ± 1 (‰) (Atekwana and Krishnamurthy, 1997). Streams in the region have $\delta^{13}\text{C}$ values in this range. These streams may be considered to be recharged by base flow consisting of isotopically fully evolved groundwater during 100% baseflow conditions. For the study site, groundwater near a stream discharge point may be expected to have carbon isotopic values similar to that of isotopically fully evolved groundwater. Carbon isotope surveys show that the water in the study site is not fully evolved isotopically. The carbon isotope distribution for sampling locations is shown in Table 13. The

Kalamazoo River flood plain in the study area contains wetland vegetation. Biogenic carbon dioxide generated in this wetland can influence the carbon isotope values in the groundwater. Because the upper aquifer is separated from the lower aquifer by a clay layer, wells C-Deep and B-Deep are not expected to be influenced by biogenic CO₂ from the upper aquifer. However, carbon isotope data shows the groundwater in both the shallow and deeper aquifer is influenced by the production of CO₂ from the riverine wetland. This influence appears to be indicative of discontinuity in the separating clay layer. It is noteworthy to mention that temporal shifts in the carbon isotope signature is reflected in the upper and lower aquifers which is consistent with discontinuity in the upper confining clay layer. In addition, since the carbon isotope value of the pumping well is not significantly different from those of the groundwater C-Deep and B-Deep, it is possible to infer the mixing of riverine wetland derived water with normal evolving groundwater supplied upgradient from the pumping well.

In the interpretation of the chemical tracer models, the actual magnitude of the chemical tracer signal in the river was not assessed. It is possible that the river water sampled during the survey did not represent the actual water that induced the chemical gradients observed in the groundwater sampled at the site. In addition, the duration of the chemical signal in the groundwater system was not assessed.

Summary and Conclusions

A hydrologic model of the site shows that a two-dimensional model can adequately describe flow induced from the Kalamazoo River into the groundwater

system by pumping in the City of Parchment Wellfield. Particle tracking paths provided a basis for the interpretation of chemical tracer results. The chemical tracers demonstrate that the river and the groundwater system at the study site are hydraulically connected. Perturbations in chemical parameters in the river cause increases in the concentration of these chemical species in the groundwater system. Although the data does not show any impact on water quality in the wellfield, it does show that pumping in the wellfield does cause shifts in the hydraulic gradient in the aquifer. The pumping induced gradient coupled with high stream stage appears capable of inducing river water to flow towards the wellfield.

CHAPTER VII

CONCLUSION

Under normal river flow, the regional aquifers discharge to the Kalamazoo River (Allen and others, 1972; Rheume, 1990). However, this study shows that as the river stage rises, recharge from the river to the aquifer may occur. It is during this time of high river stage that a hydraulic gradient toward the wellfield is evident. Further, it is seen that pumping from the City of Parchment wellfield augments this gradient. This increase in riverstage and increase in the hydraulic gradient is important for the protection of the wellfield from surface/riverborne contamination from the Kalamazoo River.

Conversely, during low flow conditions combined with low wellfield demand, river interaction with groundwater is minimal. In the lower production aquifer the aquifer performance and chemical tracer models demonstrate the hydraulic communication with the river.

In the past, several aquifer performance tests were run. As with the current study, the results were conflicting. The 1950 aquifer test (Williams & Works, 1980) concluded that the producing aquifer had a high transmissivity and recharge from the Kalamazoo River was good. On the other hand, the 1991 aquifer test run by Peerless-Midwest at the City of Parchment Wellfield suggested that a clay-rich layer confines the lower aquifer (Jones, 1992). The study further concluded that the clay layer

present at the site is continuous throughout the area. The conflicting findings of these studies come from the nature of the tests, lack of control wells and interpretation of the data.

Through the use of geophysical mapping, the extent of the clay-rich layer was mapped between 1995 and 1997. GPR and resistivity surveys indicate that the clay-rich layer is not of uniform thickness nor is it continuous. From the GPR surveys, buried river channels were identified which appear to persist throughout the area, and provide a means of interconnectivity between the upper and lower aquifers.

Seepage meters used to measure the flux across the Kalamazoo River demonstrated constant discharge into the river. It was observed that the river fluctuates relatively quickly compared to changes in groundwater levels. These fluctuations in the river stage and thus the head differences between the river and the adjacent unconfined aquifer appear to be the major controlling factor in seepage flux variations. As the river stage rises the seepage flux decreases and as the river stage decreases (preceding a storm) the seepage flux increases. Thus, as the river stage increases, discharge to the stream diminishes (but, does not reverse as would be the case in bank storage situation) and when the river stage decreases the discharge to the river by groundwater increases.

The hydrologic model for the study site shows hydrologic induced flow due to pumping in the City of Parchment Wellfield. Particle tracking paths combined with geochemical and isotopic data provided the basis for this interpretation. The chemical tracers demonstrate that the river and the groundwater system at the study

site are hydraulically connected. Perturbations in chemical parameters in the river cause increase in the concentration of these chemical species in the groundwater system. Although the data does not show impact to the wellfield, it does show that pumping in the wellfield does cause shifts in the hydraulic gradient in the aquifer and in the distribution of chemical species. The pumping induced gradients coupled with high stream stage appear to induce river water to flow towards the wellfield.

CHAPTER VIII

FUTURE WORK

Several possibilities for future work exist in and around the City of Parchment Wellfield. Establishing a greater density of monitoring points between the wellfield and the Kalamazoo River, along with several permanent upgradient wells would facilitate more detailed study of the sites hydrogeochemistry. It is recommended that a higher frequency of sampling events be done, on the order of daily to weekly monitoring for an extended period of time based on previous results. This will allow for small changes to be documented and trends associated with river fluctuations to be looked at closely. By closely monitoring the chemical changes taking place in both the wellfield and the river, the researcher will be able to better establish the quantitative relationship of the river and wellfield.

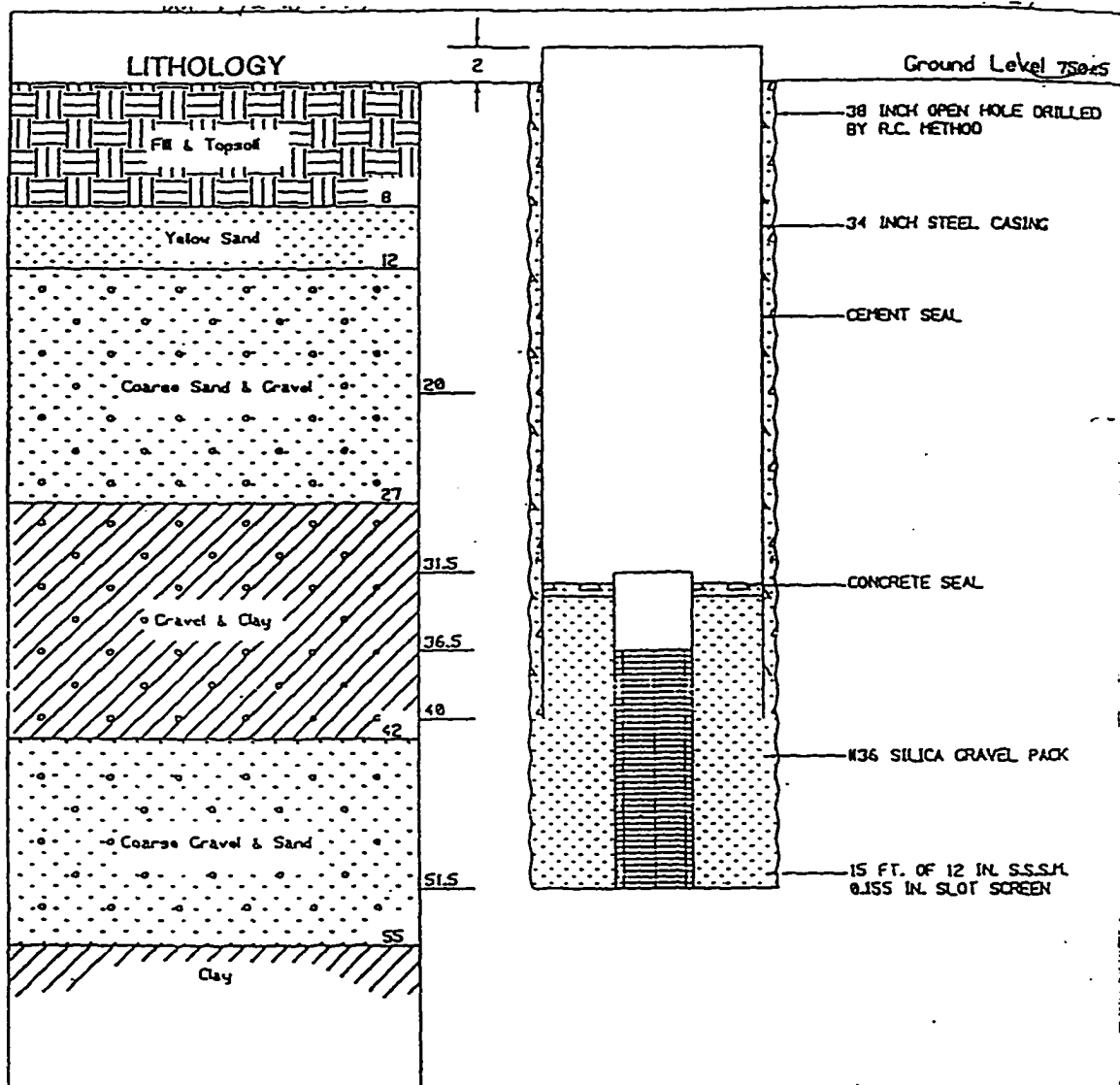
Establishing a monitoring network on the west side of the Kalamazoo River is another important step that needs to be done with any ensuing research on the wellfield. The possibility of recharge coming from the west side of the river has been proposed by the MDEQ. By establishing a monitoring network on the west side of the river, these and other wetlands can be looked at in terms of what they contribute to the river/wellfield system.

Geophysical studies should be performed on the bedrock in the area. This will allow for a better determination of the bottom boundary of the producing aquifer.

Finally, a longer, more closely monitored aquifer test should also be run to develop the exact extent of the area of pumping influence. This would allow for a better recharge model to be developed. The test should run for at least 54 hours with no pumping taking place during the recovery period. This prolonged aquifer stress test would prove whether the wellfield is pulling water from under the river or from the river itself.

Appendix A

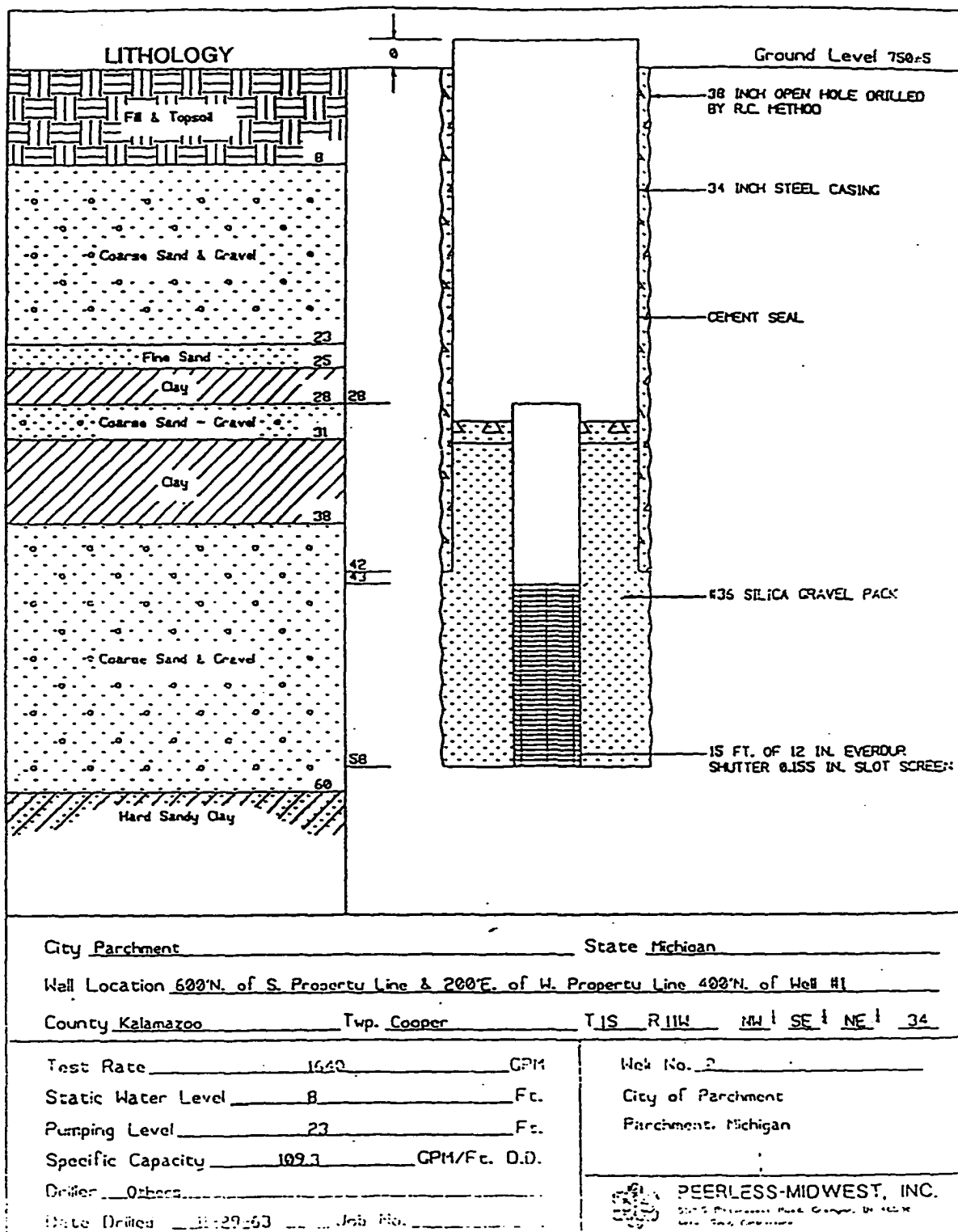
Well Logs

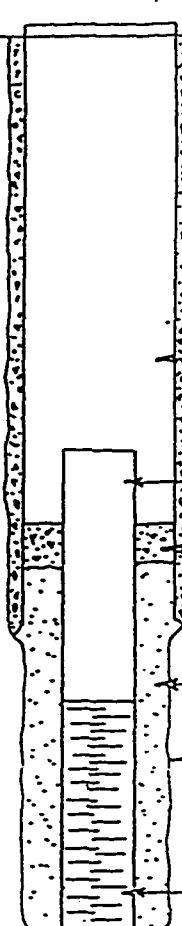


City <u>Parchment</u> State <u>Michigan</u>	
Well Location <u>200' N. of S. Property Line 200' E. of W. Property Line 400' S. of Well #2</u>	
County <u>Kalamazoo</u>	Twp. <u>Cooper</u> T. <u>1S</u> R. <u>11W</u> NW <u>1</u> SE <u>1</u> NE <u>1</u> <u>34</u>
Test Rate <u>836</u> GPM	Well No. <u>1</u>
Static Water Level <u>7</u> Ft.	City of <u>Parchment</u>
Pumping Level <u>34</u> Ft.	Parchment, <u>Michigan</u>
Specific Capacity <u>29.8</u> GPM/Ft. D.D.	
Driller <u>Others</u>	
Date <u>12.6.00</u> Job No. <u></u>	



PEERLESS-MIDWEST, INC.
 5155 Westwood Road, Grand Rapids, MI 49508
 (616) 941-1111



WELL LOG		GROUND LEVEL							
<div style="text-align: center; margin-bottom: 5px;">FILL</div> <div style="text-align: center; margin-bottom: 5px;">CLAY</div> <div style="text-align: center; margin-bottom: 5px;">COARSE SAND AND GRAVEL</div> <div style="text-align: center; margin-bottom: 5px;">CLAY</div> <div style="text-align: center; margin-bottom: 5px;">COARSE SAND AND GRAVEL</div> <div style="text-align: center; margin-bottom: 5px;">CLAY</div>	<div style="text-align: center; margin-bottom: 5px;">7'</div> <div style="text-align: center; margin-bottom: 5px;">9'</div> <div style="text-align: center; margin-bottom: 5px;">22'</div> <div style="text-align: center; margin-bottom: 5px;">32'</div> <div style="text-align: center; margin-bottom: 5px;">58'</div>	<div style="text-align: center; margin-bottom: 5px;">27'</div> <div style="text-align: center; margin-bottom: 5px;">32'</div> <div style="text-align: center; margin-bottom: 5px;">35'</div> <div style="text-align: center; margin-bottom: 5px;">38'</div> <div style="text-align: center; margin-bottom: 5px;">43'</div> <div style="text-align: center; margin-bottom: 5px;">58'</div>	 <p>42" open hole drilled by R. C. method to 38, ft.</p> <p>15#/gal. neat cement seal between 34" casing and 42" open hole.</p> <p>34" casing from 2' above grade to 38' below</p> <p>16' of 12" screen blank from 27' to 43'.</p> <p>3' cement seal on top of gravel pack from 32' to 35'.</p> <p>#612 silica gravel from 35' to 58'. 12 yards.</p> <p>34" open hole drilled by R. C. method from 38' to 58'.</p> <p>15' of Polygon Fiberglass W.W. screen with .050 slot set 43' to 58'.</p>						
<p>FIELD ANALYSIS OF WATER AFTER PUMPING 1000 GPM FOR 24 HOURS</p> <table style="width: 100%; border: none;"> <tr> <td style="width: 40%;">HARDNESS</td> <td>14.5 GPG</td> </tr> <tr> <td>IRON</td> <td>0.48 PPM - Some Crenothrix</td> </tr> <tr> <td>PH</td> <td>7.5</td> </tr> </table>				HARDNESS	14.5 GPG	IRON	0.48 PPM - Some Crenothrix	PH	7.5
HARDNESS	14.5 GPG								
IRON	0.48 PPM - Some Crenothrix								
PH	7.5								
<p>City <u>Parchment</u> State <u>Michigan</u></p> <p>Location <u>950' W. of 20th Street and 1660' N. of EW 1/4 Line Sec. 34</u></p> <p>County <u>Kalamazoo</u> Twp. <u>Cooper</u> Section <u>34 - T 15, R 11 W</u></p> <p style="margin-left: 40px;"><u>400' N. of Well #2</u></p>									
<p>Test Capacity <u>1000</u> GPM Static Water Level <u>8</u> ft. Pumping Level <u>14</u> ft.</p> <p>Specific Capacity <u>167</u> GPM/Ft. D.D.</p> <p>Date Drilled <u>April 11, 1973</u></p> <p>Driller: <u>Paul Wyatt</u></p> <p>Job No. <u>14</u></p>		<p>Well No. <u>3</u></p> <p>CITY OF PARCHMENT</p> <p>PARCHMENT, MICHIGAN</p> <p>PEERLESS MIDWEST, INC. Grand Rapids, Michigan</p>							

LITTON-NORTHERN COMPANY

மதுரைக்குப் போய்

435

PERMANENT

File No. 45027

WELL LOG No. 60E CITY Partridge County Kingman, Kan

Owner City of Parchment Township Cooper

Section SE 1/4 34

பெருகாப்பு:௦௩

Sic: Michigan

From Land Description _____ ft. East and _____ ft. North of SW Corner of S

From Street or Road 475' S. of Center Line of 20th St. & 200' N. of South Prop
Approx 562' S. of E. 1/4 line - 50' W. of T. 60.

[illegible]

שלום רב

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SECRET

2. 325

255425

Lab No. ML5027

WELL LOC No. 600 CTR: Parchment

Country: Malaysia

Owner City of Parchment

Trevithick Cooper

Series ≡ 14 34

LOCES:06

State Michigan

From Land Description _____ ft. East and _____ ft. North of SW Corner of Se

From Street or Road 825' W. of center line of 20th St. and 200' W. of S. Prop.
approx. 562' S. of EW 1/4 line - 600' W of T160A

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二、研究设计

ipb No. 415027

WELL LOG No. 50 cm Parchment

Case: Kalzoo

Owner City of Puchezant

Township Cooper

Section SE 1/4 22

State Michigan

Loction

State Michigan

From Land Description _____ ft. East and _____ ft. North of SW Corner of S

From Street or Road 1200' E. of Center line of 20th St. - 25' E. of Consumers R.

N. of U - LOC: U. of S. Prop. line - 350' S. of E/L line

— 2 — inch diameter hole drilled by ☐ Cable Tool ☐ Rotary Drilling

Fig 1c: a hole

Page Sixteen

12-10-1950

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11. 12. 13.

2. ELEMENT

Lab. No. M15027

3121200

WELL LOG No. 20 CITY Frederick

Subject: _____

Owner City of Parchment

Township Cooper

Site #2 - School Property

উদ্দেশ্য

State Michigan

Location

From Land Description _____ ft. East and _____ ft. North of SW Corner of Sec

From Street or Road 100' N. of 5th St 60' - 620' N. of Parchment St.

875' W. of Extension of Clarnen St.

2 inch diameter hole drilled by C-Case Tool & Supply Co. Inc.

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256 257 258

Figure 1. 1999-2000

44. ———, 1990, *Journal of the Philosophy of Education Society of Great Britain*, 20, 1, 101–112.

1. 2. 3. 4. 5. 6. 7. 8. 9. 10. 11. 12. 13. 14. 15. 16. 17. 18. 19. 20. 21. 22. 23. 24. 25. 26. 27. 28. 29. 30. 31. 32. 33. 34. 35. 36. 37. 38. 39. 40. 41. 42. 43. 44. 45. 46. 47. 48. 49. 50. 51. 52. 53. 54. 55. 56. 57. 58. 59. 60. 61. 62. 63. 64. 65. 66. 67. 68. 69. 70. 71. 72. 73. 74. 75. 76. 77. 78. 79. 80. 81. 82. 83. 84. 85. 86. 87. 88. 89. 90. 91. 92. 93. 94. 95. 96. 97. 98. 99. 100. 101. 102. 103. 104. 105. 106. 107. 108. 109. 110. 111. 112. 113. 114. 115. 116. 117. 118. 119. 120. 121. 122. 123. 124. 125. 126. 127. 128. 129. 130. 131. 132. 133. 134. 135. 136. 137. 138. 139. 140. 141. 142. 143. 144. 145. 146. 147. 148. 149. 150. 151. 152. 153. 154. 155. 156. 157. 158. 159. 160. 161. 162. 163. 164. 165. 166. 167. 168. 169. 170. 171. 172. 173. 174. 175. 176. 177. 178. 179. 180. 181. 182. 183. 184. 185. 186. 187. 188. 189. 190. 191. 192. 193. 194. 195. 196. 197. 198. 199. 200. 201. 202. 203. 204. 205. 206. 207. 208. 209. 210. 211. 212. 213. 214. 215. 216. 217. 218. 219. 220. 221. 222. 223. 224. 225. 226. 227. 228. 229. 230. 231. 232. 233. 234. 235. 236. 237. 238. 239. 240. 241. 242. 243. 244. 245. 246. 247. 248. 249. 250. 251. 252. 253. 254. 255. 256. 257. 258. 259. 260. 261. 262. 263. 264. 265. 266. 267. 268. 269. 270. 271. 272. 273. 274. 275. 276. 277. 278. 279. 280. 281. 282. 283. 284. 285. 286. 287. 288. 289. 290. 291. 292. 293. 294. 295. 296. 297. 298. 299. 300. 301. 302. 303. 304. 305. 306. 307. 308. 309. 310. 311. 312. 313. 314. 315. 316. 317. 318. 319. 320. 321. 322. 323. 324. 325. 326. 327. 328. 329. 330. 331. 332. 333. 334. 335. 336. 337. 338. 339. 340. 341. 342. 343. 344. 345. 346. 347. 348. 349. 350. 351. 352. 353. 354. 355. 356. 357. 358. 359. 360. 361. 362. 363. 364. 365. 366. 367. 368. 369. 370. 371. 372. 373. 374. 375. 376. 377. 378. 379. 380. 381. 382. 383. 384. 385. 386. 387. 388. 389. 390. 391. 392. 393. 394. 395. 396. 397. 398. 399. 400. 401. 402. 403. 404. 405. 406. 407. 408. 409. 410. 411. 412. 413. 414. 415. 416. 417. 418. 419. 420. 421. 422. 423. 424. 425. 426. 427. 428. 429. 430. 431. 432. 433. 434. 435. 436. 437. 438. 439. 440. 441. 442. 443. 444. 445. 446. 447. 448. 449. 450. 451. 452. 453. 454. 455. 456. 457. 458. 459. 460. 461. 462. 463. 464. 465. 466. 467. 468. 469. 470. 471. 472. 473. 474. 475. 476. 477. 478. 479. 480. 481. 482. 483. 484. 485. 486. 487. 488. 489. 490. 491. 492. 493. 494. 495. 496. 497. 498. 499. 500. 501. 502. 503. 504. 505. 506. 507. 508. 509. 510. 511. 512. 513. 514. 515. 516. 517. 518. 519. 520. 521. 522. 523. 524. 525. 526. 527. 528. 529. 530. 531. 532. 533. 534. 535. 536. 537. 538. 539. 540. 541. 542. 543. 544. 545. 546. 547. 548. 549. 550. 551. 552. 553. 554. 555. 556. 557. 558. 559. 560. 561. 562. 563. 564. 565. 566. 567. 568. 569. 570. 571. 572. 573. 574. 575. 576. 577. 578. 579. 580. 581. 582. 583. 584. 585. 586. 587. 588. 589. 590. 591. 592. 593. 594. 595. 596. 597. 598. 599. 600. 601. 602. 603. 604. 605. 606. 607. 608. 609. 610. 611. 612. 613. 614. 615. 616. 617. 618. 619. 620. 621. 622. 623. 624. 625. 626. 627. 628. 629. 630. 631. 632. 633. 634. 635. 636. 637. 638. 639. 640. 641. 642. 643. 644. 645. 646. 647. 648. 649. 650. 651. 652. 653. 654. 655. 656. 657. 658. 659. 660. 661. 662. 663. 664. 665. 666. 667. 668. 669. 670. 671. 672. 673. 674. 675. 676. 677. 678. 679. 680. 681. 682. 683. 684. 685. 686. 687. 688. 689. 690. 691. 692. 693. 694. 695. 696. 697. 698. 699. 700. 701. 702. 703. 704. 705. 706. 707. 708. 709. 710. 711. 712. 713. 714. 715. 716. 717. 718. 719. 720. 721. 722. 723. 724. 725. 726. 727. 728. 729. 730. 731. 732. 733. 734. 735. 736. 737. 738. 739. 740. 741. 742. 743. 744. 745. 746. 747. 748. 749. 750. 751. 752. 753. 754. 755. 756. 757. 758. 759. 760. 761. 762. 763. 764. 765. 766. 767. 768. 769. 770. 771. 772. 773. 774. 775. 776. 777. 778. 779. 780. 781. 782. 783. 784. 785. 786. 787. 788. 789. 790. 791. 792. 793. 794. 795. 796. 797. 798. 799. 800. 801. 802. 803. 804. 805. 806. 807. 808. 809. 810. 811. 812. 813. 814. 815. 816. 817. 818. 819. 820. 821. 822. 823. 824. 825. 826. 827. 828. 829. 830. 831. 832. 833. 834. 835. 836. 837. 838. 839. 840. 84

WATER WELL AND PUMP RECORD

PERMIT NUMBER

| | | | | | | |
|--|---------------------------------|--|--|-----------------------------|-------------|-----------------|
| 1. LOCATION OF WELL | | Fraction | | Section Number | Town Number | Range Number |
| County <u>Kalamazoo</u> | | Township Name <u>Cooper</u> | | <u>SW 1/4 SW 1/4 SW 1/4</u> | <u>26</u> | <u>1 N 15 E</u> |
| Distance And Direction From Road Intersection
<u>1 mi. W of Riverview</u>
<u>80' So of Traverse Ave</u> | | | | | | |
| Street Address & City of Well Location
Locate with "X" in Section Below | | | | | | |
| Sketch Map: | | 3. OWNER OF WELL
<u>Hand Riggs Tracts</u>
Address <u>2048 Traverse Ave</u>
Address Same As Well Location? <input type="checkbox"/> Yes <input type="checkbox"/> No | | | | |
| 4. WELL DEPTH: <u>182</u> ft. | | Date Completed <u>1-12-88</u>
<input type="checkbox"/> New Well <input type="checkbox"/> Replacement Well | | | | |
| 5. <input type="checkbox"/> Cable tool <input checked="" type="checkbox"/> Rotary <input type="checkbox"/> Driven <input type="checkbox"/> Dug
<input type="checkbox"/> Hollow rod <input type="checkbox"/> Auger <input type="checkbox"/> Jetted <input type="checkbox"/> | | 6. USE: <input checked="" type="checkbox"/> Domestic <input type="checkbox"/> Type I Public <input type="checkbox"/> Type III Public
<input type="checkbox"/> Irrigation <input type="checkbox"/> Type II Public <input type="checkbox"/> Heat pump
<input type="checkbox"/> Test Well <input type="checkbox"/> Type IV Public <input type="checkbox"/> | | | | |
| 7. CASING: <input checked="" type="checkbox"/> Steel <input type="checkbox"/> Threaded <input type="checkbox"/> Welded
Diameter <u>5</u> in. to <u>131</u> ft. depth
<input type="checkbox"/> Plastic <input type="checkbox"/> Height: Above/Below Surface <u>3</u> ft.
Height <u>182</u> ft. to <u>177</u> ft. depth
Ground Drill Hole Diameter <u>8</u> in. to <u>177</u> ft. depth
Dive Shoe <input type="checkbox"/> Yes <input checked="" type="checkbox"/> No
Packer <input type="checkbox"/> Yes <input checked="" type="checkbox"/> No | | 8. SCREEN: <input type="checkbox"/> Not installed
Type <u>Plastic</u> Diameter <u>8</u> in.
Slot/Gauge <u>3/16</u> Length <u>2</u> ft.
Set between <u>119</u> ft. and <u>122</u> ft.
FITTINGS: <input type="checkbox"/> K-Packer <input type="checkbox"/> Lead Packer <input type="checkbox"/> Bremer Check
<input type="checkbox"/> Blank above screen <input type="checkbox"/> Other | | | | |
| 2. FORMATION DESCRIPTION | | 9. STATIC WATER LEVEL: <u>Flowed</u> ft. below land surface <input type="checkbox"/> Flow | | | | |
| Gravel + Sand | THICKNESS OF STRATUM <u>20'</u> | 10. PUMPING LEVEL: below land surface
<u>120</u> ft. after <u>1</u> hrs. pumping at <u>3</u> G.P.M.
ft. after _____ hrs. pumping at _____ G.P.M. | | | | |
| Clay | <u>99'</u> | 11. WELL HEAD COMPLETION: <input type="checkbox"/> Pileless adaptor <input checked="" type="checkbox"/> 12" above grade
<input type="checkbox"/> Basement offset <input type="checkbox"/> Approved pit | | | | |
| Gravel + Clay (Dry) | <u>3'</u> | 12. WELL GROUTED? <input type="checkbox"/> No <input checked="" type="checkbox"/> Yes From <u>0</u> to <u>119</u> ft.
<input type="checkbox"/> Neat cement <input checked="" type="checkbox"/> Bentonite <input type="checkbox"/> Other | | | | |
| Clay | <u>3'</u> | No. of Bags of Cement _____ Additives _____ | | | | |
| Coldwater Shale + Clay | <u>6'</u> | 13. Nearest source of possible contamination
Type <u>SPR</u> Distance <u>150</u> ft. Direction <u>So</u>
Well disinfected upon completion? <input checked="" type="checkbox"/> Yes <input type="checkbox"/> No
Was old well plugged? <input checked="" type="checkbox"/> Yes <input type="checkbox"/> No | | | | |
| water Bearing Shale | <u>57'</u> | 14. PUMP: <input checked="" type="checkbox"/> Not installed <input type="checkbox"/> Pump Installation Only
Manufacturer's name _____
Model number _____ HP _____ Volts _____
Length of Drop Pipe _____ ft. capacity _____ G.P.M.
TYPE: <input type="checkbox"/> Submersible <input type="checkbox"/> Jet
PRESSURE TANK: Manufacturer's name _____
Model number _____ Capacity _____ Gallons | | | | |
| 15. Remarks, elevation, source of data, etc. | | 16. WATER WELL CONTRACTOR'S CERTIFICATION:
This well was drilled under my jurisdiction and this report is true to the best of my knowledge and belief.
<u>Kate Well Drilling Inc 0393</u>
REGISTERED BUSINESS NAME
Address <u>140 So Main St</u> Registration No. _____
Signed <u>Rich Lacey</u> Date <u>1-12-88</u>
AUTHORIZED REPRESENTATIVE | | | | |
| 17. Rig Operator's Name: <u>Rich Lacey</u> | | Authority: Act 366 PA 1978
Completion: Required
Penalty: Conviction of a violation of any provision is a misdemeanor | | | | |

OG7d 12/85

GEOLOGICAL SURVEY COPY

UNRECORDED COPY

SECRET

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二、参考文献

Doc No. K15C27

WELL LOG No. 50 J CITY Farchmont

County Kalamazoo

Owner City of Bucharest

Township Cooper

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Senior 34, 2115

Location

State Michigan

From Land Description _____ ft. East and _____ ft. North of SW Corner of Se

~~From Street or Road 900ft W. of 20th St. 650ft W. of E. 1/4 of 1/4 Sec. 34~~

750 E. of Kalamazoo River - Property owned by Devey & Pearl Polmatier

[illegible][illegible]

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BIBLIOGRAPHY

- Abdul, A. S. and Gillham, R. W. (1984). Laboratory studies of the effects of the capillary fringe on streamflow generation. *Water Resources Research* **20**, 691-698.
- Abdul, A. S. and Gillham, R. W. (1989). Field studies of the effects of the capillary fringe on streamflow generation. *Journal of Hydrology* **112**, 1-18.
- Agertved, J., Rugge, K., and Barker, J. F. (1992). Transformation of the herbicides MCPP and atrazine under natural aquifer conditions. *Ground Water* **30**, 500-506.
- Allen, W. B., Miller, V. B., and Wood, M. W. (1972). Availabitliy of water in Kalamazoo County, Southwestern Michigan. *U. S. Geological Survey, Water Supply Paper* **1973**.
- Andrews, R., Brewer, S., Clarey, T., Dixon, J., Hunt, J., Marin, J., and Smith, J. (1993). West Kalamazoo River Assignment Area. Western Michigan University. Kalamazoo, Michigan. (*Unpublished Report*).
- Andricevic, R. (1996). Evaluation of sampling in the subsurface. *Water Resources Research* **32**, 863-874.
- Appleyard, S. J. (1995). Investigation of ground water contamination by fenamiphos and atrazine in a residential area: Source and distribution of contamination. *Ground Water Monitoring and Remediation* **15**, 110-113.
- Arcement, G. J. and Schneider, V. R. (1989). Guide for selecting Manning's roughness coefficients for natural channels and flood plains. *U. S. Geological Survey Water Supply Paper* **2339**.
- Arihood, L. D. and Glatfelter, D. R. (1991). Method for estimating low-flow characteristics of ungaged streams in Indiana. *U. S. Geological Survey Water Supply Paper* **2372**.
- Arnold, J. G., Allen, P. M., Muttiah, R., and Bernhardt, G. (1995). Automated base flow separation and recession analysis techniques. *Ground Water* **33**, 1010-1018.

- Atekwana, E. A. and Krishnamurthy, R. V. (1997). Stable isotope investigations of landfill groundwater interaction. *Water Resources Research*. (In review).
- Austin, F. R. (1979). Soil Survey of Kalamazoo County, Michigan. U. S. D. A. Soil Conservation Service and Michigan Agricultural Experiment Station.
- Ballard, S. (1996). The in situ permeable flow sensor: A groundwater flow velocity meter. *Ground Water* 34, 231-240.
- Ballard, S., Barker, G. T., and Nichols, R. L. (1996). A test of the in situ permeable flow sensor at Savannah River, SC. *Ground Water* 34, 389-396.
- Banks, W. S. L., Paylor, R. L., and Hughes, W. B. (1996). Using thermal-infrared imagery to delineate ground-water discharge. *Ground Water* 34, 434-443.
- Belanger, T. V. and Kirkner, R. A. (1994). Groundwater/surface water interaction in a Florida augmentation lake. *Lake and Reservoir Management* 8, 165-174.
- Beres, M. and Haeni, F. P. (1991). Application of ground-penetrating-radar methods in hydrogeologic studies. *Ground Water* 29, 375-386.
- Blair, T. C. and McPherson, J. G. (1994). Alluvial fans and their natural distinction from rivers based on morphology, hydraulic processes, sedimentary processes, and facies assemblages. *Journal of Sedimentary Research* A64, 450-489.
- Blasland & Bouck Engineers P. C. (1992). Allied Paper, Inc./Portage Creek/Kalamazoo River Superfund Site, description of the current situation. (*Unpublished Report*).
- Blystra, A., Dellapenna, T. M., Lal, I., Rudiman, W., and Stee, J. V. (1993). Kalamazoo River east wetlands delineation report. Western Michigan University. Kalamazoo, Michigan. (*Unpublished Report*).
- Born, S. M., Smith, S. A., and Stephenson, D. A. (1979). Hydrogeology of glacial-terrain lakes, with management and planning applications. *Journal of Hydrology* 43, 7-43.
- Bouchard, R., Higgins, M., and Rock, C. (1996). Using constructed wetland-pond systems to treat agricultural runoff: A watershed perspective. *Lake and Reservoir Management* 11, 29-36.
- Buckett, J. and Oliver, F. R. (1977). Fitting the Pearson Type 3 distribution in practice. *Water Resources Research* 13, 851-852.

- Campbell, B. D. (1988). Breach analysis of the Calkins Bridge hydropower project. Western Michigan University. Kalamazoo, Michigan. (*Unpublished*).
- Cherakauer, D. A. and McBride, J. M. (1988). A remotely operated seepage meter for use in large lakes and rivers. *Ground Water* 26, 165-171.
- Chu, S. T. (1978). Infiltration during an unsteady rain. *Water Resources Research* 14, 461-466.
- Cousins-Leatherman, C., Foust, T. S., and West, M. K. (1992). Kalamazoo County Groundwater Protection Strategy 1993. Kalamazoo County Human Services Department. Kalamazoo, Michigan.
- Cox, W. B. and Stephens, D. B. (1988). Field study of ephemeral stream-aquifer interaction. In *Proceedings of FOCUS conference on southwestern ground water issues*, 337-358.
- Cronshey, R. (1975). Urban hydrology for small watersheds. Soil Conservation Service, Report No. SCS/ENG/TR-55.
- Cummings, T. R. (1980). Chemical and physical characteristics for natural ground waters in Michigan: A preliminary report. *U. S. Geological Survey Open-File Report* 80-953.
- Daniel, J. F. (1976). Estimating groundwater evapotranspiration from streamflow records. *Water Resources Research* 12, 360-364.
- Daniels, J. J. (1989). Fundamentals of ground penetrating radar. In *Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP)* 2, 62-142.
- Dolan, T. J., Hermann, A. J., Bayley, S. E., and Zoltek, J. (1984). Evapotranspiration of a Florida, U. S. A. freshwater wetland. *Journal of Hydrology* 74, 355-371.
- Downing, J. A. and Peterka, J. J. (1978). Relationship of rainfall and lake groundwater seepage. *Limnology and Oceanography* 23, 821-825.
- Duband, D., Obled, C., and Rodriguez, J. Y. (1993). Unit hydrograph revisited: An alternate iterative approach to UH and effective precipitation identification. *Journal of Hydrology* 150, 115-150.
- Duncan, D., Pederson, D. T., Shepherd, T. R., and Carr, J. D. (1991). Atrazine used as a tracer of induced recharge. *Ground Water Monitoring and Remediation* 144-164.

- Durfor, C. N. and Becker, E. (1964). Public water supplies of the 100 largest cities in the United States, 1962. *U. S. Geological Survey Water Supply Paper 1812*.
- Eagleman, J. R. (1967). Pan evaporation, potential and actual evapotranspiration. *Journal of Applied Meteorology* 6, 482-488.
- Eagleson, P. S. (1978). Climate, soil and vegetation: 1. Introduction to water balance dynamics. *Water Resources Research* 14, 705-712.
- Eagleson, P. S. (1978). Climate, soil and vegetation: 2. The distribution of annual precipitation derived from observed storm sequences. *Water Resources Research* 14, 713-721.
- Eagleson, P. S. (1978). Climate, soil and vegetation: 3. A simplified model of soil moisture movement in the liquid phase. *Water Resources Research* 14, 722-730.
- Eagleson, P. S. (1978). Climate, soil and vegetation: 4. The expected value of annual evapotranspiration. *Water Resources Research* 14, 731-739.
- Eagleson, P. S. (1978). Climate, soil and vegetation: 5. A derived distribution of storm runoff. *Water Resources Research* 14, 741-748.
- Eagleson, P. S. (1978). Climate, soil and vegetation: 6. Dynamics of the annual water balance. *Water Resources Research* 14, 749-764.
- Eagleson, P. S. (1978). Climate, soil and vegetation: 7. A derived distribution of annual water yield. *Water Resources Research* 14, 765-776.
- Eichenlaub, V. L., Harman, J. R., Nurnberger, F. V., and Stolle, H. J. (1990). The Climatic Atlas of Michigan. The University of Notre Dame Press, Notre Dame, Indiana.
- El-Kadi, A. I., Oloufa, A. A., Eltahan, A. A., and Malik, H. U. (1994). Use of a Geographic Information System in site-specific ground-water modeling. *Ground Water* 32, 617-625.
- Faulkner, S. P., Patrick, W. H., and Gambrell, R. P. (1989). Field techniques for measuring wetland soil parameters. *Soil Science Society of America Journal* 53, 883-890.
- Fetter, C. W. Jr. (1994). Applied Hydrogeology. 3rd Edition. Prentice Hall. Englewood Cliffs, NJ.

- Freedman, P. L. and Marr, J. K. (1986). Kalamazoo River water quality analysis and model simulation. Limno-Tech, Inc. (*Unpublished Report*).
- Freeze, R. A. and Cherry, J. A. (1979). Groundwater. Prentice-Hall. Englewood Cliffs, NJ.
- Fritz, P., Reardon, E. J., Barker, J. and others (1978). The carbon isotope geochemistry of a small groundwater system in Northeastern Ontario. *Water Resources Research* 14, 1059-1067.
- Gat, J. R. and Gonfiantini, R. (1981). Stable isotope hydrology Deuterium and Oxygen-18 in the water cycle. *Technical Reports Series* 210. International Atomic Energy Agency, Vienna.
- Gerla, P. J. (1992). The relationship of water-table changes to the capillary fringe, evapotranspiration, and precipitation in intermittent wetlands. *Wetlands* 12, 91-98.
- Giese, G. L. and Mason, R. R. (1993). Low-flow characteristics of streams in North Carolina. *U. S. Geological Survey Water Supply Paper* 2403.
- Gillham, R. W. (1984). The capillary fringe and its effects on water-table response. *Journal of Hydrology* 67, 307-324.
- Gray, D. M. (1961). Interrelationships of watershed characteristics. *Journal of Geophysical Research* 66, 1215-1223.
- Gupta, S. K. and Solomon, S. I. (1977). Distributed numerical model for estimating runoff and sediment discharge of ungaged rivers: 1. The information system. *Water Resources Research* 13, 613-618.
- Gupta, S. K. and Solomon, S. I. (1977). Distributed numerical model for estimating runoff and sediment discharge of ungaged rivers: 3. Comparison with other simple techniques. *Water Resources Research* 13, 631-636.
- HACH Company (1992). Water Analysis Handbook. HACH Company.
- Haeni, F. P. (1986). The use of electromagnetic methods to delineate vertical and lateral lithologic changes in glacial aquifers. In *Proceedings of the Surface and Borehole Geophysical Methods and Ground Water Instrumentation Conference and Exposition*, 259-282.
- Hanshue, S. (1993). Allied Paper, Inc./Portage Creek/Kalamazoo River Superfund Site. MDNR, Surface Water Quality Division. (*Unpublished Report*).

- Harris, D. M., McDonnell, J. J., and Rodhe, A. (1995). Hydrograph separation using continuous open system isotope mixing. *Water Resources Research* 31, 157.
- Harvey, J. W., Wagner, B. J., and Bencala, K. E. (1996). Evaluating the reliability of the stream tracer approach to characterize stream-subsurface water exchange. *Water Resources Research* 32, 2441-2451.
- Heath, R. C. (1987). Basic ground-water hydrology. *U. S. Geological Survey Water Supply Paper* 2220.
- Heliotis, D. F. and DeWitt, C. B. (1987). Rapid water table responses to rainfall in a northern peatland ecosystem. *Water Resources Bulletin* 23, 1011-1016.
- Heller, C. and Dickason, D. (1993). Yesterday's decisions, today's impact, tomorrow's outlook. The land use histories of Kalamazoo County & Barry County. Western Michigan University. Kalamazoo, Michigan. (*Unpublished*).
- Hensel, B. R. and Miller, M. V. (1991). Effects of wetlands creation on groundwater flow. *Journal of Hydrology* 126, 293-313.
- Hoggan, D. H. (1989). Computer-Assisted Floodplain Hydrology and Hydraulics. McGraw-Hill Publishing Company. New York.
- Hollands, G. G. (1987). Hydrogeologic classification of wetlands in glaciated regions. *National Wetlands Newsletter* 9, 6-9.
- Holtschlag, D. J. and Salehi, H. (1991). Statistical models for estimating daily streamflow in Michigan. *U. S. Geological Survey Water Resources Investigations Report* 91-4194.
- Hoos, A. B. (1990). Recharge rates and aquifer hydraulic characteristics for selected drainage basins in middle and east Tennessee. *U. S. Geological Survey Water Resources Investigations Report* 90-4015.
- Horton, R. E. (1933). The role of infiltration in the hydrologic cycle. *American Geophysical Union Transactions* 14, 446-460.
- Hunt, R. J., Krabbenhoft, D. P., and Anderson, M. P. (1996). Groundwater inflow measurements in wetland systems. *Water Resources Research* 32, 495-507.
- Hyder, Z. and Butler, J. J. (1995). Slug tests in unconfined formations: An assessment of the Bouwer and Rice technique. *Ground Water* 33, 16-22.

- Inman, E. J. (1987). Simulation of flood hydrographs for Georgia streams. *U. S. Geological Survey Water Supply Paper 2317*.
- John, P. H. and Lock, M. A. (1977). The spacial distribution of groundwater discharge into the littoral zone of a New Zealand lake. *Journal of Hydrology* 33, 391-395.
- Jones, G. E. (1992). City of Parchment Well Head Protection Program Report. (*Unpublished Report*).
- Jorgensen, D. G. (1989). Using geophysical logs to estimate porosity, water resistivity, and intrinsic permeability. *U. S. Geological Survey Water Supply Paper 2321*.
- Kaufman, R. W. and others (1977). A water and land resource plan for the Kalamazoo-Black-Macatawa-Paw Paw Rivers basin. Citizen's Advisory Council, County Task Forces, Michigan Department of Natural Resources, and U. S. Department of Agriculture.
- Kawecki, M. W. (1995). Meaningful interpretation of step-drawdown tests. *Ground Water* 33, 23-32.
- Kehew, A. E. and Passero, R. N. (1990). pH and redox buffering mechanism in a glacial drift aquifer contaminated by landfill leachate. *Ground Water* 28, 728-737.
- Kehew, A. E., Straw, W. T., Steinmann, W. K., Barrese, P. G., Passarella, G., and Peng, W. S. (1996). Ground-water quality and flow in a shallow glaciofluvial aquifer impacted by agricultural contamination. *Ground Water* 34, 491-500.
- Kennedy, E. J. (1984). Discharge ratings at gaging stations. In *Techniques of Water-Resources Investigations of the United States Geological Survey, Book 3*. Washington, D. C.
- Knapp, B. D. (1987). Soil Survey of Allegan County, Michigan. U. S. D. A. Soil Conservation Service.
- Knight, A. W. and Lauff, G. H. (1969). Water-quality studies on the Kalamazoo River. Technical Report No. 5. Institute of Water Research, Michigan State University.
- Kondolf, G. M., Maloney, L. M., and Williams, J. G. (1987). Effects of bank storage and well pumping on base flow, Carmel River, Monterey County, California. *Journal of Hydrology* 91, 351-369.

- Krabbenhoft, D. P. (1990). Estimating groundwater exchange with lakes: 1. The stable isotope mass balance method. *Water Resources Research* 26, 2445-2453.
- Krabbenhoft, D. P. (1990). Estimating groundwater exchange with lakes: 2. Calibration of a three-dimensional, solute transport model to a stable isotope plume. *Water Resources Research* 26, 2455-2462.
- Krabbenhoft, D. P. and Anderson, M. P. (1986). Use of numerical ground-water flow model for hypothesis testing. *Ground Water* 24, 49-55.
- Krunkle, G. R. (1962). The baseflow-duration curve, a technique for the study of groundwater discharge from a drainage basin. *Journal of Geophysical Research* 67, 1543-1554.
- Lafave, J. I. (1989). The effect of an intermittent stream on a shallow groundwater system and the implications for groundwater remediation. In *Proceedings of the National Outdoor Action Conference on Aquifer Restoration, Ground Water Monitoring, and Geophysical Methods* 3, 719-732.
- Lee, D. R. (1977). A device for measuring seepage flux in lakes and estuaries. *Limnology and Oceanography* 22, 140-147.
- Lee, D. R. (1985). Method for locating sediment anomalies in lakebeds that can be caused by groundwater flow. *Journal of Hydrology* 79, 187-193.
- Lee, D. R. and Cherry, J. A. (1978). A field exercise on groundwater flow using seepage meters and mini-piezometers. *Journal of Geology Education* 27, 6-10.
- Lee, D. R. and Harvey, F. E. (1996). Installing piezometers in deepwater sediments. *Water Resources Research* 32, 1113-1117.
- Lilienthal, M. R. (1978). Stratigraphic cross-sections of the Michigan Basin. *Michigan Geological Survey Divisions Report Investigation* 19.
- Lohman, S. W. (1972). Ground-water hydraulics. *U. S. Geological Survey Professional Paper* 708.
- Machavaram, M. V. (1993). Precipitation dynamics in Kalamazoo, SW Michigan: A stable isotope perspective. Western Michigan University. Kalamazoo, Michigan. (*Unpublished Masters Thesis*).
- Machavaram, M. V. and Krishnamurthy, R. V. (1994). Survey of factors controlling the stable isotope ratios in precipitation in the Great Lakes Region, USA. *Isr. Journal of Earth Science* 43, 195-202.

- Martin, H. M. (1957). Outline of the geologic history of Kalamazoo County. Michigan Department of Conservation, Geological Survey Division. Lansing, Michigan.
- McBride, M. S. and Pfannkuch, H. O. (1975). The distribution of seepage within lakebeds. *Journal of Research of the U. S. Geological Survey* 3, 505-512.
- McDonald, M. G., Harbaugh, A. W., Orr, B. R., and Ackerman, D. J. (1991). A method of converting no-flow cells to variable-head cells for the U.S. Geological Survey Modular Finite-Difference Ground-Water Flow Model. *U.S. Geological Survey Open-File Report 91-536*.
- McNeil, J. (1994). Problems associated with using ground penetrating radar to locate a LNAPL plume. Western Michigan University. Kalamazoo, Michigan. (*Unpublished Masters Thesis*).
- Melcher, N. B. and Walker, J. F. (1992). Evaluation of selected methods for determining streamflow during periods of ice effect. *U. S. Geological Survey Water Supply Paper 2378*.
- Milson, J. (1989). *Field Geophysics*. John Wiley & Sons. New York.
- Mohr, T. K. G., Davisson, M. L., Criss, R. E., and Fogg, G. E. (1992). Small scale application of stable isotopes ^{18}O and Deuterium to delineate migration pathways at a Class III landfill site. In *Proceedings of the 6th National Outdoor Action Conference* 11, 231-244.
- Moore, R. D. (1989). Tracing runoff sources with Deuterium and Oxygen-18 during spring melt in a headwater catchment, Southern Laurentians, Quebec. *Journal of Hydrology* 112, 135-148.
- Neild, S. P., Townley, L. R., and Barr, A. D. (1994). A framework for quantitative analysis of surface water-groundwater interaction: Flow geometry in a vertical section. *Water Resources Research* 30, 2461.
- Nemerow, N. L. (1985). *Stream, Lake, Estuary and Ocean Pollution*. Van Nostrand Reinhold Company. New York.
- Nikolaidis, N. P., Hu, H. L., and Escedy, C. (1994). Effects of climatic variability of freshwater watersheds case studies. *Water Resources Research* 30, 161.
- Osborne, P. S. (1993). Suggested Operating Procedures for aquifer pumping tests. U.S. Environmental Protection Agency, EPA/540/S-93/503.

- Owen, C. R. (1995). Water budget and flow patterns in an urban wetland. *Journal of Hydrology* **169**, 171-187.
- Panda, M. N. and Lake, L. W. (1994). Estimation of single-phase permeability from parameters of particle-size distribution. *AAPG Bulletin* **78**, 1028-1039.
- Parlange, J. Y. and Sander, G. (1985). A simplified hydrological rainfall-runoff model-Comment. *Journal of Hydrology* **80**, 395-398.
- Parrett, C. and Cartier, K. D. (1990). Method for estimating monthly streamflow characteristics at ungaged sites in Western Montana. *U. S. Geological Survey Water Supply Paper* **2365**.
- Parrett, C., Melcher, N. B., and James, R. W. (1993). Flood discharges in the Upper Mississippi River Basin, 1993. *U. S. Geological Survey Circular* **1120-A**.
- Passero, R. N. and Straw, W. T. (1988). Groundwater in Southwest Michigan. Center for Water Research, Western Michigan University. Kalamazoo, Michigan.
- Passero, R. N. and others (1978). Kalamazoo County, Geology and the Environment. Western Michigan University. Kalamazoo, Michigan.
- Pettyjohn, W. A. and Henning, R. J. (1979). Preliminary estimate of regional effective ground-water recharge rates, related streamflow and water quality in Ohio. The Ohio State University Water Resources Center. Columbus, Ohio.
- Rankl, J. G. (1990). A point-infiltration model for estimating runoff from rainfall on small basins in semiarid areas of Wyoming. *U. S. Geological Survey Water Supply Paper* **2366**.
- Raymond, L. H. and Rezin, K. V. (1989). Evapotranspiration estimates using remote-sensing data, Parker and Palo Verde Valleys, Arizona and California. *U. S. Geological Survey Water Supply Paper* **2334**.
- Rheaume, S. J. (1990). Geohydrology and water quality of Kalamazoo County, Michigan 1986-88. *U. S. Geological Survey Water-Resources Investigation Report* **90-4028**.
- Rheaume, S. J. (1991). Hydrologic provinces of Michigan. *U. S. Geological Survey Water-Resources Investigation Report* **91-4120**.

- Rogers, G. D. and Werley, M. R. (1992). A computer program (FLOWSTAT) for summarizing daily and peak streamflow statistics. *U. S. Geological Survey Open-File Report* 92-115.
- Rogers, W. F. and Singh, V. P. (1986). Some geomorphic relationships and hydrograph analysis. *Water Resources Bulletin* 22, 777-784.
- Rorabaugh, M. I. (1963). Estimating changes in bank storage and ground-water contribution to streamflow. In *Symposium—Surface Waters, General Assembly of Berkeley of IUGG*, Publication 63, 432-441.
- Rumbaugh, J. O. (1991). Quickflow Analytical Model of 2D Ground-Water Flow. Geraghty and Miller, Inc.
- Rushton, K. R. and Rathod, K. S. (1985). Horizontal and vertical components of flow deduced from groundwater heads. *Journal of Hydrology* 79, 261-278.
- Rutledge, A. T. and Daniel, C. C. (1994). Testing an automated method to estimate ground-water recharge from streamflow records. *Ground Water* 32, 180-189.
- Sartz, R. S., Curtis, W. R., and Tolsted, D. N. (1977). Hydrology of small watersheds in Wisconsin's driftless area. *Water Resources Research* 13, 524-530.
- Sauck, W. T. (1995). Geophysical reconnaissance work at Wurtsmith AFB, Fire-training Area 2(FT-02). Project Report, Institute for Water Sciences. Western Michigan University. Kalamazoo, Michigan.
- Sharma, P. V. (1986). Geophysical Methods in Geology. 2nd Edition. Elsevier, New York.
- Shan, C. (1995). Analytical solutions for determining vertical air permeability in unsaturated soils. *Water Resources Research* 31, 2193-2200.
- Shaw, R. D. and Prepas, E. E. (1989). Anomalous, short-term influx of water into seepage meters. *Limnology and Oceanography* 34, 1343-1351.
- Shaw, R. D. and Prepas, E. E. (1990). Groundwater-lake interactions: I. Accuracy of seepage meter estimates of lake seepage. *Journal of Hydrology* 119, 105-120.
- Shaw, R. D. and Prepas, E. E. (1990). Groundwater-lake interactions: II. Nearshore seepage patterns and the contributions of ground water to lakes in Central Alberta. *Journal Hydrology* 119, 121-136.

- Shirmohammadi, A., Knisel, W. G., and Sheridan, J. M. (1984). An approximate method for partitioning daily streamflow data. *Journal of Hydrology* 74, 335-354.
- Siegel, D. I. And Glaser, P. H. (1987). Groundwater flow in a bog-fen complex, Lost River Peatland, Northern Minnesota. *Journal of Ecology* 75, 743-754.
- Sikonia, W. G. (1992). Mass-conserving method of characteristics for streamflow modeling. *U. S. Geological Survey Water Supply Paper* 2369.
- Simpson, M. R. and Oltman, R. N. (1993). Discharge-measurement system using an acoustic doppler current profiler with applications to large rivers and estuaries. *U. S. Geological Survey Water Supply Paper* 2395.
- Singh, V. P. and Singh, K. (1985). Derivation of the Pearson Type (PT) III distribution by using the Principle of Maximum Entropy (POME). *Journal of Hydrology* 80, 197-214.
- Sklash, M. G. and Farvolden, R. N. (1979). The role of groundwater in storm runoff. *Journal of Hydrology* 43, 45-65.
- Solomon, S. I. and Gupta, S. K. (1977). Distributed numerical model for estimating runoff and sediment discharge of ungaged rivers: 2. Model development. *Water Resources Research* 13, 619-629.
- Squillance, P. J. (1996). Observed and simulated movement of bank-storage water. *Ground Water* 34, 121-134.
- Straw, W. T. (1976). Guidebook for a field trip on some aspects of the glacial geology of the Kalamazoo Area. North-Central Section of the Geological Society of America and Western Michigan University. Department of Geology, Western Michigan University. Kalamazoo, Michigan.
- Straw, W. T. and Kehew, A. E. (1995). Interplay of advances, meltwater events, and surges during retreat of the southeast margin of the Lake Michigan Lobe. In *Abstracts with Programs—Geological Society of America* 27, 169.
- Swain, E. D. (1993). Documentation of a computer program (STREAMLINK) to represent direct-flow connections in a coupled ground water and surface water model. *U. S. Geological Survey Water-Resources Investigation* 93-4011.
- Swain, E. D. and Wexler, E. J. (1993). A coupled surface-water and ground-water flow model for simulation of stream-aquifer interaction. *U. S. Geological Survey Open-File Report* 92-138.

- Swenson, H. A. and Baldwin, H. L. (1965). A Primer on Water Quality. U. S. Government Printing Office. Washington, D. C.
- Taniguchi, M. (1992). Development of automatic seepage meter and the application in the bottom of Lake Biwa. *Journal of Japanese Association of Hydrological Sciences* **22**, 67-74.
- Taniguchi, M. and Fukuo, Y. (1993). Continuous measurements of ground-water seepage using an automatic seepage meter. *Ground Water* **31**, 675-679.
- Tselentis, G. A. (1985). The processing of geophysical well logs by microcomputers as applied to the solution of hydrogeological problems. *Journal of Hydrology* **80**, 215-236.
- Walesh, S. G. (1989). Urban Surface Water Management. John Wiley and Sons, Inc. New York.
- Watson, I. and Burnett, A. D. (1993). Hydrology: An Environmental Approach. Buchanan Books. Ft. Lauderdale, Florida.
- Weeks, E. P. and Sorey, M. L. (1973). Use of finite-difference arrays of observation wells to estimate evapotranspiration from ground water in the Arkansas River Valley, Colorado. *U. S. Geological Survey Water Supply Paper* **2029-C**.
- Wiche, G. J., Jenson, S. K., Baglio, J. V., and Domingue, J. O. (1992). Application of digital elevation models to delineate drainage areas and compute hydrologic characteristics for sites in the James River Basin, North Dakota. *U. S. Geological Survey Water Supply Paper* **2383**.
- Williams, G. P. (1978). Bank-full discharge of rivers. *Water Resources Research* **14**, 1141-1154.
- Williams & Works (1980). Hydrogeologic report on an existing landfill. Brown Company. Kalamazoo, Michigan. (*Unpublished Report*).
- Winter, T. C. (1976). Numerical simulation analysis of the interaction of lakes and ground water. *U. S. Geological Survey Professional Paper* **1001**.
- Winter, T. C. (1983). The interaction of lakes with variably saturated porous media. *Water Resources Research* **19**, 1203-1218.
- Woessner, W. W. and Sullivan, K. E. (1984). Results of seepage meter and mini-piezometer study, Lake Mead, Nevada. *Ground Water* **22**, 561-568.

- Wolf, R. J. and Helgesen, J. O. (1993). Ground- and surface-water interaction between the Kansas River and associated alluvial aquifer, Northeastern Kansas. *U. S. Geological Survey Water Resources Investigations Report 92-4137*.
- Wood, E. F. and Szollosi-Nagy, A. (1978). An adaptive algorithm for analyzing short-term structural and parameter changes in hydrologic prediction models. *Water Resources Research* 14, 577-581.
- Yeasted, G. J. (1986). Feasibility study of alternatives, Volume 1, Kalamzoo River PCB project, Kalamazoo and Allegan Counties, Michigan. *NUS Corporation Report*.
- Younger, P. L. (1993). Sample generalized methods for estimating aquifer storage parameters. *Journal of Engineering Geology* 26, 127-135.
- Zecharias, Y. B. and Brutsaert, W. (1988). The influence of basin morphology on groundwater outflow. *Water Resources Research* 24, 1645-1650.